REANALYSES OF CERTAIN NUCLEAR EVAPORATION SPECTRA EXHIBITING ANOMALIES

SHAHIDA PARVIN ALI

13642

REANALYSES OF CERTAIN NUCLEAR EVAPORATION SPECTRA EXHIBITING ANOMALIES

by

Shahida Parvin Ali, M.Sc. (Peshawar)

Submitted in partial fulfilment
of the requirements for the degree of Master of Science
Memorial University of Newfoundland

April, 1971

TABLE OF CONTENTS

ABSTRACT

The situation concerning the 'anomalous dependence of the shape of level density plots of nuclear evaporation spectra on the energy of the incident particle' is rather confusing. Some authors have reported observing this anomaly while others have claimed that their results did not indicate any anomaly. It is, however, not always clear if different incident energy spectra have been compared for the same excitation energy of the residual nucleus, as they should be for establishing the existence (or non-existence) of this type of anomaly. Moreover in some (n,α) and (p,n) spectra it has been reported that different choices of the inverse cross section σ_c lead to different conclusions concerning this anomaly. No thorough study of evaporation spectra with protons as emitted particles has been reported. A thorough examination of published (n,p) and (α,p) spectra was undertaken by us and those sets of spectra which were available for different incident energies were reanalyzed (using the method of least squares for straight line fitting) by us for the constant temperature model as well as for the Fermi gas model with n = 2, 1.67, 1.5, 1.25 and 0 in the expression

$$\frac{\exp 2\sqrt{aE}}{E^n}$$

and in each case we tried six different sets of σ_c; Blatt & Weisskopf (r_o = 1.3, r_o = 1.5), Shapiro (r_o = 1.3, r_o = 1.5), Lindner (optical model), and Mani et al (optical model). The aim was to find out if the conclusions concerning these spectra depended significantly on the choice of σ_c and

of level density expression. In particular, it was hoped that some combination(s) of σ_c and level density expression(s) might lead to a more consistent and less anomalous description of these spectra. Our reanalysis did indicate in many cases significantly different results for different σ_c but no overall consistent and clearer pattern has emerged. In addition to the conventional analysis a 'level density independent' approach has also been employed by us. From the detailed results certain conclusions about the relative magnitudes of T and different level density parameters have been drawn.

CHAPTER 1

INTRODUCTION

1.1 The Project

Nuclear reactions proceeding according to the 'complete statistical model' are usually analyzed on the basis of the Weisskopf-Ewing formula (Eqn. 2.7A and 2.7B). To examine the shape of these 'evaporation spectra', 'level density plots' are obtained by using suitable expression(s) representing the dependence of nuclear level density on the nuclear excitation energy. The formula involves $\omega(E_y)$, the level density of the residual nucleus Y at the excitation energy E_y. The expression based on the Fermi gas model is of the form $\frac{\exp 2\sqrt{aE_y}}{E_y^n}$ where various values of n ranging from 0 to 2 have been tried. The constant 'a' is called the level density parameter. Another commonly used form is $\exp(\frac{E_y}{T})$, the constant temperature model, where T is the nuclear temperature of the residual nucleus and is supposedly independent of E_y in this 'approximate' or more correctly 'empirical' model. (According to the Fermi gas model the nuclear temperature should be approximately proportional to $\sqrt{E_y}$.) If the use of a particular level density expression leads to a linear level density plot one can determine from the slope the appropriate level density parameter or the constant nuclear temperature. A linear level density plot is considered to be an evidence of the validity of the particular level density expression, but the basis of such models also requires that the level density parameter or T should be independent of the incident energy, i.e. the slopes of the appropriate level density plots be the same for

spectra obtained with different incident energies. Many authors have reported 'anomalous' dependence of 'a' or T on the incident energy. It is not, however, always clear whether the same criteria have been used for different spectra, particularly whether the same range of the excitation energy of the residual nucleus applies to the determination of the slopes of spectra for different incident energies. Furthermore, the analysis involves inverse cross sections for the formation of the compound nucleus if the emitted particles were to be incident on the excited residual nuclei. In actual practice, because of unavailability of cross sections for excited nuclei, one uses the cross sections calculated for the ground state. Different types of calculations have resulted in different sets of such cross sections. Concerning some (n,α) spectra it has been reported that whereas cross sections based on the 'continuum model' lead to anomalous dependence of the slopes of the level density plots on the incident energy the cross sections based on the 'optical model' remove this anomaly (ref: Bormann 1962, also see figures 3.1(a) to 3.1(e) of this thesis). Effect of the choice of these inverse cross sections has also been reported in spectra with neutrons as the emitted particles (e.g. ref. Holbrow and Barschall 1962). No thorough examination has been reported of the evaporation spectra involving protons as the emitted particles using different inverse cross sections and using different level density expressions (at the same time, following the basic criterion of comparing spectra from different incident energies for the same excitation energy region of the residual nucleus). The work presented in this thesis was undertaken to do this thorough examination by reanalyzing the available nuclear evaporation

spectra with protons as emitted particles. In addition to the examination of the slopes of the level density plots a different approach 'independent of particular forms of level density' has also been employed.

1.2 Scope of the Work Presented in This Thesis

(n,p) and (α,p) spectra have been examined from the point of view of the above mentioned anomaly. In addition to the constant temperature model analysis, five different values of n (0, 1.25, 1.5, 1.67 and 2) have been used in the Fermi gas expression of the nuclear level densities. Where applicable, effect of the 'pairing energy correction' has been studied. Six different sets of values of inverse cross section have been tried. They are: continuum model, Blatt and Weisskopf 1952 (for nuclear radius parameter r_o = 1.3f, r_o = 1.5f); continuum model, Shapiro 1953 (r_o = 1.3f, r_o = 1.5f); optical model, Lindner 1962; optical model, Mani et al 1963. Our approach is an empirical one in the sense that no detailed examination of the theoretical basis of various calculations of these inverse cross sections has been included in this work.

In view of the fact that values of the inverse cross sections could be different without really affecting the 'relative' slopes of level density plots for different incident energies, preliminary investigations were carried out to see if different sets of these cross sections were, in fact, expected to yield different results of the analysis of a given set of spectra. These preliminary investigations indicated the possibilities of noticeable differences in the results and, therefore, a detailed reanalysis of available spectra was undertaken to see if any noticeably different pattern emerges from this comparative study.

In this work no attempt has been made to examine critically the very important question of the possible effects of using inverse cross sections calculated for nuclei in their ground states, whereas the formula required values for nuclei in excited states. Our 'level density independent' approach does provide a starting point but a proper study of this aspect should be based on only very carefully selected sets of spectra. Several research and review papers do contain some comments on this question but for convenience we are listing two papers, Lane and Parker 1960 and Dudey et al 1967, which deal with this aspect more directly.

CHAPTER 2

THE STATISTICAL MODEL OF NUCLEAR REACTIONS

2.1 Introduction

The complete statistical model of nuclear reactions has the following implications:

(1) The reaction proceeds via the formation of a compound nucleus, i.e. the incident particle interacts with the target nucleus (which we will assume is not too light) in such a way that its energy and momentum are shared very quickly by other nucleons of the target nucleus and an equilibrium system of long life compared with $\sim 10^{-22}$ sec, the so-called nuclear transit time, is created. Properties of such an 'equilibrium system' are governed by the laws of conservation but are otherwise independent of the details of its formation. In particular, the decay of this equilibrium system, the compound nucleus, does not depend on the mode of its formation, except through the laws of conservation. This independence of the modes of creation and decay, implying a loss of memory by the compound nucleus, is the well-known Bohr (1936) assumption and can be expressed simply for the cross section of a nuclear reaction X(a,b)Y by the equation

$$\sigma(a,b) = \sigma_{cx}(E_a)\, G_c(b) \qquad (2.1)$$

where $\sigma_{cx}(E_a)$ is the cross section for the formation of the compound nucleus when the particle a is incident with energy E_a on the target nucleus X and $G_c(b)$ is the probability that this compound nucleus will

decay by the emission of the particle 'b' by leaving a proper residual nucleus Y, which is generally in some excited state.

(2) The incident energy is high enough to lead to a compound nucleus in the high excitation region where levels of the compound nucleus are overlapping. In view of the fact that the incident energy in any experimental set up is bound to have some spread, the overlapping of levels ensures that a large number of levels are excited and methods of statistical thermodynamics can be used in investigating the probability of the decay of such compound nuclei. The phases between the different transition amplitudes do interfere but their random distribution ensures cancellation of the cross terms in the cross section. This statistical hypothesis of randomness of phases was the basis of the pioneering contributions of Bethe 1937, Weisskoff 1937 and Ewing and Weisskopf 1940.

It may be noted that at lower incident energies compound nucleus is formed at either a well-defined level or with the participation of very few levels thus resulting in the well-known 'sharp-resonances' in the excitation functions (with possible complications due to interference terms between the 'few' excited levels).

(3) The decay of the compound nucleus leads to a residual nucleus of sufficiently high excitation energy where its energy levels are also overlapping. If, on the other hand, the transition leads to a 'well-defined level' of the residual nucleus, then the statistical methods apply to the compound nucleus but not to the residual nucleus, hence one cannot speak of the 'complete' statistical model.

In order to put the statistical model in its proper perspective it would be appropriate to refer briefly to the direct reaction model. This model implies the interaction between the incident particle and one nucleon or a small group of nucleons of the target nucleus, the whole reaction finishing in a much shorter time (of the order of nuclear transit time) compared to the time taken by the above mentioned 'slow' compound nucleus type reactions. At much higher incident energies (several tens of Mev) one naturally expects such 'fast reactions' but even at intermediate energies (few Mev to few tens of Mev) reactions such as (n,d) called pick-up reactions, and such as (d,n) called stripping reactions are of the direct reaction type, and in addition to them, inelastic scatterings such as (p,p') are predominantly of the direct reaction type. We have, furthermore, knock-out type of direct reactions competing with statistical model reactions. In a particular reaction such as (n,p) or (α,p) it is customary to check if there is a significant contribution from the direct reaction type of transition by studying angular distributions, the criterion being that the reactions going according to the statistical model are expected to show symmetry about 90^{o} (with not too much anisotropy), whereas the direct reaction mechanism is not expected to preserve this symmetry about 90^{o} and usually leads to forward peaking (reference, e.g. Wolfenstein 1951; Ericson and Strutinski 1958, 1959). This approach is of great help in separating the statistical model and the direct reaction model contributions, e.g. in an observed (n,p) spectrum, provided it is studied at different angles. It may be stressed, however, that such a procedure could be an oversimplification of the real facts.

At this point it might have been justifiable to write a few sentences about the 'optical model' but it is desirable to leave this topic for a later section (2.5) dealing with the cross section for the formation of compound nucleus.

Before giving essential outlines of the theory of the 'statistical model' in the following section we would like to remark that we are restricting our discussion to only the reactions of the type

$$a + X \rightarrow b + Y^* \qquad (2.2)$$

and are thus excluding cases of break up of the compound nucleus into more than two particles. We have denoted the above reaction simply as X(a,b)Y.

2.2 Shape of Evaporation Spectra

For the reaction X(a,b)Y we wish to know the predictions of the statistical model about the shape of the spectrum, i.e. we wish to know the appropriate expression for $\frac{dN(E_b)}{dE_b}$ where $dN(E_b)$ is the number of the emitted particles 'b' in the energy range E_b, $E_b + dE_b$. All quantities refer to the centre of mass system of the co-ordinate. The quantity $dN(E_b)$ is proportional to $\sigma_{ab}(E_a,E_b)dE_b$ where $\sigma_{ab}(E_a,E_b)$ is the cross section for the emission of the particles b per unit energy interval with the energy E_b, when the particles 'a' are incident with energy E_a on the target nuclei. First we give the outline of a simplified solution.

Now, according to equation (2.1)

$$\sigma(a,b) = \sigma_{cx}(E_a)\, G_c(b) \quad .$$

Note that here the cross section $\sigma(a,b)$ refers to all particles of the species b regardless of their energy. Instead of defining transitions only in terms of the nature of the particles it is more convenient to first focus attention on the transitions defined in greater detail which includes the nature as well as the quantum states of the particles involved. Such a detailed description denotes a specific channel. In simplified versions spins are first ignored and their effects are taken into account by using appropriate weight factors. For transitions from channel α to β we have

$$\sigma(\alpha,\beta) = \sigma_c(\alpha)\, G_c(\beta) \tag{2.3}$$

where $\sigma_c(\alpha)$ indicates cross section for the formation of the compound nucleus through the incident channel α and $G_c(\beta)$ indicates the probability of the decay of this compound nucleus to the channel β. Now,

$$G_c(\beta) = \frac{\Gamma_\beta}{\sum_\gamma \Gamma_\gamma} \tag{2.4}$$

where $\sum_\gamma \Gamma_\gamma \equiv \Gamma_{total}$, the total width of the compound nuclear states and Γ_β is the partial width.

Application of the reciprocity theorem leads to the result that

$$\frac{\sigma_c(\gamma)}{\lambda\!\!\!^{-2}_\gamma\, \Gamma_\gamma} \quad \left(\equiv \frac{k_\gamma^2\, \sigma_c(\gamma)}{\Gamma_\gamma}\right)$$

is independent of channel γ, i.e.

$$\Gamma_\gamma = \text{constant} \times k_\gamma^2\, \sigma_c(\gamma) \quad . \tag{2.5}$$

This immediately leads to the expression

$$G_c(\beta) = \frac{k_\beta^2 \, \sigma_c(\beta)}{\sum_\gamma k_\gamma^2 \, \sigma_c(\gamma)} \quad . \tag{2.6}$$

We note that the events denoted by $\frac{dN(E_b)}{dE_b}$ or $\sigma_{ab}(E_a,E_b)dE_b$ include transitions to residual nuclei with the excitation energy in the corresponding region dE_y encompassing excited levels $\omega_y(E_y)dE_y$ where $\omega_y(E_y)$ is the total density of the states (summed over all angular momenta) in the residual nucleus at the excitation energy E_y.

Use of the above mentioned reciprocity theorem leads to

$$\alpha_{ab}(E_a,E_b)dE_b = \sigma_{cx}(E_a) \, \frac{g_b M_b E_b \sigma_{cy}(E_b)\omega_y(E_y)dE_b}{\sum_i g_i M_i \int_0^{(E_i)_{max}} E_i \sigma_{cz}(E_i)\omega_z(E_z)dE_i} \tag{2.7A}$$

$$\text{i.e.} \quad \sigma_{ab}(E_a,E_b)dE_b \propto E_b \, \sigma_{cy}(E_b)\omega_y(E_y)dE_b \tag{2.7B}$$

Here $\sigma_{cx}(E_a)$ is, as already stated, the cross section for the formation of the compound nucleus for the incident particle 'a' interacting with the target nucleus X with incident energy E_a. The numerator of the other factor refers to the emission of the particle b with energy between E_b and $E_b + dE_b$ and the denominator refers to all possible modes of decays of the compound nucleus with the allowed energies (the summation term includes the numerator term, also), g_b and g_i refer to the spin weight factors $(2I_b + 1)$ and $(2I_i + 1)$, where I_b and I_i are the respective spins. M_b and M_i refer to the reduced masses. $\sigma_{cy}(E_b)$ is the inverse cross section for the formation of a compound nucleus

if the particle 'b' with energy E_b were incident on the residual nucleus y in its excited state of energy E_y. Similar meanings hold for $\sigma_{cz}(E_i)$ referring to other modes of decay.

Equations (2.7A) and (2.7B) give the well-known Weisskopf-Ewing formula for the 'evaporation spectrum'.

This Weisskopf-Ewing formula can be shown to be an approximate form of a more general formula when certain additional assumptions are made. In the general formalism one can first write for transitions between specific channels,

$$\sigma(\alpha,\beta) = \pi\lambda^2 \sum_{J,j,\ell,j',\ell'} \frac{(2J+1)}{(2I_a+1)(2I_x+1)} \left[\frac{T^J_{\beta j'\ell'}\, T^J_{\alpha j\ell}}{\sum_{\gamma,j'',\ell''} T^J_{\gamma,j'',\ell''}} \right] \tag{2.8}$$

where J is the total angular momentum (i.e. the angular momentum of the compound nucleus) and is one of the vector sums of I_a (spin of the incident particle), I_x (spin of the target X) and ℓ, the orbital angular momentum of the relative motion of a and X. J is also one of the vector sums of I_b, I_y and ℓ' (orbital angular momentum of the relative motion of the emitted particle b and the residual nucleus Y). j and j' are channel spins for the channel α and β, respectively, and by definition j is the vector sum $(I_a + I_x)$ or equally the vector difference $(J - \ell)$, and, similarly, j' is the vector sum $(I_b + I_y)$ or the vector difference $(J - \ell')$.

$T^J_{\alpha j\ell}$ is the 'penetrability' for the incident particle entering the target nucleus to form a compound nucleus under the circumstances

specified by (J,α,j,ℓ). Similarly, $T^J_{\beta j'\ell'}$ is the 'penetrability' for the inverse process of the formation of the compound nucleus by the emitted particle b incident on the excited residual nucleus under the circumstances specified by J, β, j', ℓ'. The terms under the summation $\sum_{\gamma j''\ell''} T^J_{\gamma j''\ell''}$ refer to all possible open channels for the decay of the compound nucleus. The terms under the first summation $\sum_{J,j,\ell,j',\ell'}$ must satisfy the conservation of the angular momentum

$$\begin{aligned} |J - \ell| &\le j \le J + \ell \\ |J - I_a| &\le j \le J + I_a \\ |J - \ell'| &\le j' \le J + \ell' \\ |J - I_b| &\le j' \le J + I_b \quad . \end{aligned} \tag{2.9}$$

The summation terms must also satisfy the parity requirements.

When transitions lead to a 'continuum' of the final states, instead of a well-defined separate state, expression (2.8) should be summed (or integrated) over the appropriate energy range. Neglecting fission or radiative transitions and noting that no parity conservation restrictions are present since the continuum is supposed to have equal population of positive and negative parity states, one obtains for the cross section for the reaction induced by the particle a with energy E_a leading to the particle b with energy in the interval E_b, $E_b + dE_b$ as

$$\sigma_{a,b}(E_a,E_b)dE_b = \pi\lambda^2 \sum_{J,j,\ell} \frac{(2J+1)}{(2I_a+1)(2I_x+1)} \times \frac{T^J_{aj\ell}(E_a) \sum_{j'\ell'I_y} T^J_{bj'\ell'}(E_b)\omega_y(I_y,E_y)dE_b}{\sum_{i,j'',\ell'',I''_z} \int_0^{(E_i)_{max}} T_{ij''\ell''}(E_i)\omega_z(I_z,E_z)dE_i} \tag{2.10}$$

where $\omega_y(I_y,E_y)$ is the density of levels with spin I_y and excitation energy E_y referring to the residual nucleus Y; similarly, the terms $\omega_z(I_z,E_z)$ refer to residual nuclei of all open channels.

The Weisskopf-Ewing formula (2.7A) and (2.7B) can be obtained from the more generally valid equation (2.10) by adding two more assumptions:

(i) The spin and excitation energy dependence of the level density of a nucleus can be factored into

$$\omega(I,E) = (2I + 1)\ \omega_0(E) \quad . \tag{2.11}$$

$\omega_0(E)$ is such that $\sum_I \omega(I,E) = \omega(E)$. Equation (2.11) amounts to the statement that $\omega(I,E)$ is proportional to $(2I + 1)$.

(ii) The penetrabilities do not depend on j' or J but only on ℓ.

The assumption (ii) further implies that the combinations $\sum_\ell (2\ell + 1)T_\ell$ can be replaced according to the expressions like

$$\sigma_{cy}(E_b) = \frac{\pi}{k_b^2} \sum_{\ell'} (2\ell' + 1)T_{\ell'}(E_b) \tag{2.12}$$

where $\sigma_{cy}(E_b)$ as explained earlier is the cross section for the formation of the compound nucleus in the inverse process of the particle 'b' interacting with the residual nucleus Y (at the excitation energy E_y).

The significance of the assumption expressed in the form of equation (2.11) above is as follows. It has been shown (reference, e.g. Marmier and Sheldon 1970) that a more realistic spin and energy dependence of the level density of a nucleus is of the form

$$\omega(I,E) = \frac{1}{(8\pi\ \sigma^6)^{\frac{1}{2}}}\ (2I + 1)\ \exp\left[-\frac{I(I+1)}{2\sigma^2}\right]\ \omega(E) \qquad (2.13)$$

where σ is the so-called spin cut-off parameter. (It may be mentioned that σ^2 is also equal to $\mathcal{J}T/\hbar^2$, where $\mathcal{J}$ is the moment of inertia of the nucleus and T is the nuclear temperature which is defined later on.) This equation expresses the fact that the contribution from the spin I levels to the total level density $\omega(E)$ is not merely given by the usual (2I + 1) weight factor but is strongly influenced by the exponential term decreasing the contribution from large values of I, hence the term "spin cut-off" for the parameter σ. Equation (2.11) ignores this angular momentum effect which may not be a justified approximation in many cases. In this thesis the analyses of the spectra has been based on the approximate Weisskopf-Ewing formula for the evaporation spectra, a practice which has been almost invariably followed by the researchers in analyzing the evaporation spectra. In the section dealing with the discussion of our results we have made some comments on this practice.

2.3 Level Density Parameters and Nuclear Temperature According to the Fermi Gas Model

By treating the nucleus as a fermion gas of A nucleons and by using an approach analogous to the statistical thermodynamics, Bethe 1937 obtained the following expression for the level density at the excitation energy E

$$\omega(E) = \frac{\exp(S(E)/k)}{kt\left(\frac{2\pi}{k}\ \frac{dE}{dt}\right)^{\frac{1}{2}}} \qquad (2.14)$$

where S(E) is the entropy of the nucleus, k is Boltzmann's constant and 't' is the 'thermodynamic nuclear temperature' defined by

$$\frac{dS(E)}{dE} = \frac{1}{t} \tag{2.15}$$

However, the temperature is usually defined in energy units equivalent to the usual thermodynamic temperature multiplied by Boltzmann's constant. We define the thermodynamic nuclear temperature in energy units as $\tau = kt$.

In analyzing the evaporation spectra it has become customary to define an 'experimental nuclear temperature' by the equation

$$\frac{1}{T} = \frac{d}{dE} [\ell n\ \omega(E)] \quad . \tag{2.16}$$

T like τ is expressed in energy units, otherwise the right-hand side of the equation (2.16) would be $\frac{d}{dE}$ [k ℓn ω(E)]. Now from equations (2.13) to (2.15)

$$\frac{1}{T} = \frac{1}{\tau} - \frac{1}{2} \frac{d}{dE} [\ell n(\tau^2 \frac{dE}{d\tau})] \tag{2.17}$$

and for practical purposes the second term can be neglected, thus giving

$$T \sim \tau \quad . \tag{2.18}$$

T, the 'experimental nuclear temperature', is always slightly greater than the 'thermodynamic (or true) nuclear temperature' but the difference becomes significant only for light nuclei at low excitation energies. The actual numerical relationship between T and τ depends on the model furnishing connection between E and τ

The Fermi gas model also has been used by several authors to obtain expressions for dependence of level density on the excitation

energy of the nucleus. The formulation by Lang and Le Couteur 1954 gives the following result which finds widespread application

$$\omega(E) \propto \frac{\exp 2\sqrt{aE}}{(E + \tau)^{5/4}} \tag{2.19}$$

where 'a', called the level density parameter, is a constant for the nucleus and is expected to depend on mass number and Fermi energy according to the equation

$$a = \frac{3\pi^2}{12} \frac{A}{E_{Fermi}} \quad . \tag{2.20}$$

Consistent with equations (2.19) and (2.20) is the following relation between E and τ

$$E = a\tau^2 - \tau \quad . \tag{2.21}$$

Frequently, one uses an approximate form

$$E = aT^2 \quad . \tag{2.22}$$

If equation (2.19) is substituted in the Weisskopf-Ewing formula (i.e. eq. 2.7B) the predicted spectral shape then takes the form

$$\sigma_{ab}(E_a,E_b)dE_b \propto E_b\sigma_{cy}(E_b) \frac{\exp 2\sqrt{aE_y}}{(E_y + \tau_y)^{5/4}} dE_b \tag{2.23}$$

For high excitation energies the term $\frac{\exp 2\sqrt{aE_y}}{(E_y + \tau_y)^{5/4}}$ approaches $\frac{\exp 2\sqrt{aE_y}}{E_y^{5/4}}$.

For convenience we shall refer to this approximation as

$$\omega(E_y) \propto \frac{\exp 2\sqrt{aE_y}}{E_y^n} \qquad \text{with } n = 1.25 \quad . \tag{2.24}$$

Other calculations based on equivalent assumptions may lead to a different value of n in the high energy approximation. For example, Thomas 1964 shows that n = 2 for high energy approximation and that n = 1.67 for a more realistic approximation for the energy region usually covered by experiments in the A = 50 region.

A somewhat poorer approximation n = 0 has also been used by several researchers in analyzing the evaporation spectra. Without going into detailed arguments about the merits or demerits of different values of n we take an empirical approach of taking n = 0, 1.25, 1.5 1.67 and 2 in examining the evaporation spectra. It may be pointed out that n = 1.25 and 1.5 are quite realistic values according to Thomas under certain other approximations but because for comparison purposes n = 0 has to be included in our analyses we look at various n values from an empirical point of view.

The level density expressions introduced here have been improved further by including the odd-even effect, i.e. the pairing energy effect which changes E_y in $\frac{\exp 2\sqrt{aE_y}}{E_y}$ to an 'effective' excitation energy'

$$U = E_y - \delta_p \tag{2.25}$$

where δ_p is the pairing energy correction term for the odd nucleon(s), i.e. for only odd proton nucleus.

$$U = E_y - \delta_{pp} \tag{2.26}$$

for an odd neutron nucleus

$$U = E_y - \delta_{pn} \quad . \tag{2.27}$$

and for an odd-odd nucleus

$$U = E_y - (\delta_{pn} + \delta_{pp}) \quad . \tag{2.28}$$

It may be added that the pairing energy corrected level density formula

$$\omega(E_y) \propto \frac{\exp 2\sqrt{a'U}}{U^n}$$

expresses the fact that among comparable nuclei smaller values of level density are obtained at a given excitation energy if they are of even-even type than if they are of odd-odd type and that the case for the odd A nuclei occupies an intermediate position. From a practical point of view we would like to add that almost universally the experimentalists use values of the pairing energy correction term as calculated and tabulated by Cameron 1958, but it sould be noted that he has taken $\delta_p = 0$ for odd-odd nuclei and, therefore, negative values for δ_{pp} and δ_{pn} are listed for even proton and even neutron numbers.

2.4 Constant Temperature Model for Level Densities

Now from equation (2.15) and the definition $\tau = kt$ one obtains

$$\frac{dS(E)}{dE} = \frac{k}{\tau} \tag{2.29}$$

and if one accepts the approximation $T \approx \tau$ we get

$$\frac{dS(E)}{dE} \simeq \frac{k}{T} = k \frac{d}{dE} (\ell n\ \omega(E)) \tag{3.30}$$

from equation (2.16). Thus

$$\omega(E) \propto \exp(S(E)/k) \quad . \tag{2.31}$$

Applying this to the Weisskopf-Ewing formula we get

$$\sigma_{ab}(E_a,E_b)dE_b \propto E_b\ \sigma_{cy}(E_b)\ \exp(S_y(E_y)/k)dE_b \quad . \tag{2.32}$$

Now

$$E_y = E_{b_{max}} - E_b \tag{2.33}$$

where $E_{b_{max}}$ is the maximum energy of the emitted particle, If $E_b << E_{b_{max}}$ then by Taylor's expansion we obtain

$$S_y(E_y) \cong S_y(E_{b_{max}}) - E_b \left(\frac{dS_y}{dE_y}\right)_{E_y = E_{b_{max}}} \tag{2.34}$$

Denoting $(\frac{dS_y}{dE_y})_{E_y = E_{b_{max}}} \cong \frac{k}{T_m}$ (compare with equation (2.30)) and substituting from equation (2.34) into equation 2.32) we get

$$\sigma_{ab}(E_a,E_b)dE_b \propto E_b\, \sigma_{cy}(E_b) \exp\,(-\frac{E_b}{T_m})dE_b \quad . \tag{2.35}$$

It should be stressed that equation (2.35) implying a constant temperature T_m has been derived for the approximation $E_b << E_{b_{max}}$.

The spectral shape given by (2.35) also implies

$$\omega_y(E_y) \propto \exp\,(-\frac{E_b}{T_m}) \tag{2.36}$$

or alternatively expressing in terms of $E_y = E_{b_{max}} - E_b$, it implies

$$\omega_y(E_y) \propto \exp\,(\frac{E_y}{T_m}) \quad . \tag{2.37}$$

It so happens that the constant temperature model of level densities has been found to be valid in many cases not satisfying the condition $E_b << E_{b_{max}}$. Thus, though this form of level density expression is justified for the approximation $E_b << E_{b_{max}}$, researchers have tended to try this expression on an empirical basis implying T being constant and independent of excitation energy of the residual nucleus, a feature

which is contrary to the Fermi gas model expressions (except for situations justifying the approximation $E_b << E_{b_{max}}$).

2.5 The Cross Section for the Formation of Compound Nucleus

For comparing the experimental results with the Weisskopf-Ewing formula we need to know $\sigma_{cy}(E_b)$, i.e. the cross section for the formation of the compound nucleus in the inverse process of the particle 'b' impinging with energy E_b on the excited residual nucleus Y at the excitation energy E_y. No calculations or experimental data are available for this quantity for excited nuclei. However, a great deal of work has been done on the calculation of the cross section for the formation of compound nucleus for target nuclei in ground state and these values are used in the analysis of evaporation spectra even when values are required for excited nuclei. For neutrons, protons and alpha particles, calculations are available for different energies and targets. The calculated values could be checked with direct experimental results only in relatively few cases and one relies heavily on calculated values in analyzing spectra. In the following paragraphs we give a brief outline of the 'continuum model' and the 'optical model' employed in the calculation of these cross sections.

2.5(a) The Continuum Model. In this model, the nucleus is assumed to have the property of 'strongly absorbing' the impinging particle resulting in a quick amalgamation and formation of a compound nucleus. At incident energies high enough to provide a very large number of open channels for the decay of the compound nucleus one can ignore the 'compound elastic scattering' and, thus, the total reaction cross

section can be put equal to the cross section for the formation of the compound nucleus. We express this by the equation

$$\sigma_c \cong \sigma_r \quad . \tag{2.38}$$

Now

$$\sigma_r = \pi\lambda^2 \sum_{\ell} (2\ell + 1)\ (1 - |\eta_\ell|^2) \tag{2.39}$$

where the complex number $\eta_\ell (|\eta_\ell| < 1)$ appears in the radial wave function $u_\ell(r)$ (of the subwave of angular momentum ℓ) outside the nucleus and written as a sum of 'ingoing' and 'outgoing' waves

$$u_\ell(r) = A\, u_\ell^{(-)}(r) + \eta_\ell\, A\, u_\ell^{(+)}(r) \quad . \tag{2.40}$$

The continuum model makes certain assumptions about the conditions at the nuclear surface and then relates η_ℓ to them. Briefly these assumptions are that for $r < R$, $u_\ell(r)$ is of the form of an ingoing wave only, i.e. $u_\ell(r) \sim \exp(-iKr)$ and that this wave number inside the nucleus is

$$K^2 = k^2 + k_o^2 \tag{2.41}$$

where k is the wave number outside the nucleus and k_o is the contribution from the 'intra-nuclear motion'. One then obtains

$$\sigma_c = \pi\lambda^2 \sum_{\ell} (2\ell + 1)\, \frac{4p_\ell KR}{S_\ell^2 + (KR + p_\ell)^2} \tag{2.42}$$

where R is the nuclear radius and the quantities p_ℓ and S_ℓ are completely determined from conditions outside the nucleus through the equation (used to define these quantities)

$$R\left[\frac{du_\ell^{(+)}(r)}{dr} \Big/ u_\ell^{(+)}(r)\right]_{r=R} = S_\ell + ip_\ell \quad . \qquad (2.43)$$

Certain reasonable values have to be assumed for k_o to calculate σ_c from equation (2.42). Quite frequently, σ_c is also expressed in the form

$$\sigma_c = \pi\lambda^2 \sum_\ell (2\ell + 1)\, T_\ell \qquad (2.44)$$

where T_ℓ, the 'transmission coefficient' or 'the penetrability' of the ℓth partial wave, is

$$T_\ell = (1 - |n_\ell|^2) = \frac{4p_\ell KR}{S_\ell^2 + (KR + p_\ell)^2} \quad . \qquad (2.45)$$

Calculation of σ_c or T_ℓ for neutrons is straightforward but for charged particles appropriate Coulomb wave functions have to be used. Values for protons, deuterons and alpha particles have been tabulated for a number of target nuclei by Blatt and Weisskopf 1952 for $R = r_o A^{1/3}$ with r_o = 1.5f and 1.3f, and by Shapiro 1953 again for r_o = 1.5f and 1.3f. More extensive tables have been compiled by Feshbach, Shapiro and Weisskopf 1953.

2.5(b) The Optical Model. Whereas in the continuum model the target nucleus is taken to be a perfectly absorbing 'black sphere' the optical model treats it as a 'semi-transparent sphere' represented by a complex potential well analogous to the optical situation of a partially absorbing medium represented by a complex refractive index. Such a potential well does not reproduce the well-known sharp resonances at low energy scattering and reactions so successfully described by the 'black sphere' nucleus and the compound reaction mechanism but the

average variation of cross sections with incident energies is in better agreement with the optical model picture of the interaction. The optical model permits the formation of a compound nucleus through the probability of absorption of the incident particle because of the imaginary term in the potential. However, every absorbed particle need not necessarily lead to a compound nucleus because much faster direct reaction mechanism is also consistent with the 'average description' of the process in terms of the complex potential. On the basis of many experimental results it has been generally recognized that the optical model picture of the nucleus is more realistic than the 'black sphere' picture of the continuum model.

The frequently used form of the radial dependence of the complex potential is

$$V(r) = V_0 f(r) + iWg(r) \tag{2.46}$$

where f(r) and g(r) are usually of the Woods-Saxon type or of the Gaussian type. For example, for f(r) and g(r) both of the Woods-Saxon type the potential has the following form

$$V(r) = \frac{V_0}{\left[1 + \exp\left(\frac{r-R}{q}\right)\right]} + \frac{iW}{\left[1 + \exp\frac{r-R}{q}\right]} \tag{2.47}$$

where R is the effective nuclear radius and q determines the 'diffuseness' of the nuclear surface.

Several other forms have also been used and a spin-orbit term along with some other modifications is also included in a more general form. Absorption (i.e. reaction) cross sections and hence the cross section for the formation of compound nucleus (neglecting direct

reactions) can be calculated using the complex potential well provided the parameters are known. Elastic scattering cross sections when explained in terms of the optical model give 'best fit' values of the parameters which can then be used to calculate the 'reaction cross section'. Naturally, earliest calculations were performed for neutrons.

Reaction cross sections or penetrabilities T_ℓ for protons have been calculated in 1963 by Mani et al and earlier in 1963 by Lindner. Calculations for alpha particles were carried out by Igo (1959), and Huizenga and Igo (1961). Our interest is primarily in the penetrabilities calculated for protons because not many spectra with protons as emitted particles have been analyzed on the basis of the optical model values of σ_c.

2.6 Summary of Important Equations and Symbols

For convenience we list here those equations to which references are made several times later in this thesis.

Weisskopf-Ewing Formula: (changing to a simpler notation σ_c)

$$\sigma_{ab}(E_a,E_b)dE_b \propto E_b\sigma_c(E_b)\omega(E_y)dE_b \qquad (2.48)$$

or simply in terms of the number of emitted particles per unit energy interval with

$$\frac{dN(E_b)}{dE_b} \propto E_b\ \sigma_c(E_b)\omega(E_y) \quad . \qquad (2.49)$$

Level Density Expressions (Fermi Gas Model):

(i) without pairing energy correction:

$$\omega(E_y) \propto \frac{\exp 2\sqrt{aE_y}}{E_y^n} \qquad (2.50)$$

$a = a_o$ for $n = 0$

$a = a_1$ for $n = 2$

$a = a_2$ for $n = 1.25$

$a = a_3$ for $n = 1.5$

$a = a_4$ for $n = 1.67$

(ii) with pairing energy correction:

$$\omega(E_y) \propto \frac{\exp 2\sqrt{a'U}}{U^n} \qquad (2.51)$$

with

$$U = E_y \pm (\delta_{pp} + \delta_{nn}) \qquad (2.52)$$

(+ ve sign for negative correction terms applied to even nucleon numbers;
- ve sign for positive correction terms applied to odd nucleon numbers)
and again corresponding symbols

a_o' , a_1' , a_2' , a_3' and a_4' .

Level Density Expression (Constant Temperature Model):

$$\omega(E_y) \propto \exp\left(\frac{E_y}{T}\right) \qquad (2.53)$$

Equations of the Level Density Plots from the Spectra:

(i) Fermi Gas Model: (without pairing energy correction)

$$\frac{dN(E_b)}{dE_b} \quad \frac{E_y^n}{E_b\, \sigma_c(E_b)} \propto \exp 2\sqrt{aE_y} \qquad (2.54)$$

with appropriate values of n and symbols for a (i.e. plot of the natural logarithm of the quantity on the left against $\sqrt{E_y}$ should be a straight line, the slope yielding the value of 'a').

(ii) Fermi Gas Model: (with pairing energy correction)

$$\frac{dN(E_b)}{dE_b} \quad \frac{U^n}{E_b\ \sigma_c(E_b)} \propto \exp 2\sqrt{a'U} \quad . \tag{2.55}$$

Here the plot of the natural logarithm of the quantity on the left against $\sqrt{U}$ should be a straight line yielding the value of a'.

(iii) Constant Temperature Model:

$$\frac{dN(E_b)}{dE_b} \quad \frac{1}{E_b\ \sigma_c(E_b)} \propto \exp\left(\frac{E_y}{T}\right) \quad . \tag{2.56}$$

Here the plot of the natural logarithm of the quantity on the left against E_y should be a straight line, the slope giving the value of the nuclear temperature T.

Finally, it may be pointed out that consistent with the Fermi gas model, energy and temperature are related by the approximate equation

$$E_y = aT^2 \tag{2.57}$$

or by some more accurate forms of the above equation.

CHAPTER 3

ANOMALIES IN EVAPORATION SPECTRA

3.1 Introduction

In this chapter a survey is presented of the experimental results on selected 'evaporation spectra' from the viewpoint of examining the 'inconsistencies' or 'anomalies' in the interpretation of such spectra on the basis of the Statistical (or evaporation) model. The attention is paid primarily to those reactions which have been studied at different incident energies in order to find the extent of anomalies concerning the dependence of the nuclear temperature and the level density parameter 'a' on the energy of the bombarding particle. There are some additional related questions which attract attention, though a thorough review of such questions would need coverage of many more papers not surveyed here, e.g. in order to examine the question whether on the basis of the experimental spectra one can judge the extent of the validity of the different expressions for the level density, the survey should logically also include the spectra obtained only at one energy.

3.2 Nuclear Temperature and Level Density Parameters for Reactions Studied at Different Incident Energies

3.2 (a) Criteria: In order to get a clear understanding of the problem it is appropriate to explain the criteria for labelling a certain feature to be 'anomalous'. First of all, only those spectra or part of spectra need to be considered which are reasonably assumed to have some feature(s) justifying their being called evaporation spectra or 'evaporation part' of the spectra.

If there is a significant contribution from Direct Interaction mode of the reaction the problem may be very complex and the evidence for labelling particular parts of the spectra as 'evaporation type' may not be conclusive. Information about angular distributions, if available, can be helpful but in many cases one may have to rely only on getting a 'linear level density plot' based on one or more of the commonly used expressions for energy dependence of the nuclear level density. In our discussion, regions of only single particle emission are included. Again, though the threshold for secondary particle emission may be known from the energy requirements there is some justification in paying attention to the expected abrupt changes (if any) in the slope of the level density plot to determine the part of the spectra relatively uncontaminated by the secondary particle emission.

In these analyses as stated earlier in Section 2.5 the inverse cross section $\sigma_c(E_b)$ is used for the ground state of the residual nucleus. Constant slope of a level density plot based on Fermi gas model would yield the parameter 'a' insensitive to the excitation energy of the residual nucleus as required by the model. If the slope and hence the parameter 'a' changes with the incident energy (i.e. for another plot for a different incident energy) it is an 'anomaly' from the viewpoint of the model. If one cannot obtain even a constant slope for a given level density plot it would suggest that the particular level density expression is not valid. As stated earlier, to the "empirical constant temperature" expression for the level density

$$\omega(E_y) \propto \exp\left(\frac{E_y}{T}\right)$$

corresponds the linear level density plot

$$\ell n \frac{dN(E_b)/dE_b}{E_b \sigma_c(E_b)} \quad \text{vs} \quad E_y \tag{3.1}$$

It would be recalled that a constant temperature insensitive to the excitation energy of the residual nucleus is consistent with the 'Fermi gas expression' only when approximation $E_b << E_{b_{max}}$ is valid, otherwise it is inconsistent because Fermi gas expressions imply a dependence of T on E_y according to the expression

$$E_y = aT^2 \tag{3.2}$$

or to some other improved form of it. If one does find a linear level density plot with the constant temperature form of the level density but finds slope of the plots and hence the temperature to be dependent on the incident energy such a behaviour can be termed 'temperature anomaly'. If on the basis of the experimental results one could always find agreement with only one type of the level density expression i.e. either the Fermi gas type (in any one of its various commonly used forms) or the constant temperature type the line of further investigations would be relatively straightforward but in many cases an 'ambiguous' situation arises when 'equally good' fits are obtained with both types of level density expressions. Because experimental inaccuracies may be a major cause of the situation it should be referred to 'as an ambiguous' situation to distinguish it from the 'anomalous' situations which are the subject of this thesis.

3.2(b) Literature Survey: Some of the earlier indications of possible anomalies in the behaviour of T or 'a' were seen in a critical examination

of comparable spectra from different reactions [(n,n'), (p,p'), (p,n), (n,p)] at different energies (ref: Gugelot 1954; Colli et al 1957). The accumulated data since then has not in anyway resolved the issue of the dependence or lack of dependence of T and 'a' on incident energy. As an elaboration of this statement we present a resumé in the form of a table (No. 3.1). However, for a proper evaluation of the material presented in this table it is essential to make some additional comments.

In the following paragraphs when referring to any paper listed in the table 3.1 we shall for convenience quote the entry number in that table.

Storey et al (No. 2) also reported that their results on the spectra listed by us in the table and on Fe^{56}, Co^{59}, Ni^{60}, Cu^{63} which they studied only at one neutron energy (14.1 Mev) yielded the following empirical relation:

$$\frac{E_c}{AT^2} = \text{constant} = 0.158 \pm 0.003 \text{ Mev}^{-1} \qquad (3.3)$$

where E_c refers to the excitation energy of the compound nucleus and A is the mass number of the compound nucleus. It should be noted that a normal behaviour of T according to Fermi gas model would be

$$\frac{E_y}{AT^2} = \text{constant}$$

where the excitation energy E_y and the mass number A refer to the residual nucleus. Two other elements studied by them at 14.1 Mev, Al^{27} and Cu^{65}, did not conform to the above empirical equation. Langkau's results on

TABLE 3.1

A RESUME OF BEHAVIOUR OF 'T' AND 'a'

No.	Authors	Reaction, Targets and Incident Energies	Anomaly or absence of anomaly
1.	Colli et al 1958	(n,p): Al, Ni (13.4, 17.5 Mev)	Level density plots (anomalously) dependent on incident energy
2.	Storey et al 1959	(n,p): Fe^{54}, Ni^{58}, Zn^{64} (13.0, 14.1, 15.7 Mev)	T increases with incident energy
3.	Armstrong & Rosen 1960	(n,p): Zn^{64} (8 and 14 Mev)	Apparently T increases with incident energy (statistically poor spectra)
4.	Langkau 1963	(n,p): CsI (21.5, 19.6, 18.0 16.0, 14.1, 12.1 Mev) KI (19.6, 17.5, 15.2, 12.7 Mev)	T increases and 'a' decreases with increasing incident energy
5.	Debertin & Rössle 1965	(n,p): Ni^{58} (8.4, 14.1, 22.0 Mev)	For 8.4 and 14.1 Mev 'a' same within experimental errors. For 22 Mev situation not clear.
6.	Lassen & Sidorov 1960	(α,p): V^{51}, Co^{59}, Ni^{58}, Ni^{60}, Cu^{63}, Cu^{65} (19.3, 17.8, 16.3, 11.9 Mev for $Cu^{63,65}$ while others at fewer energies)	T increases with incident energy

..... continued

No.	Authors	Reaction, Targets and Incident Energies	Anomaly or absence of anomaly
7.	Fox and Albert 1961	(α,p): Ni (9.65, 10.00, 10.35, 12.8 Mev) (p,p'): Ni (7.8, 8.4, 9.15, 10.05, 11.25, 11.4 Mev)	'a_0' independent of incident energy
8.	Lassen & Larsen 1963	(α,p): Ca^{40} (19.2, 17.8, 16.2 Mev)	T increases with incident energy
9.	Sherr & Brady 1961	(p,α): Ni (15.6, 19.4 Mev) Co (15.4, 19.0 Mev)	T same for different incident energies but poor agreement with the level density expression exp $2\sqrt{a_0 E_y}$
10.	Bormann 1962	(n,α): CsI (12.1, 14.1, 16.0, 18.0, 19.6, 21.5 Mev) KI (12.7, 15.2, 17.5, 19.6 Mev)	T increases with incident energy if σ_c (continuum model) used but is independent of T if σ_c (optical model) is used. Also, a_2 independent of incident energy if σ_c (optical model) used.
11.	Albert et al 1960	(p,n): V^{51}, Mn^{55}, Co^{59} (7 & 8 Mev)	From the results no clear pattern emerges.
12.	Holbrow & Barschall 1963	(p,n): Rh and some other elements (6 - 12 Mev)	With Rh (for which experimental accuracy is reasonable) T increases with incident energy if σ_c is taken independent of neutron energy. The anomaly becomes less significant if σ_c is taken dependent on energy.

.... continued

TABLE 3.1, continued

No.	Authors	Reaction, Targets and Incident Energies	Anomaly or absence of anomaly
13.	Wong et al 1964	(p,n): V^{51}, Fe^{56}, Co^{59}, Cu^{65}, Nb^{93} Rh^{103} (7 - 13 Mev)	a_1', independent of incident energy and $\approx \frac{A}{8}$. Apparently T varies anomalously with incident energy but according to authors it is in actuality dependence on the excitation energy of the residual nucleus.
14.	Wood et al 1965	(p,n): Tin Isotopes (7 - 14 Mev)	T varies with excitation energy as well as with the incident energy.
15.	Sidorov 1962	(α,n): V, Co, Ni (11 - 20 Mev)	T, a_0, a_1, depend on incident energy (spectral shapes best according to a_1 expression)
16.	Alevera et al 1964	(α,n): Mn^{55}, Fe^{56} (14, 17, 20 Mev)	T varies with incident energy
17.	Thomson 1963	(n,n'): Several elements	Taking σ_c independent of neutron energy, T for some elements varies significantly with incident energies while for others variation not so pronounced.
18.	Buccino et al 1964	(n,n'): Several elements from Zr to U (4.0, 5.0, 6.0, 6.5 Mev)	For some elements T same for different energies, for others T increases with incident energy but (according to the authors) due to an increase in the average excitation of the residual nucleus

(n,p) (No. 4) and Bormann's results on (n,α) (No. 10) both carried out with 'pulse shape discrimination technique' offer an interesting comparison. With the (n,α) reaction in CsI and KI Bormann reported that σ_c based on the Continuum model yielded level density plots with 'anomalous shape dependence' on the incident energy but with σ_c on the Optical model (Igo 1959) this anomaly was removed. This significant difference is obvious from the figures (No. 3.1(a) to 3.1(e)) which we reproduce from that paper but it will be noticed that the extent of the overlapping region of the excitation energy of the residual nucleus is also significantly altered. In analyzing the (n,p) spectra from CsI and KI Langkau also tried σ_c on the Continuum model (Blatt & Weisskopf 1952) as well as its values based on the Optical model calculations of Lindner 1963. With σ_c (Continuum) he reported anomalies and with σ_c (Optical - Lindner) he found that for reasonable slopes the parallel straight lines were almost tangents to the experimental points instead of passing through a reasonable number of points. It may be remarked that Langkau 1963 could not use σ_c based on the Optical model calculations of Mani et al 1963. Some other features of these two papers are as follows. For Bormann's (n,α) spectra σ_c (Optical) gave equally good fits for constant T form of level density expression as well as for

$$\frac{\exp 2\sqrt{a_1 E_y}}{E_y^{\,2}}$$

but poorer results with $\exp 2\sqrt{a_0 E_y}$ form. Langkau obtained qualitatively same features for constant T, $\exp 2\sqrt{a_0 E_y}$, $\dfrac{\exp 2\sqrt{a_1 E_y}}{E_y^{\,2}}$, and $\dfrac{\exp 2\sqrt{a_2 E_y}}{E_y^{\,5/4}}$.

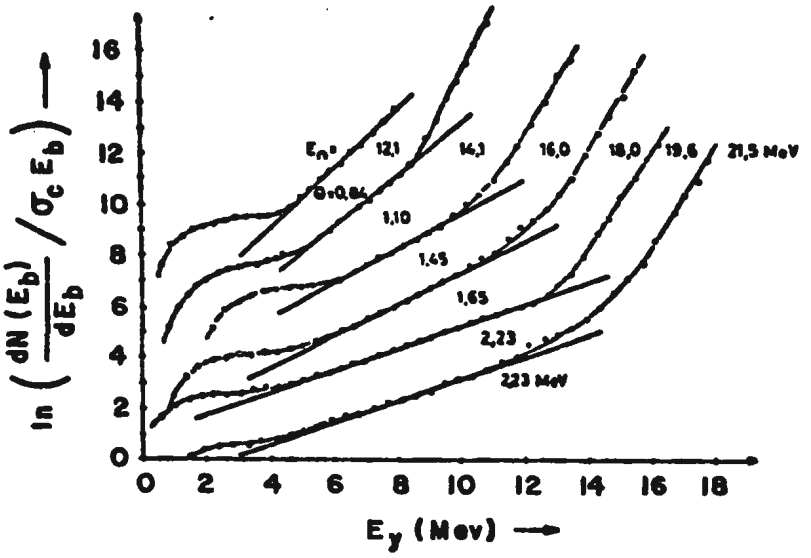

Figure 3.1(a): (ref: Bormann 1962). Level density plots of CsI(n,α) Spectra using constant temperature model. σ_c based on continuum model.

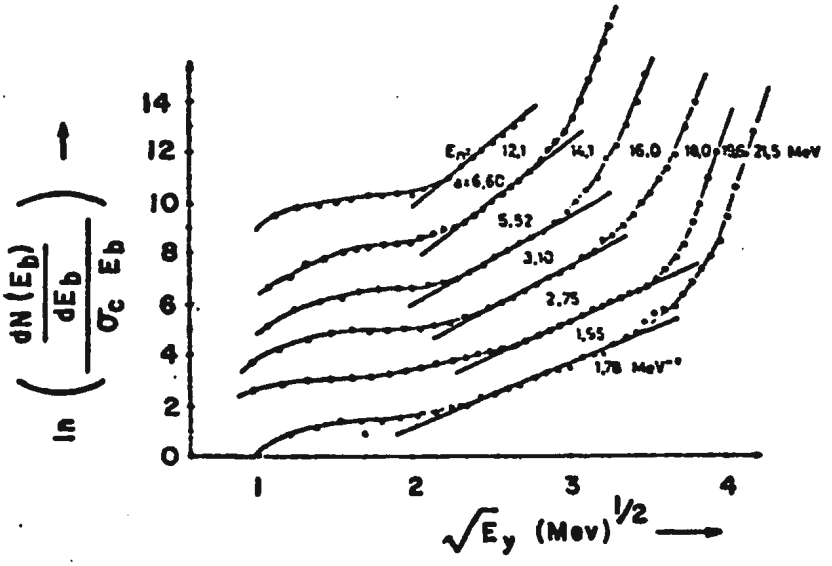

Figure 3.1(b): (ref: Bormann 1962). Level density plots of CsI(n,α) Spectra using $\exp 2\sqrt{a_1 E_y}$ form. σ_c based on continuum model. E_y^2

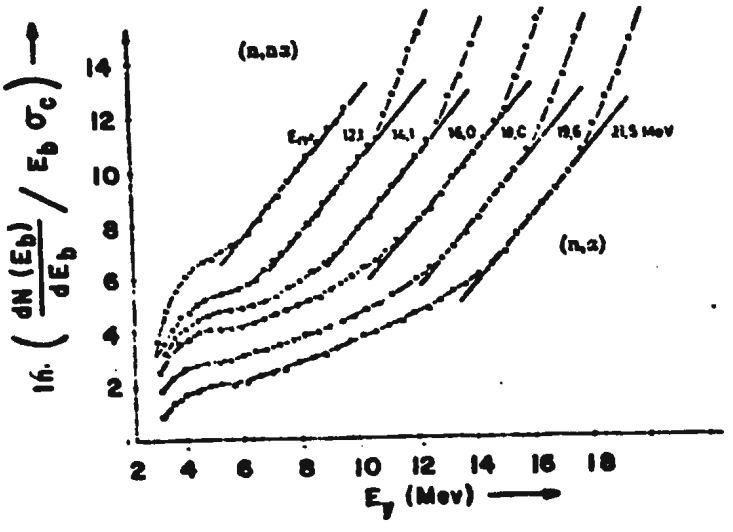

Figure 3.1(c): (ref: Bormann 1962). Level density plots of CsI(n,α) Spectra using constant temperature model. σ_c based on optical model.

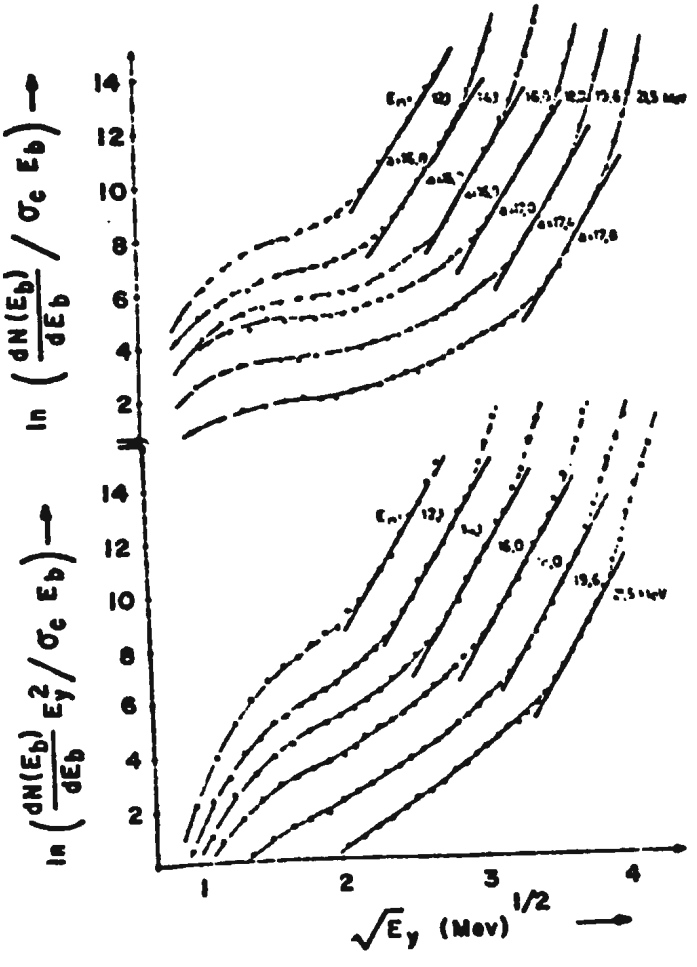

Figure 3.1(d): (ref: Bormann 1962). Level density plots of CsI(n,α) Spectra using exp $2\sqrt{a_0 E_y}$ form. σ_c based on optical model.

Figure 3.1(e): (ref: Bormann 1962). Level density plots of CsI(n,α) Spectra using $\frac{\exp 2\sqrt{a_1 E_y}}{E_y^2}$ form. σ_c based on optical model.

More will be said later on these (n,p) spectra in connection with our own reanalysis of them.

Debertin and Rössle (No. 5) who reported 'absence of anomaly' analyzed the (n,p) spectra on Ni^{58} using σ_c (Optical - Lindner) only, based on calculations of Meldner and Lindner 1964. We have reanalyzed these spectra also and additional comments are made at appropriate places.

In their (α,p) results, Lassen and Sidorov (No. 6) also reported that for nuclear radius parameter r_o = 1.41 fm the experimental points agreed better with the constant T form of the level density expression than with exp $2\sqrt{a_o E_y}$ form but for r_o = 2 fm it was difficult to choose between the two. σ_c values were used for the Continuum model (Shapiro 1953). From this paper only Cu^{63} spectra have been reanalyzed by us because for other targets information available from the paper was insufficient. We reproduce here a table (No. 3.2) from that paper to indicate results on other targets also. Fox and Albert paper (No. 7) is discussed at some length later on in connection with reanalysis performed by us.

In the (p,α) studies Sherr and Brady (No. 9) found that the energy spectra of the alpha particles had peaks at the same energy for different proton incident energies. This feature was also reported earlier by Fulmer and Goodman 1960 in their studies of (p,α) reactions in the energy range 9.5 - 23 Mev with several target elements. Fulmer and Goodman thought that the explanation might be in the possible lowering of the coulomb barrier for alpha emission from more highly excited nucleus. They however pointed out and Sherr and Brady 1961 further emphasized that this feature was consistent with the constant temperature model. The argument

TABLE 3.2

NUCLEAR TEMPERATURES IN Mev*

Target nucleus		V^{51}	Co^{59}	Ni^{58}	Ni^{60}	Cu^{63}	Cu^{65}
Residual nucleus		Cr^{54}	Ni^{62}	Cu^{61}	Cu^{63}	Zn^{66}	Zn^{68}
Energy in Mev incoming α's	19.3	1.35	1.17	1.10	1.05	1.07	1.05
Energy in Mev incoming α's	17.8	1.22		1.04		0.97	0.92
Energy in Mev incoming α's	16.3		0.99	0.98		0.85	0.83
Energy in Mev incoming α's	11.9	1.00	0.74			0.65	0.62

* (Reference: Lassen & Sidorov 1960).

goes as follows:

$$\sigma_{p\alpha}(E_p,E_\alpha) \propto f(E_p)E_\alpha\ \sigma_c(E_\alpha)\ \omega(E_y) \qquad (3.4)$$

where $f(E_p)$ is a function of incident energy only.

Now $E_y = E_p + Q - E_\alpha$ where Q is the Q-value of the reaction. (3.5)

Therefore, for $\omega(E_y) \propto \exp(\frac{E_y}{T})$

$$\sigma_{p\alpha}(E_p,E_\alpha) \propto f\ (E_p)\ \exp(\frac{E_p + Q}{T})\ \left[E_\alpha\sigma_c(E_\alpha)\ \exp(\frac{-E_\alpha}{T})\right] \qquad (3.6)$$

Thus for a constant T the peak energy E_α determined by the expression inside the brackets is same for all incident energies.

An examination of the (p,n), (α,n) and (n,n') spectra, i.e. reactions involving neutrons as emitted particles, also reveals the complexity of the situation. In this connection it may be remarked that many spectra have been analyzed on the assumption that σ_c for neutrons is independent of neutron energy. In some cases analysis has been performed with σ_c independent of energy as well as with σ_c calculated on the basis of optical model. In the context of the critical examination of the statistical model, however, results based on σ_c being energy independent should be treated with caution because discrepancies and anomalies from such results could be due to a lack of justification of this energy independence approximation of σ_c. Wong et al (No. 13) for their (p,n) spectra and Buccino et al (No. 18) for their (n,n') spectra have mentioned 'apparent variation' of T with incident energies suggesting that the observed variation was due to a change in the 'excitation energy' of the residual nucleus and that such

a variation would be expected on the basis of the Fermi gas model. There is one feature of this explanation which is not quite satisfactory. It is implied that the individual spectra do conform to the constant T level density expression but comparison of different incident energy spectra is inconclusive on this point because observed features are consistent with the Fermi gas level density expressions. It is worth noting that these authors have determined the level density parameters of the Fermi gas expressions using the experimental values of T and applying the following equation or some approximate form of the following equation

$$a'T^2 = \bar{U} + 2nT + \frac{n^2T^2}{\bar{U}} \qquad (3.7)$$

where $\bar{U} = \bar{E}_y - \delta_p$, δ_p being the pairing energy and n corresponding to the expression $(E_y - \delta_p)^{-n} \exp 2\sqrt{a'(E_y - \delta_p)}$. The point is that a' can also be determined from the level density plots using the appropriate Fermi gas level density expression. It is not clear if one would obtain same value for a' by such direct determinations as are obtained by using the above equation. These authors have also reported that all elements do not show the same spectral features. Some elements yielded spectra with T independent of incident energy also.

Results of Holbrow and Barschall 1962 on (p,n)(No. 12), of Sidorov on (α,n) (No. 15), of Alevra et al on (α,n) (No. 16) indicate anomalous incident energy dependence of level densities. In the (p,n) spectra Wood et al (No. 14) reported that T varied with excitation energy as well as incident energy.

From the material discussed in this section so far it is clear that in some cases a thorough re-examination of the analyses may be worthwhile. We have not included here some of the very pertinent comments made by the authors themselves or by other workers but the need for the re-examination of the spectra stems from the possibility of validity of level density expressions other than those used by the authors in a specific paper and from the desirability of applying the same criteria to the results of different authors and different reactions. It can be said that one has been handicapped in a proper comparison of different results to some extent due to variations in the methods of analysis. We list here some excellent review articles by Peaslee 1955, Ericson 1960, Bodansky 1962, and Cindro 1966.

CHAPTER 4

DETAILED REANALYSES OF (n,p) AND (α,p) EVAPORATION SPECTRA AT DIFFERENT INCIDENT ENERGIES

4.1 Selection of Spectra

Literature search was carried out for (n,p) evaporation spectra from as many target nuclei as possible provided spectra were available for different incident energies for each target. Light nuclei were excluded because of their general unsuitability for 'evaporation type of spectra'. Ideally we would have liked to examine for each target several sets of different incident energy spectra with spectra in each set measured under the same experimental conditions. We would have, furthermore, liked to know the detailed angular distributions of these spectra. A detailed examination of such sets of spectra would have not only told about the dependence or lack of dependence of the spectral shapes on incident energies but would also have provided us with data to check closely possible discrepancies originating in varying experimental conditions. In actual practice, however, we found a disappointingly small number of spectra suitable for reanalysis. In order to obtain additional material for reanalysis the scope of search was broadened to include closely related (α,p) spectra. Table 4.1 lists the (n,p) and (α,p) spectra reanalyzed by us. It will be noticed that the table also includes some 14 Mev spectra of the same target but measured by different researchers (naturally, the selection was again restricted to those targets from which spectra at energies other than 14 Mev were available).

In addition to the spectra listed in table 4.1 some other spectra

TABLE 4.1

(n,p), (α,p) SPECTRA SELECTED FOR REANALYSIS

REACTION	REFERENCES	INCIDENT ENERGIES (Mev)	ANGLE
$Ni^{58}(n,p)Co^{58}$	Storey et al 1959	12.9, 14.1, 15.7	90^0
$Ni^{58}(n,p)Co^{58}$	Jack & Ward 1959	14.1	forward angle
$Ni^{58}(n,p)Co^{58}$	Kumabe & Fink 1960	14.8	$0\text{-}40^0$, $40^0\text{-}90^0$, $90^0\text{-}140^0$, $140^0\text{-}180^0$
$Ni^{58}(n,p)Co^{58}$	Colli et al 1961	14.0	forward angle
$Ni^{58}(n,p)Co^{58}$	Debertin & Rössle 1965	8.4, 14.1	60^0, 8^0, 145^0
$Ni^{58}(n,p)Co^{58}$	Emmerich & Hofmann 1967	14.0	forward angle
$Fe^{54}(n,p)Mn^{54}$	Allan 1958	14.0	25^0, 45^0, 65^0, 90^0, 120^0, 145^0
$Fe^{54}(n,p)Mn^{54}$	Storey et al 1959	12.9, 14.1, 15.7	90^0
$Fe^{54}(n,p)Mn^{54}$	Jack & Ward 1959	14.1	forward angle
$Fe^{54}(n,p)Mn^{54}$	Colli et al 1961	14.0	forward angle
$Fe^{54}(n,p)Mn^{54}$	Emmerich & Hofmann 1967	14.0	forward angle
$Zn^{64}(n,p)Cu^{64}$	Storey et al 1959	12.9, 14.1, 15.7	90^0
$Zn^{64}(n,p)Cu^{64}$	Emmerich & Hofmann 1967	14.0	forward angle
$Zn^{64}(n,p)Cu^{64}$	K. Iwatani et al 1968	14.0	backward angle
CsI(n,p)	M. Bormann & Langkau 1961 Langkau 1963	12.1, 14.1, 16.0 18.0, 19.6, 21.5	
KI(n,p)	Langkau 1963	12.7, 15.2, 17.5, 19.6	
Ni(α,p)Cu	Fox & Albert 1961	9.65, 10.00, 10.35, 12.8	135^0
$Cu^{63}(\alpha,p)Zn^{66}$	Lasson & Sidorov 1960	11.9, 16.3, 17.8, 19.3	90^0

were also investigated by us for possible inclusion in this work. They were either rejected after preliminary analysis because of poor quality of spectra [$Ca^{40}(n,p)K^{40}$ at 6.0 Mev (Ureh et al 1961), $Cu^{63}(n,p)Ni^{63}$ at 14.3 and 16.6 Mev (Eddy 1967), $Al^{27}(n,p)Na^{27}$ at 13.4, 14.7 and 17.5 Mev (Colli et al 1957), Ni(n,p)Co at 13.4 and 17.5 Mev (Colli et al 1957), $Ni^{58}(n,p)Co^{58}$ at 22.0 Mev, $Al^{27}(n,p)Na^{27}$ at 8.4, 14.1, and 22.0 Mev (Debertin & Rössle 1965), and $Zn^{64}(n,p)Cu^{64}$ at 8.4 and 14.1 Mev (Armstrong & Rosen 1960)] or could not be pursued further because of lack of sufficient information [($Ca^{40}(\alpha,p)Se^{43}$ at 16.2, 17.8, and 19.2 Mev (Lassen & Larsen 1963), $V^{51}(\alpha,p)Cr^{54}$, $Co^{59}(\alpha,p)Ni^{62}$, $Ni^{58,60}(\alpha,p)Cu^{61,63}$, $Cu^{63}(\alpha,p)Zn^{66}$, and $Cu^{65}(\alpha,p)Zn^{68}$ at different incident energies between 11 - 20 Mev (Lassen & Sidorov 1960)].

4.2 Conventional Analysis

We give the title 'Conventional Analysis' to describe those analyses which were performed with our selected spectra using the equations described in chapter 2. In addition we adopted another approach in examining these spectra and section 4.3 describes that part of this project.

First those spectra were analyzed which were available as sets measured under comparable experimental conditions at different incident energies. This group included $Ni^{58}(n,p)Co^{58}$, $Fe^{54}(n,p)Mn^{54}$, $Zn^{64}(n,p)Cu^{64}$ spectra measured by Storey et al 1959; $Ni^{58}(n,p)Co^{58}$ spectra by Debertin & Rössle 1965; CsI(n,p) spectra by Bormann & Langkau 1961 and Langkau 1963; KI(n,p) spectra by Langkau 1963; Ni(α,p)Cu spectra by Fox & Albert 1961 and $Cu^{63}(\alpha,p)Zn^{66}$ spectra by Lassen & Sidorov 1960. Level density plots were

drawn from these spectra using the inverse cross section σ_c values obtained by appropriate interpolations from each of the following available tabulated sets (i) Blatt & Weisskopf 1952 (Continuum model, $r_o = 1.3$); (ii) Blatt & Weisskopf 1952 (Continuum model, $r_o = 1.5$); (iii) Shapiro 1953 (Continuum model, $r_o = 1.3$); (iv) Shapiro 1953 (Continuum model; $r_o = 1.5$); (v) Lindner 1962 (Optical model), (vi) Mani et al 1963 (Optical model). For level density expressions we used (i) constant temperature model; (ii) Fermi gas model, for n = 0, 2, 1.25, 1.5 and 1.67. Possible effects of pairing energy correction were also studied as described later in this section.

The level density plots were examined for 'straight line fits' using the method of the least squares. No centre of mass correction was applied by us to the proton energies (either in some cases the given energies were already corrected or in others the effect was ignored). The plots were examined in sections of width of about 2 Mev (for E_y) each time 'shifting' the section by about 0.5 Mev, thus looking for the best straight line region covering at least a 2 Mev interval E_y. A programme was written to perform this detailed examination using IBM 360/40 computer. The region of best straight line was thus selected for each plot from the computed results of standard deviations of the slopes of various sections but at the same time a great deal of attention was paid to the possible variations in the slopes of 'neighbouring sections'. The idea was to determine as wide a range as possible consistent with a good straight line fit. The information obtained from the computed results for the 'best straight line region' was checked with the actual graphs (of the level density plots) to make sure that the selected region did not contain those points which 'obviously' seemed to be outside the single particle emission

at the high E_y end or in the direct interaction region at the low E_y end. For this visual comparison we had to rely on the existence of possible abrupt changes in the slope. Where information was available use was also made of the angular distribution of emitted particles of different energies to exclude any region of spectrum known to show assymmetry about 90^o. In such cases we found conclusions from the inspection of the plots and from the angular distribution to be consistent. We also excluded, from the best straight line regions those points which were in statistically poor part of the spectra. It may be emphasized that visual inspection of the graphs was very helpful because 'inclusion of few unwanted points' in the data yielding computed results did not necessarily show any large errors to warn about the situation. If our 'best straight line' regions had turned out to be covering a much wider interval, it would not have been too important to pay such attention to these details. One could also have adopted the approach of first selecting the suitable region from the graphs and then applying the method of least squares to that region. However, in order to draw the graphs computations of the quantities to be plotted were in any case necessary and we decided to examine closely the graphs as well as the computed straight line fits generally for the complete spectra (in sections as discussed above).

From the above information on the 'best straight line' regions we then proceeded to select the same energy region (of E_y) for different incident energy spectra from each target. This proved to be a very restrictive condition in some cases but we had to accept these restrictions because the main idea behind our 'reanalyses' was to make sure that energy

spectra at different incident energies were compared for the same excitation energy of the residual nucleus.

After studying the 'sets' of spectra we analyzed 'single' 14 Mev spectra measured by different authors but this analysis was restricted to the earlier selected 'best straight line' region from the sets of spectra. Similarly spectra for different angles (where available) were also analyzed in the 'best straight line region'.

It is important to note that in these analyses mentioned above experimental points from the measured spectra were used wherever available though 'mean values' from the average smoothed curves had to be used in some cases. The standard deviations of the computed slopes (or of the level density parameters 'a' or T) do not reflect experimental errors on these points. In order to get an estimate of the effect of such errors on the computed values of 'a' or T we computed these parameters again by shifting the alternate points of the level density plots by (i) ± 5%, (ii) ± 10% (only ordinates (involving $\frac{dN(E_b)}{dE_b}$) were shifted and not E_y or $\sqrt{E_y}$). The figures ± 5% and ± 10% were selected somewhat arbitrarily but bearing in mind the quality of spectra analyzed by us.

Possible effects of pairing energy corrections were investigated only on the selected 'best straight line regions' obtained from the analyses already described earlier. These investigations are needed only for the Fermi gas model (level density expressions) because for constant temperature model the correction implies only shifting the origin of the E_y axis whereas for the Fermi gas expressions the plots are versus $\sqrt{E_y}$ and $\sqrt{U}$ respectively in the two cases.

4.3 An Approach 'Independent of Level Density Expressions'

(i.e. Comparison of spectra in a manner which does not depend on particular forms of level density expressions). Whereas the conventional analysis discussed so far involves particular level density expressions in order to compare different incident energy spectra the following procedure provides a method of comparing spectra independent of particular level density models. Only two spectra can be compared at a time. The method is a modification of the procedure adopted by some authors (eg. Fox & Albert 1961, Holbrow & Barschall 1963, Thomson 1963) of comparing the spectra by drawing normalized 'superimposed' level density plots of different incident energy spectra.

$$\text{Now, } \sigma_{ab}(E_a,E_b)dE_b = K_a \cdot E_b\, \sigma_c(E_b)\, \omega(E_y)dE_b \qquad (4.1)$$

where K_a depends on the incident energy and does not depend on E_b (or E_y). Though we have mentioned earlier that in analyzing spectra $\sigma_c(E_b)$ is used for ground state residual nuclei whereas it should be for the appropriate excited state here in this section we stick to the proper meaning of $\sigma_c(E_b)$ i.e. it is for the excited state.

For another incident energy E'_a, but same excitation energy of the residual nucleus E_y (implying an appropriately different energy of the emitted particle E'_b) we have

$$\sigma'_{ab}(E'_a, E'_b)dE'_b = K'_a \cdot E'_b\, \sigma_c(E'_b)\, \omega(E_y)dE'_b \qquad (4.2)$$

Now if we write

$$\sigma_c(E_b) = \sigma_c^{o}(E_b) \times f(E_b,E_y) \qquad (4.3)$$

where $\sigma_c^{o}(E_b)$ is the inverse cross section for the formation of a compound

nucleus when the particle b is supposed to be incident with energy E_b on the nucleus Y in the ground state and not in the excited state as the residual nucleus is and the factor $f(E_b,E_y)$ is a sort of correction factor to give the required $\sigma_c(E_b)$ from $\sigma_c^{o}(E_b)$.

Thus for the same E_y we write

$$\sigma_{ab}(E_a,E_b)dE_b = K_a\, E_a\, \sigma_c^{o}(E_b)\, f(E_b,E_y) \cdot \omega(E_y)dE_b \qquad (4.4)$$

and

$$\sigma_{ab}(E'_a,E'_b)dE'_b = K'_a \cdot E'_b\, \sigma_c^{o}(E'_b)\, f(E'_b,E_y)\, \omega(E_y)dE'_b \qquad (4.5)$$

we shall denote for brevity $f = f(E_b,E_y)$ and $f' = f(E'_b,E_y)$ (4.6)

We get for points corresponding to the same excitation energy of the residual nucleus

$$\frac{\sigma ab(E_a,E_b)}{E_b\sigma_c^{o}(E_b)f} \Big/ \frac{\sigma_{ab}(E'_a,E'_b)}{E'_b\sigma_c^{o}(E'_b)f'} = \frac{K_a}{K'_a} \qquad (4.7)$$

= a constant for the two spectra.

Writing down this expression for a specific value of $E_y = E_{yo}$, having corresponding values $E_b = E_{bo}$ and $E'_b = E'_{bo}$ we get (writing $f(E_{bo},E_{yo}) = f_o$ and $f(E'_{bo},E_{yo}) = f'_o$)

$$\frac{\alpha_{ab}(E_a,E_{bo})}{E_{bo}\sigma_c^{o}(E_{bo}) \cdot f_o} \Big/ \frac{\sigma_{ab}(E'_a,E'_{bo})}{E'_{bo}\sigma_c^{o}(E'_{bo})f'_o} = \frac{K_a}{K'_a} \qquad (4.8)$$

Dividing the two equations we get

$$\frac{\dfrac{\sigma_{ab}(E_a,E_b)}{E_b\sigma_c^{\,o}(E_b)} \Big/ \dfrac{\sigma_{ab}(E_a,E_{bo})}{E_{bo}\sigma_c^{\,o}(E_{bo})}}{\dfrac{\sigma_{ab}(E'_a,E'_b)}{E'_b\sigma_c^{\,o}(E'_b)} \Big/ \dfrac{\sigma_{ab}(E'_a,E'_{bo})}{E'_{bo}\sigma_c^{\,o}(E'_{bo})}} \left[\frac{\dfrac{f_o}{f}}{\dfrac{f'_o}{f'}}\right] = 1 \qquad (4.9)$$

Now if we assume that

$$\frac{f_o}{f} \approx \frac{f'_o}{f'} \qquad (4.10)$$

we obtain

$$\frac{\dfrac{\sigma_{ab}(E_a,E_b)}{E_b\sigma_c^{\,o}(E_b)} \Big/ \dfrac{\sigma_{ab}(E_a,E_{bo})}{E_{bo}\sigma_c^{\,o}(E_{bo})}}{\dfrac{\sigma_{ab}(E'_a,E'_b)}{E'_b\sigma_c^{\,o}(E'_b)} \Big/ \dfrac{\sigma_{ab}(E'_a,E'_{bo})}{E'_{bo}\sigma_c^{\,o}(E'_{bo})}} = 1 \qquad (4.11)$$

or alternatively

$$\frac{\dfrac{\dfrac{dN}{dE_b}(E_a,E_b)}{E_b\sigma_c^{\,o}(E_b)} \Big/ \dfrac{\dfrac{dN}{dE_b}(E_a,E_{bo})}{E_{bo}\sigma_c^{\,o}(E_{bo})}}{\dfrac{\dfrac{dN}{dE_b}(E'_a,E'_b)}{E'_b\sigma_c^{\,o}(E'_b)} \Big/ \dfrac{\dfrac{dN}{dE_b}(E'_a,E'_{bo})}{E'_{bo}\sigma_c^{\,o}(E'_{bo})}} = 1 \qquad (4.12)$$

Deviation from unity of the experimental quantity (in conjunction with calculated σ_c^o values but now appropriately for the ground state nuclei) would be an indication of that either (i) our assumption $\frac{f_o}{f} \approx \frac{f'_o}{f'}$ is not justified or (ii) that the calculated values of σ_c^o are not reliable or (iii) that the spectra under comparison do not conform to the Weisskopf-Ewing formula. It will be noticed that the usual practice of using for $\sigma_c(E_b)$ the values for the ground state (here denoted by $\sigma_c^o(E_b)$) amounts to putting $f_o = f = f'_o = f' = 1$ which is a stronger condition than our assumption $\frac{f_o}{f} \approx \frac{f'_o}{f'}$. If equation (4.12) is applied to different parts of the spectra (but always having equal E_y for the two points under comparison) and if the results turn out to be <u>same constant</u> but different from unity the possibility that the discrepancy might be due to 'improper normalization' of the spectra should not be overlooked (i.e. the points corresponding to $E_y = E_{yo}$ may for some reason, be inaccurate). Several of the spectra analyzed by us using the conventional method were also examined from the point of view of validity or otherwise of equation (4.12). Generally complete spectra were covered in point by point comparisons. Graphs were also drawn of the computed results vs E_y.

In the comparisons of spectra measured from a target under different experimental condition but at the same incident energy (or approximately same incident energy) equation (4.12) reduces to the simpler form independent of σ_c^o. The equation becomes

$$\frac{\left[\dfrac{\dfrac{dN}{dE_b}(E_b)}{E_b} \Big/ \dfrac{\dfrac{dN}{dE_b}(E_{bo})}{E_{bo}}\right]_{\text{Spectrum 1}}}{\left[\dfrac{\dfrac{dN}{dE_b}(E_b)}{E_b} \Big/ \dfrac{\dfrac{dN}{dE_b}(E_{bo})}{E_{bo}}\right]_{\text{Spectrum 2}}} = 1 \qquad (4.13)$$

which of course is independent of σ_c^o.

CHAPTER 5

RESULTS OF THE ANALYSES

5.1 Introduction

Values of T and other level density parameters obtained from the conventional analysis are presented in detail in an appendix following chapter 6. Some values have been omitted from the table because of large standard deviations. The errors and the uncertainties have been discussed in chapter 6. In the following sections we present the essential features of these tabulated results and also the results of the 'level density independent' approach.

5.2 Level Density Plots of Spectra at Different Angles

In this section we give the results of comparing spectra for the same incident energy but different angles of emissions. The most detailed analysis in this connection could be performed on the 14.1 Mev $Fe^{54}(n,p)Mn^{54}$ spectra (at 25^{o}, 45^{o}, 65^{o}, 90^{o}, 120^{o}, 145^{o}) by Allan (1958) and the results indicate that T for 120^{o} spectrum is somewhat higher than that for any other angle (by about 10%) and that 'a' for 90^{o} and 120^{o} are somewhat smaller than for spectra at other angles (by about 20%). Results from spectra measured by Kumabe & Fink (1960) at 14.8 Mev for $Ni^{58}(n,p)Co^{58}$, have large errors but give some indication that 'a' for (140^{o} - 180^{o}) region is higher than for (90^{o} - 140^{o}) region. Debertin and Rössle's (1965) $Ni^{58}(n,p)Co^{58}$ spectrum at 8^{o} has same T as the forward angle $Ni^{58}(n,p)Co^{58}$ spectrum measured by Colli et al (1961) but has lower T than that of 90^{o} $Ni^{58}(n,p)Co^{58}$ spectrum of Storey et al (1959) as well as that of forward

angle $Ni^{58}(n,p)Co^{58}$ spectrum of Jack & Ward (1959) same values of T are found for the 90^{o} and forward angle $Ni^{58}(n,p)Co^{58}$ spectra measured by Storey et al, and Jack & Ward respectively. Values of 'a' are generally consistent with the behaviour of T.

5.3 $Ni^{58}(n,p)Co^{58}$ Spectra

5.3(a) Conventional Analysis: For convenience the spectra are referred to in an abbreviated form as follows:

(1)	E(8.4)	Debertin & Rössle 1965	(60^{o} spectrum)
(2)	E(12.9)	Storey et al 1959	(90^{o} spectrum)
(3)	E_1(14.1)		
(4)	E(15.7)		
(5)	E_2(14.1)	Debertin & Rössle 1965	(8^{o} spectrum)
(6)	E_3(14.1)		(145^{o} spectrum)
(7)	E_4(14.0)	Colli et al 1961	(forward angle spectrum)
(8)	E_5(14.0)	Emmerich & Hofmann 1967	(forward angle spectrum)
(9)	E_6(14.1)	Jack & Ward 1959	(forward angle spectrum)

Whereas excluding the E(8.4) spectrum all spectra could be compared in the (6.2 to 8.3 Mev) region of the excitation energy of the residual nucleus the E(8.4) spectra could only be compared with the E(12.9) in the energy region (5.0 to 3.0 Mev). The results of this latter comparison indicates lower temperature for lower incident energy for all sets of σ_c but the difference is smaller for σ_c (Optical - Lindner). Results for 'a' parameters are consistent with this picture, i.e. larger 'a' for lower incident energy.

Comparison of other spectra brings out some interesting points concerning E(12.9), E_1(14.1) and E(15.7). The spectra farthest apart in the incident energy, i.e. E(12.9) and E(15.7) have same temperature and 'a' values for σ_c (Continuum, Shapiro, r_o 1.3, r_o 1.5) and for σ_c (Optical, Lindner) but lower temperature for lower incident energy when other values of σ_c are used. But inclusion of E_1(14.1), i.e. an intermediate energy spoils this 'normal pattern' except for σ_c (Continuum, Shapiro, r_o 1.5). It is, however, possible to include some other 14.1 Mev spectrum to be able to say that there is no anomaly in the comparison of 12.9, 14.1 and 15.7 Mev spectra even for σ_c (Optical, Lindner). This situation also implies that all 14.1 Mev spectra, i.e. (E_i(14.1) i = 1,2,3,4,5 do not agree among themselves. The difference between E_1(14.1) and E_4(14.1) could perhaps be due to the difference in the angle of emission but this would not explain discrepancies in other spectra or 'lack of discrepancy' in a comparable situation. It has been stated earlier that for those σ_c values which do not yield same T for E(12.9) and E(15.7) the lower incident energy corresponds to lower temperature. In contrast with this situation for E(12.9) and E_1(14.1) when T does not have same value for the two spectra the lower incident energy has slightly higher T except for σ_c (Optical, Mani) when T is higher for higher incident energy. Comparison of E(12.9) and E_1(14.1) at a lower excitation energy does reverse this trend. The spectra also indicate that T is either not very sensitive to the excitation energy or increases slightly with the excitation energy. Situation concerning the level density parameters 'a' is generally consistent with that of temperature but discrepancies appear to be more pronounced for these parameters than for T.

5.3(b) Level Density Independent Approach: The left hand side quantity of the equation (4.12) is abbreviated in the form

$$\frac{E(n_1 Mev)}{E(n_2 Mev)} .$$

It is found that $\frac{E_1(14.1)}{E(15.7)}$ is much closer to unity than $\frac{E(12.9)}{E_1(14.1)}$ or $\frac{E(12.9)}{E(15.7)}$.

Furthermore for σ_c (Continuum, Shapiro, r_o 1.5) and σ_c (Optical, Lindner) $\frac{E_1(14.1)}{E(15.7)}$ is 1 ± 12% and is 1 ± 15% for all σ_c values. It may be noted that these ranges are quoted for an excitation energy region about the same as used in the conventional analysis.

For the same incident energy spectra $\frac{E_1(14.1)}{E_6(14.0)}$ turns out to be of the order of 1 ± 12%. For the other comparisons carried out $\frac{E_6(14.1)}{E_4(14.1)}$ and $\frac{E_1(14.1)}{E_4(14.1)}$ the values deviate more significantly from unity. It is interesting to note that $E_1(14.1)$ and $E_6(14.1)$ for which the ratio turns out to be closest to unity are spectra at 90^o and forward angle respectively.

5.4 $Fe^{54}(n,p)Mn^{54}$ Spectra

5.4(a) Conventional Analysis: The spectra are labelled as follows:

(1)	E(12.9)	Storey et al 1959	(90^o spectrum)
(2)	$E_1(14.1)$		
(3)	E(15.7)		
(4)	$E_2(14.1)$	Emmerich & Hofmann 1967	(forward angle spectrum)
(5)	$E_3(14.1)$	Jack & Ward 1959	(forward angle spectrum)
(6)	$E_4(14.1)$	Colli et al 1961	(forward angle spectrum)

Comparison of E(12.9), $E_1(14.1)$ and E(15.7) indicates that for all sets of

σ_c values T increases with incident energy and the behaviour of 'a' is also consistent with this picture. For σ_c (Shapiro, r_o 1.5) T and 'a' for $E_1(14.1)$ and E(15.7) are generally in good agreement. The same incident energy spectra $E_i(14.1)$ i = 1,2,3,4 do not show agreement among themselves.

5.4(b) Level Density Independent Approach:

In order of closeness to unity in the energy region of the conventional analysis $\frac{E_1(14.1)}{E(15.7)}$ is better than $\frac{E(12.9)}{E_1(14.1)}$.

In a wider energy region $\frac{E(12.9)}{E(15.7)}$ appears to be the best. Values are reasonably closer to unity for $\frac{E(12.9)}{E(15.7)}$ and $\frac{E_1(14.1)}{E(15.7)}$ in a wider energy region for σ_c (Optical, Lindner) and for σ_c (Shapiro, r_o 1.5).

In comparisons of the same energy spectra $\frac{E_1(14.1)}{E_3(14.1)}$ looks better than $\frac{E_1(14.1)}{E_4(14.1)}$ and $\frac{E_3(14.1)}{E4(14.1)}$. Here again $E_1(14.1)$ and $E_3(14.1)$ are 90^o and forward angle spectrum respectively.

5.5 $Zn^{64}(n,p)Cu^{64}$ Spectra

5.5(a) Conventional Analysis: The spectra are labelled as follows:

(1)	E(12.9)	Storey et al 1959	(90^o spectrum)
(2)	$E_1(14.1)$		
(3)	E(15.7)		
(4)	$E_2(14.1)$	K. Iwatani et al 1968	(backward angle spectrum)
(5)	$E_3(14.0)$	Emmerich & Hofmann 1967	(forward angle spectrum)
(6)	$E_4(14.1)$	Jack & Ward 1959	(forward angle spectrum)

Comparison of E(12.9), $E_1(14.1)$ and E(15.7) in the excitation energy (6.2 to 7.8 Mev) indicate generally T for E(12.9) > T for E(14.1) < T for E(15.7) but for σ_c (Optical, Mani) the discrepancies are less pronounced and T for

E(12.9) $\approx$ T for E(14.1) and the difference between T for E(14.1) and T for E(15.7) is reduced.

For σ_c (Shapiro, r_o 1.3, r_o 1.5) and σ_c (Optical, Lindner) T for E(12.9) and E(15.7) are in agreement, i.e. here again situation is somewhat like $Ni^{58}(n,p)Co^{58}$, i.e. for the spectra farthest apart in incident energy the temperature is independent of incident energy for σ_c (Shapiro, r_o 1.3, r_o 1.5) and σ_c (Optical, Lindner) but this normal pattern is spoiled by the inclusion of the intermediate energy spectrum $E_1(14.1)$. One can again, however, find another 14.1 Mev spectrum to get a 'normal pattern' for the three energies. We refer to E(12.9), $E_3(14.1)$ and E(15.7) which have same T for σ_c (Blatt and Weisskopf, r_o 1.3, r_o 1.5) and for σ_c (Shapiro, r_o 1.3, r_o 1.5) and to some extent for σ_c (Optical, Lindner) and σ_c (Optical, Mani). The level density parameter 'a' however agrees only for σ_c (Shapiro, r_o 1.5). With few exceptions the behaviours of level density parameters 'a' are consistent with the picture presented by the temperature.

Comparison of same energy spectra leads to discrepancies.

5.5(b) Level Density Independent Approach:

Here generally $\frac{E(12.9)}{E_1(14.1)}$ is closer to unity than $\frac{E(12.9)}{E(15.7)}$ or $\frac{E_1(14.1)}{E(15.7)}$. For $\frac{E(12.9)}{E_2(14.1)}$ values are generally 1 ± 15% and for $\frac{E(12.9)}{E(15.7)}$ values are generally 1 ± 17%. In a wider energy region σ (Optical, Lindner) gives 'flattest' graphs of these ratios plotted against E_γ.

For the same incident energy only $\frac{E_1(14.1)}{E_4(14.1)}$ is calculated and here the deviations from unity are much larger than were obtained for the comparable

cases of $\frac{E_1(14.1)}{E_6(14.1)}$ in $Ni^{58}(n,p)Co^{58}$ and $\frac{E_1(14.1)}{E_3(14.1)}$ in $Fe^{54}(n,p)Mn^{54}$.

5.6 KI(n,p) Spectra (Only Conventional Analysis)

Because of unreliable interpolation σ_c (Optical, Lindner) could not be used. For other σ_c sets out of E(12.7), E(15.2), E(17.5) and E(19.6) spectra only two, E(15.2) and E(17.5), have reasonable straight lines. The slopes of the level density plots for these two spectra when compared in the excitation energy region (7.0 - 9.0 Mev) indicate that T increases with incident energy and consistent with this picture 'a' is smaller for higher incident energy. It may be added that according to Langkau all protons are assumed to be emitted from K^{39} only and we have accepted this assumption as the basis for our reanalysis also.

5.7 CsI(n,p) Spectra (Only Conventional Analysis). [following the authors, equal contributions from $_{55}Cs^{133}$ and $_{53}I^{127}$ assumed]

In comparing all different incident energy spectra E(12.1), E(14.1), E(16.0), E(18.0), E(19.6) and E(21.5) it is not possible to find a region of excitation energy which would be the same for all spectra and which would also be consistent with the 'best straight line' region of individual spectra. However, E(21.5), E(19.6), E(18.0) and E(16.0) spectra can be compared with reasonable justification in (7.0 - 9.0 Mev) excitation energy region. The result is that for all σ_c values T is quite high for high energies and low for lower energies but the difference in T for E(21.5) and E(19.6) spectra is not so pronounced as that between E(18.0) and E(16.0). Behaviour of the 'a' parameters is consistent with that of T.

In a different excitation energy region, 3.0 - 6.0 Mev, values of T and 'a' for E(16.0) and E(14.1) spectra do not differ much generally but

it is particularly true for σ_c (Blatt & Weisskopf, r_0 1.5) and σ_c (Shapiro, r_0 1.5). About the 12.1 Mev spectrum we can only say that it has rather a low value of T compared with other spectra.

5.8 Ni(α,p)Cu Spectra

5.8(a) Conventional Analysis: These four spectra E(9.65), E(10.0), E(10.35) and E(12.8) were analyzed for excitation energy region 1 to 3.7 Mev as well as in two other regions, 0.6 to 3.9 Mev and 1.5 to 3.9 Mev. Pairing energy corrected analysis was also performed for the 1.5 to 3.9 Mev excitation energy region. The results are as follows.

Generally T for E(10.0) and E(10.35) are in agreement, but except for σ_c (Optical, Mani) T for E(9.65) is somewhat less than that for E(10.0). For σ_c (Optical, Mani) T for three spectra E(9.65), E(10.00) and E(10.35) comes out with the same value. The inclusion of E(12.8) spoils this 'normal pattern' even for σ_c (Optical, Mani). Except for σ_c (Optical, Lindner) T for E(12.8) is always higher than for other spectra. The situation with σ_c (Optical, Lindner) is rather unusual because if only E(10.0), E(10.35) and E(12.8) are compared there is some evidence that T decreases with increasing incident energy. The reason for this behaviour lies in the unusually high values of T for lower incident energy spectra for σ_c (Optical, Lindner). If we exclude the case of σ_c (Optical, Lindner) it can be said that there is some evidence for increase of T with incident energy. For the level density parameter 'a' the situation with σ_c (Optical, Mani) and σ_c (Optical, Lindner) is generally consistent with the picture presented by T but in an overall comparison (excluding σ_c (Optical, Lindner)) it is difficult to

establish any pattern such as 'decreasing 'a' with increasing incident energy'.

The pairing energy correction generally reduces the differences between the values of level density parameter for different incident energies. However, the errors in this analysis are somewhat higher.

5.8 (b) Level Density Independent Approach: Comparisons could be made only for E(9.65), E(10.0), and E(10.35). For σ_c (Shapiro, r_o 1.3) the ratios $\frac{E(9.65)}{E(10.0)}$ and $\frac{E(9.65)}{E(10.35)}$ are generally closer to unity than for other σ_c values and for $\frac{E(10.0)}{E(10.35)}$ though values for σ_c (Blatt & Weisslopf, r_o 1.5) are best those for σ_c (Shapiro, r_o 1.3, r_o 1.5) and σ_c (Optical, Mani) are not far behind.

5.9 $Cu^{63}(\alpha,p)An^{66}$ Spectra

5.9(a) Conventional Analysis: For three spectra E(19.3), E(17.8) and E(16.3) the trend of T increasing with incident energy (and a decreasing with increasing incident energy) is clearly established for all σ_c values, though the differences are somewhat reduced for σ_c (Optical, Lindner). No significant change in the trend is found on applying pairing energy corrections. Spectra E(11.9) and E(16.3) when compared in their overlapping excitation energy region give same results as above.

5.9(b) Level Density Independent Approach: Generally with σ_c (Optical, Lindner) ratios $\frac{E(17.8)}{E(16.3)}$, $\frac{E(19.3)}{E(17.8)}$ and $\frac{E(19.3)}{E(16.3)}$ are closest to unity (in the excitation energy region 9.6 to 11.7 Mev) of the order of 1 ± 17%. Values for other σ_c deviate much more significantly from unity, though somewhat less so for σ_c (Shapiro, r_o 1.5).

5.10 Relative Magnitudes of T and 'a' for Different σ_c

The relative magnitudes of temperatures obtained by using different σ_c values indicate that σ_c (Blatt & Weisskopf, r_0 1.3) and σ_c (Shapiro, r_0 1.3) give generally lower values while σ_c (Optical, Lindner) σ_c (Shapiro, r_0 1.5) and σ_c (Optical, Mani) give generally higher values. There are, however, numerous exceptions to the above statement, e.g. to σ_c (Optical, Mani) correspond generally lower values of temperature in Ni(α,p)Cu and $Cu^{63}(\alpha,p)Zn^{66}$ reactions whereas σ_c (Optical, Lindner) gives generally unusually high values for the same reactions. The continuum model σ_c values from Blatt & Weisskopf and from Shapiro have sometimes given significantly different values of temperature.

The level density parameters 'a' generally follow a pattern consistent with the above description for temperatures.

5.11 Magnitudes of Parameters 'a'

With very rare exceptions the relative magnitudes of various level density parameters satisfy the following order

$$a_1 > a_4 > a_3 > a_2 > a_0$$

i.e. the magnitude of the parameter decreases as the magnitude of n in the expression

$$\frac{\exp 2\sqrt{aE_y}}{E_y^{\,n}}$$

is decreased as follows

$$2,\ 1.67,\ 1.5,\ 1.25,\ 0\ .$$

For the (n,p) spectra values of a_1 generally range between 5 to 8 Mev^{-1},

though some exceptionally smaller values are also observed, especially in some spectra of CsI(n,p) reaction.

For Ni(α,p)Cu spectra typical magnitude of a_1 is around 14 Mev^{-1}.

For $Cu^{63}(\alpha,p)Zn^{66}$ spectra magnitude of a_1 varies over a wide range, about 15-40 Mev^{-1}.

An examination of the tabulated values of 'a', particularly of the extreme values for each spectrum, enables us to make the following statements.

(i) Comparison of other 'a' parameters relative to a_1 (most commonly used value of n(=2) corresponds to our a_1) shows that on the average $\frac{a_1}{a_4} \approx 1.12$ (range 1.09 to 1.17 with some exceptions, notably for $Cu^{63}(\alpha,p)Zn^{66}$ values range between 1.03 to 1.07). $\frac{a_1}{a_3} \approx 1.20$ (range 1.14 to 1.30, again rather low values for $Cu^{63}(\alpha,p)Zn^{66}$, around 1.08). $\frac{a_1}{a_2} \approx 1.34$ (range 1.20 to 1.45, with exceptionally low values around 1.15 for $Cu^{63}(\alpha,p)Zn^{66}$). $\frac{a_1}{a_0}$ varies more widely, an average range would be 2 to 3, with several exceptions.

(ii) The observed effects of the pairing energy correction can be summarized as follows: For Ni(α,p)Cu, excitation energy region 1.5 - 3.9 Mev

$$\frac{a_1'}{a_1} \approx 1.23$$

and on the average

$$a_1' : a_4' : a_3' : a_2' : a_0'$$

$$1 : 1.26 : 1.38 : 1.77 : 6.8$$

These relative magnitudes of a' parameters should be compared with the relative magnitudes of 'a' parameters (i.e. without pairing energy correction) for the same spectra, which are as follows:

$$a_1 : a_4 : a_3 : a_2 : a_0$$

$$1 : 1.14 : 1.21 \quad 1.34 : 2.5$$

It may be pointed out that the values of a_0' vary over a very wide range. For $Cu^{63}(\alpha,p)Zn^{66}$, excitation energy region 10.1 - 11.5 Mev,

$$\frac{a_1'}{a_1} \approx 0.83$$

and

$$a_1' : a_4' : a_3' : a_2' : a_0'$$

$$1 : 1.07 : 1.09 : 1.16 : 1.5$$

whereas for the same spectra (and same excitation energy)

$$a_1 : a_4 : a_3 : a_2 : a_0$$

$$1 : 1.05 : 1.08 : 1.13 : 1.37$$

For $Cu^{63}(\alpha,p)Zn^{66}$, excitation energy region 5.8 - 7.9 Mev

$$\frac{a_1'}{a_1} \approx 0.76$$

and

$$a_1' : a_4' : a_3' : a_2' : a_0'$$

$$1 : 1.09 : 1.10 : 1.23 : 1.9$$

whereas for the same spectra (and same excitation energy region)

$$a_1 : a_4 : a_3 : a_2 : a_0$$

$$1 : 1.06 : 1.09 : 1.15 : 1.5$$

CHAPTER 6

DISCUSSION AND CONCLUSIONS

6.1 Errors and Uncertainties

Standard deviations were computed for all values of T, 'a' and a' obtained in these analyses. In comparing parameters for different spectra these standard deviations were used as uncertainties in the values of the parameters. We feel that a more realistic error calculation should involve uncertainties in the experimental data also because the standard deviations obtained from the least square analysis of the 'mean' values represented by the experimental points do not reflect the quality of the points themselves. In examining the possible effects of variations in σ_c on the incident energy dependence of the parameters it is desirable to keep the uncertainty minimum but consistent with the least square analysis, otherwise the comparisons would not be reasonably sensitive to the variations in σ_c; but contrary to the practice adopted by some authors, the values of the parameters quoted as the final results derived from a given spectrum should reflect experimental uncertainties also. In order to arrive at estimates of more realistic errors we shifted the points up and down alternately ± 5% and ± 10% and were able to assign an overall error as our best judgment bearing in mind variations in the values of the parameters due to shifting of the points and variations in the standard deviations in the values of the parameters given by the new straight lines (passing through shifted points). The errors quoted in the final results presented in the table in the appendix are these 'overall' errors estimated by us.

6.2 Discussion of the Results Presented in Chapter 5

6.2(a) General Comments. Out of all the sets of spectra analyzed by us, only for the $Ni^{58}(n,p)Co^{58}$ spectra of Storey et al 1959 are the same values of T and 'a' obtained for the different incident energies, 12.9, 14.1 and 15.7 Mev, when σ_c values are used from Shapiro for r_o = 1.5f. In most cases, with the notable exception of $Cu^{63}(\alpha,p)Zn^{66}$ spectra, it is observed that for certain σ_c values and for some members of the set, the same T and a values are obtained. In this connection, σ_c (Shapiro, r_o 1.5) and σ_c (optical, Lindner) appear more likely to make T and a values the same for different incident energies. Such an oversimplification of facts, however, must be treated with great caution. From the meagre data the only thing that can be said is that there is some evidence that for widely differing incident energies, the temperature depends anomalously on the incident energies, being higher for higher incident energies. If the results of CsI(n,p) and of $Cu^{63}(\alpha,p)Zn^{66}$ spectra in comparison with other spectra are any guide this 'anomalous energy dependence' it is more pronounced in 'higher energy regions', but it must be stressed that within a 'region', this oversimplified statement is not valid. In fact, there is no single pattern.

There is some evidence that the parameter T shows agreement among different incident energy spectra more often than the parameters 'a' but the standard deviations computed for a_1, a_2, a_3 and a_4 are usually smaller than those for T or a_o.

In the 'level density independent' approach the best agreements between two spectra are characterized by about ± 12% deviations from the

expected unity. This uncertainty is probably consistent with the realistic errors on points from each spectrum. The overall impression received from these computations is again the 'absence of any simple picture' about the dependence of spectral shape on the incident energy. Qualitatively, at least, our conclusions are the same from the 'level density independent' analysis as from the conventional analysis. There are, however, significant differences in details. For example, for the spectra in best agreement according to conventional analysis, $Ni^{58}(n,p)Co^{58}$ E(12.9), and E(15.7) for σ_c (Shapiro, r_o 1.5, r_o 1.3) and σ_c (optical, Lindner), the results of the level density independent analysis do not indicate such close agreements. On the other hand good agreement has been observed between some $Cu^{63}(\alpha,p)Zn^{66}$ spectra on the basis of the level density independent analysis on using σ_c (optical, Lindner) [the conventional analysis also tells that the 'anomalous energy dependence' of the parameters is less pronounced for σ_c (optical, Lindner)]. It is worth noting that among the very few cases which we have studied at different 'excitation energies' also, the $Cu^{63}(\alpha,p)Zn^{66}$ spectrum at 16.3 Mev incident energy shows the unusual feature of lower temperature for higher excitation energy except for the case of σ_c (optical, Lindner). Here it may be added that with some exceptions, the usual trend is either insensitivity of temperature to the excitation energy or slight increase with it (in the supposedly 'single particle evaporation' region).

6.2(b) Comparison with Author's Conclusions. First of all it should be recognized that only very few of our results can be directly compared with the results quoted by the original authors of the papers from where

these spectra were taken (for the obvious reason of our study involving many more level density expressions and σ_c values than those used by the authors of the individual papers). Even for the σ_c and the level density expressions used by the original authors, very often differences in excitation energies make direct comparisons difficult. The following sentences sum up the situation where reasonable comparisons can be made.

Concerning the (n,p) spectra of $Ni^{58}(n,p)Co^{58}$, $Fe^{54}(n,p)Mn^{54}$ and $Zn^{64}(n,p)Cu^{64}$ measured by Storey et al 1959 our results show significant differences only for $Fe^{54}(n,p)Mn^{54}$, where we have seen a more pronounced energy dependence of T than that concluded by the authors.

Debertin and Rössle on their results for $Ni^{58}(n,p)Co^{58}$ at 8.4 Mev and 14.1 Mev reported that values for a_1 corresponding to the two incident energies agree within the experimental errors. They used σ_c (optical, Lindner) and σ_c (Shapiro, r_o 1.3). Their results are as follows. For E(8.4), excitation energy 3-5.5 Mev; $a_1 = 7.2 \pm 0.4$ Mev^{-1} and 6.2 ± 0.4 Mev^{-1} for σ_c (Shapiro, r_o 1.3) and σ_c (optical, Lindner), respectively. For E(14.1), excitation energy 3.5-8 Mev; $a_1 = 6.8 \pm 0.4$ Mev^{-1} and 5.9 ± 0.4 Mev^{-1} for σ_c (Shapiro, r_o 1.3) and σ_c (optical, Lindner), respectively. Our detailed analysis did not indicate a common excitation energy region for the two spectra satisfying our requirements of good statistics, etc. We did, however, compare the spectra in the excitation energy region 3-5.0 Mev accepting poor statistics for one spectrum, and found that T and a_1 for E(8.4) at 60^o and E(14.1) at 145^o agreed within experimental errors for σ_c (optical, Lindner) but not for other σ_c; values of $a_1 = 6.0 \pm 0.4$ Mev^{-1} and

5.8 ± 0.8 Mev^{-1} for E(8.4) and E(14.1), respectively; T = 1.44 ± 15%. In comparing E(8.4) at 60^{o} excitation energy 3-5.0 Mev and E(14.1) at 8^{o} excitation energy 6.2 - 8.3 Mev it is seen that a_1, a_3 and a_4 for the two spectra agree for σ_c (Blatt and Weisskopf, r_o 1.3) and T for the two agree for σ_c (optical, Lindner).

From 14.1 Mev (n,p) spectra measured by Emmerich and Hofmann from Fe, Ni and Zn we get somewhat higher values for 'a' in the case of Fe and somewhat lower values in the case of Ni and Zn than those obtained by the original authors for σ_c (optical, Lindner). The excitation energy regions, however, are not the same. The value of T for Fe obtained by us agrees well with the value reported by them.

In the case of CsI(n,p) spectra our analysis indicates much higher temperature for E(19.6) and E(21.5) than those reported by the authors for σ_c (Blatt and Weisskopf). To some extent the same is true for KI(n,p) spectra for E(17.5) and E(15.2).

Our reanalysis of Ni(α,p)Cu spectra measured by Fox and Albert gives a_o generally of the same order as reported by the authors but our conclusions on the presence or absence of 'any anomaly' are different. Whereas Fox and Albert have concluded that the spectra are in excellent agreement with the evaporation model our detailed analysis does not present so satisfactory a picture. If the conclusions of Fox and Albert were to agree well with our analysis we would have obtained 'close to unity' for the ratios calculated by our 'level density independent' approach.

For $Cu^{63}(\alpha,p)Zn^{66}$ spectra our results qualitatively agree with those reported by Lassen and Sidorov 1960, though there are deviations in detail.

6.3 Effects of Changing Criteria

Effects of changing σ_c have already been discussed. The influence of the form of the level density expression on the comparative study of different spectra can be summed up as follows: (i) Generally speaking, the constant temperature model shows agreement among different incident energy spectra (in cases where such agreement is seen) to a slightly better degree than other expressions. (ii) Comparing different Fermi gas expressions, the overall picture is about the same for a_1 and a_4 (except that values of a_1 are generally higher; ref. section 5.11) but the range of variations affecting the 'comparative study' is wider for a_3 and a_2 and it appears that a_o is not a suitable parameter for this kind of study.

It should be stressed that the main objectives of this study were to see if different values of σ_c and/or different level density expressions had any significant or at least any consistent effect on the comparison of different spectra and from this point of view only the standard deviations resulting from the least squares analysis were considered as the uncertainties. It may be argued, however, that for making any definite statements concerning the presence or absence of any anomaly one must consider the more realistic errors as the uncertainties. Our 'level density independent' approach would have revealed if the different incident energy spectra were always consistent say within ± 15%, but in spite of differences (from the conventional analysis) in details the overall picture is not changed dramatically. Furthermore, we have examined the sets of spectra from the view point of T and 'a' parameters with larger errors to fix the range of the

uncertainties. Naturally, in this case, more spectra seem to agree among themselves but again the situation is not significantly altered for more than two different incident energy spectra. In this context the following changes from previous results are worth mentioning. The E(12.9), E(14.1) and E(15.7) spectra of $Ni^{58}(n,p)Co^{58}$ of Storey et al have the same T for the three energies (true for all σ_c), and have the same 'a' for the three energies (except when σ_c (optical, Mani) is used). For E(9.65), E(10.0) and E(10.35) spectra of Ni(α,p)Cu values of T show agreement and differences between 'a' are generally reduced (or show agreement) for the excitation energy (1.1 - 3.7) Mev and (0.6 - 3.9) Mev but not for (1.5 - 3.9) Mev. Note that E(12.8) is excluded.

In many cases the straight line region in the level density plot of a spectrum extends beyond the more restrictive selected region common to different incident energy spectra. If this restrictive but 'essential' condition is relaxed it is possible to obtain in many cases slightly different values of the slopes for each spectrum and with deliberate search for agreement it may be possible to match these values for different incident energies (but without any regard to the excitation energy of the residual nucleus).

6.4 Concluding Remarks

The amount of experimental material available for this analysis turned out to be rather small and when different measurements are available for the same incident energy and target discrepancies are not insignificant.

Use of the more accurate equation of the spectral shape

(Eq. 2.10) instead of Weisskopf-Ewing formula deserves attention, though in this context some work has already been done and the apparent conclusion has been that the 'anomalies' cannot be removed in this manner (Thomas 1964a, 1964b). More sophisticated models of 'intermediate nature' are also becoming increasingly popular with the concepts of 'doorway' and 'hallway' states preceding the realization of 'true compound state' (ref: Block and Feshbach 1963, Kennedy and Schrils 1968; Ferrel and MacDonald 1966; Fallieros and Ferrell 1967). Griffin's model 1966 attempts to separate contributions towards the 'evaporation spectrum' from the 'precompound' and the 'compound' nucleus decays and some recent papers report that the observed variation of T with incident energy in $Sn^{118}(p,n)Sb^{118}$ and in $Fe^{56}(\alpha,n)Ni^{59}$ spectra can be described in terms of these 'precompound' decays (ref: Kondiah et al 1968; Parthasardhi and Sastry 1969; Rao et al 1970).

During the course of this work we directed some attention to another 'anomaly' reported by some researchers in evaporation spectra involving emission of charged particles. We are referring to the reactions yielding values of 'a' insensitive to the mass number contrary to the predictions of the Fermi gas model. For the expected dependence of 'a' on A the following two references present the general picture; Lang 1961; Marmier and Sheldon 1970. An oversimplified statement would be that 'a' should be proportional to A. For the observed anomaly we refer to the various studies involving (α,p), (α,α') and (d,α) reactions (Igo and Wegner 1956; Hurwitze et al 1964; Mead and Cohen 1961; Kumabe et al 1962; West 1966; Swenson and Gruhn 1966). Again some attempts have been made to explain this anomaly also (e.g. ref. Swensen

and Gruhn 1966; Izumo 1961). Our analyses of CsI(n,p) spectra and (n,p) spectra from much lighter targets (Ni^{58}, Fe^{54}, Zn^{64}, etc.) do indicate an 'anomalous' insensitivity of 'a' to mass numbers. However, the overall results of (α,p) spectra complicate the situation even further and a more detailed examination of this aspect is necessary.

APPENDIX

DETAILED TABULATION OF RESULTS

Table A.1 presents most of our results from the conventional analysis and table A.2 gives additional results for those spectra to which pairing energy correction could be applied.

$\sigma_{c1} = \sigma_c$ (Blatt & Weisskopf, $r_o = 1.3$);

$\sigma_{c2} = \sigma_c$ (Blatt & Weisskopf, $r_o = 1.5$);

$\sigma_{c3} = \sigma_c$ (Shapiro, $r_o = 1.3$);

$\sigma_{c4} = \sigma_c$ (Shapiro, $r_o = 1.5$);

$\sigma_{c5} = \sigma_c$ (Optical, Lindner);

$\sigma_{c6} = \sigma_c$ (Optical, Mani).

Errors quoted in the tables refer to our realistic estimates of the uncertainties (ref. section 6.1) and each quoted figure applies to the results in that row. The standard deviations calculated for each value from the least square method is always smaller than this error and in a majority of cases is smaller by a factor of 2, but there are wide variations. Those values which had standard deviations more than about 5% have been omitted from the tables.

TABLE A.1

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Ni^{58}(n,p)Co^{58}$	Debertin & Rossle (1965)	8.4 (60°)	3.0-5.0	σ_{c1}	4	1.12	3.21	7.82	7.86	6.48	6.92
				σ_{c2}	4	1.17	2.91	7.34	5.44	6.04	6.47
				σ_{c3}	4	1.08	3.38	8.09	6.09	6.73	7.18
				σ_{c4}	4	1.22	2.70	7.01	5.16	5.74	6.16
				σ_{c5}	4	1.39	2.09	6.01	4.30	4.84	5.22
				σ_{c6}	4	1.18	2.85	7.25	5.36	5.96	6.38
$Ni^{58}(n,p)Co^{58}$	Storey et al (1959)	12.9 (90°)	3.5-5.3	σ_{c1}	8	1.49	1.72	5.49	3.83	4.35	4.72
				σ_{c2}	8	1.50	1.69	5.43	3.78	4.30	4.67
				σ_{c3}	8	1.49	1.72	5.49	3.83	4.35	4.72
				σ_{c4}	8	1.45	1.80	5.62	3.94	4.47	4.84
				σ_{c5}	8	1.54	1.60	5.27	3.65	4.16	4.52
				σ_{c6}	8	1.54	1.59	5.25	3.63	4.14	4.50
$Ni^{58}(n,p)Co^{58}$	Storey et al (1959)	12.9 (90°)	6.2-8.3	σ_{c1}	6	1.48	3.20	6.49	5.12	5.56	5.87

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c2}	6	1.57	2.85	5.99	4.67	5.09	5.38
				σ_{c3}	6	1.65	2.57	5.57	4.31	4.71	4.99
				σ_{c4}	7	1.58	2.80	5.91	4.61	5.02	5.32
				σ_{c5}	6	1.64	2.62	5.64	4.37	4.78	5.06
				σ_{c6}	6	1.53	3.00	6.20	4.87	5.29	5.59
$Ni^{58}(n,p)Co^{58}$	Storey et al (1959)	14.1 (90°)	6.2-8.3	σ_{c1}	8	1.48	3.31	6.58	5.22	5.66	5.97
				σ_{c2}	8	1.53	3.06	6.24	4.92	5.34	5.64
				σ_{c3}	8	1.54	3.04	6.21	4.89	5.31	5.61
				σ_{c4}	8	1.60	2.83	5.91	4.63	5.04	5.33
				σ_{c5}	8	1.56	2.98	6.12	4.81	5.23	5.53
				σ_{c6}	8	1.64	2.66	5.66	4.41	4.81	5.09
$Ni^{58}(n,p)Co^{58}$	Storey et al (1959)	15.7 (90°)	6.2-8.3	σ_{c1}	9	1.63	2.72	5.74	4.48	4.88	5.16
				σ_{c2}	9	1.66	2.64	5.62	4.38	4.77	5.05
				σ_{c3}	9	1.61	2.78	5.82	4.55	4.96	5.25

.... continued

TABLE A.1, continued

REACTION	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c4}	9	1.61	2.81	5.86	4.59	5.00	5.29
				σ_{c5}	9	1.67	2.60	5.55	4.31	4.71	4.99
				σ_{c6}	9	1.73	2.41	5.28	4.08	4.46	4.73
$Ni^{58}(n,p)Co^{58}$	Debertin & Rössle (1965)	14.1 (8^0)	6.2-8.3	σ_{c1}	6	1.31	4.17	7.78	6.30	6.77	7.11
				σ_{c2}	6	1.35	3.96	7.49	6.03	6.50	6.83
				σ_{c3}	6	1.34	3.98	7.53	6.07	6.53	6.86
				σ_{c4}	6	1.39	3.74	7.19	5.77	6.23	6.55
				σ_{c5}	7	1.40	3.67	7.09	5.68	6.13	6.45
				σ_{c6}	6	1.45	3.40	6.72	5.35	5.79	6.10
$Ni^{58}(n,p)Co^{58}$	Colli et al (1961)	14.1 (forward angle)	6.2-8.3	σ_{c1}	7	1.28	4.26	7.96	6.44	6.93	7.27
				σ_{c2}	8	1.33	3.96	7.54	6.06	6.54	6.87
				σ_{c3}	7	1.33	3.97	7.57	6.09	6.56	6.90
				σ_{c4}	7	1.36	3.77	7.29	5.84	6.30	6.63
				σ_{c5}	7	1.34	3.89	7.45	5.98	6.45	6.78
				σ_{c6}	8	1.43	3.42	6.79	5.39	5.84	6.16

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Fe^{54}(n,p)Mn^{54}$	Storey et al (1959)	12.9 (90°)	6.8-8.8	σ_{c1}	6	1.31	4.70	8.26	6.81	7.28	7.61
				σ_{c2}	6	1.38	4.19	7.59	6.20	6.65	6.96
				σ_{c3}	7	1.27	4.93	8.57	7.09	7.57	7.90
				σ_{c4}	6	1.47	3.74	6.98	5.65	6.08	6.38
				σ_{c5}	6	1.34	4.50	8.00	6.57	7.03	7.35
				σ_{c6}	7	1.38	4.21	7.61	6.22	6.67	6.98
$Fe^{54}(n,p)Mn^{54}$	Storey et al (1959)	14.1 (90°)	6.8-8.8	σ_{c1}	9	1.68	2.84	5.73	4.52	4.91	5.18
				σ_{c2}	9	1.75	2.62	5.42	4.25	4.63	4.89
				σ_{c3}	9	1.79	2.51	5.26	4.11	4.48	4.74
				σ_{c4}	9	1.80	2.48	5.21	4.07	4.44	4.70
				σ_{c5}	8	1.58	3.20	6.24	4.98	5.38	5.66
				σ_{c6}	9	1.61	3.09	6.08	4.84	5.24	5.52

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Fe^{54}(n,p)Mn^{54}$	Storey et al (1959)	15.7 (90^0)	6.8-8.8	σ_{c1}	8	1.92	2.19	4.78	3.69	4.04	4.28
				σ_{c2}	8	1.98	2.06	4.58	3.52	3.86	4.10
				σ_{c3}	8	1.92	2.19	4.77	3.69	4.04	4.28
				σ_{c4}	8	1.96	2.11	4.65	3.58	3.92	4.17
				σ_{c5}	8	1.82	2.43	5.13	4.00	4.36	4.62
				σ_{c6}	9	2.09	1.84	4.26	3.24	3.56	3.79
$Fe^{54}(n,p)Mn^{54}$	Jack & Ward (1959)	14.1 (forward angle)	6.8-8.8	σ_{c1}	12	1.96	2.06	4.61	3.53	3.88	4.12
				σ_{c2}	12	2.03	1.91	4.39	3.34	3.68	3.91
				σ_{c3}	12	2.09	1.80	4.22	3.20	3.52	3.75
				σ_{c4}	12	2.17	1.67	4.02	3.02	3.34	3.50
				σ_{c5}	13	1.85	2.30	4.95	3.82	4.18	4.44
				σ_{c6}	12	1.92	2.12	4.65	3.56	3.90	3.93

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Fe^{54}(n,p)Mn^{54}$	Colli et al (1961)	14.1 (forward angle)	6.8-8.8	σ_{c1}	7	1.34	4.35	7.86	6.42	6.89	7.21
				σ_{c2}	8	1.38	4.81	7.50	6.10	6.55	6.87
				σ_{c3}	7	1.43	3.81	7.14	5.77	6.21	6.52
				σ_{c4}	7	1.42	3.84	7.18	5.81	6.25	6.56
				σ_{c5}	7	1.28	4.72	8.37	6.88	7.36	7.69
				σ_{c6}	8	1.35	4.24	7.72	6.30	6.76	7.08
$Zn^{64}(n,p)Cu^{64}$	Storey et al (1959)	12.9 (90^o)	6.2-7.8	σ_{c1}	7	1.40	3.35	6.82	5.38	5.84	6.17
				σ_{c2}	7	1.50	2.91	6.19	3.81	5.25	5.56
				σ_{c3}	7	1.54	2.80	6.02	4.67	5.10	5.41
				σ_{c4}	7	1.49	2.93	6.23	4.85	5.29	5.60
				σ_{c5}	7	1.67	2.36	5.38	4.11	4.51	4.80
				σ_{c6}	7	1.46	3.08	6.44	5.04	5.49	5.80

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Zn^{64}(n,p)Cu^{64}$	Storey et al (1959)	14.1 (90°)	6.2-7.8	σ_{c1}	6	1.29	3.93	7.64	6.11	6.60	6.95
				σ_{c2}	7	1.35	3.61	7.20	5.71	6.19	6.52
				σ_{c3}	7	1.33	3.72	7.35	5.84	6.33	6.66
				σ_{c4}	7	1.36	3.57	7.13	5.65	6.12	6.46
				σ_{c5}	7	1.40	3.38	6.86	5.41	5.88	6.20
				σ_{c6}	7	1.45	3.13	6.51	5.10	5.55	5.86
$Zn^{64}(n,p)Cu^{64}$	Storey et al (1959)	15.7 (90°)	6.2-7.8	σ_{c1}	8	1.56	2.72	5.89	4.56	4.99	5.29
				σ_{c2}	8	1.59	2.63	5.75	4.44	4.85	5.15
				σ_{c3}	8	1.56	2.72	5.89	4.56	4.98	5.28
				σ_{c4}	8	1.56	2.75	5.93	4.59	5.02	5.32
				σ_{c5}	8	1.66	2.41	5.42	4.15	4.56	4.84
				σ_{c6}	8	1.67	2.40	5.41	4.14	4.54	4.83

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Zn^{64}(n,p)Cu^{64}$	Emmerich & Hofmann (1967)	14.0 (forward angle)	6.2-7.8	σ_{c1}	6	1.43	3.28	6.67	5.26	5.71	6.03
				σ_{c2}	7	1.50	2.98	6.25	4.88	5.32	5.63
				σ_{c3}	6	1.48	3.09	6.40	5.02	5.46	5.77
				σ_{c4}	7	1.55	2.82	6.01	4.67	5.10	5.40
				σ_{c5}	7	1.58	2.70	5.83	4.52	4.94	5.23
				σ_{c6}	6	1.62	2.55	5.62	4.33	4.73	5.03
KI(n,p)	Langkau (1963)	15.2	7.0-9.0	σ_{c1}	7	1.72	2.73	5.54	4.37	4.75	5.01
				σ_{c2}	7	1.72	2.75	5.56	4.39	4.77	5.03
				σ_{c3}	7	1.70	2.83	5.68	4.50	4.88	5.14
				σ_{c4}	7	1.69	2.86	5.71	4.53	4.91	5.18
				σ_{c6}	7	1.79	2.55	5.28	4.14	4.50	4.76
KI(n,p)	Langkau (1963)	17.5	4.0 - 9.0	σ_{c1}	10	2.84	0.98	2.90	2.06	2.32	2.51

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c2}	10	2.39	1.38	3.56	2.63	2.92	3.13
				σ_{c3}	10	2.81	1.00	2.92	2.08	2.35	2.54
				σ_{c4}	10	2.40	1.37	3.55	2.61	2.91	3.12
				σ_{c6}	10	3.03	0.86	2.68	1.88	2.13	2.31
CsI(n,p)	Bormann & Langkau (1961) Langkau (1963)	14.1	3.0-6.0	σ_{c1}	3	1.36	2.42	6.29	4.63	5.16	5.53
				σ_{c2}	3	1.50	2.02	5.62	4.06	4.55	4.90
				σ_{c3}	3	1.38	2.39	6.23	4.57	5.10	5.47
				σ_{c4}	3	1.47	2.07	5.71	4.13	4.63	4.98
				σ_{c5}	3	1.34	2.49	6.40	4.72	5.25	5.63
				σ_{c6}	3	1.46	2.11	5.77	4.19	4.69	5.04
CsI(n,p)	Bormann & Langkau (1961) Langkau (1963)	16.0	3.0-6.0	σ_{c1}	5	1.45	2.10	5.78	4.19	4.69	5.05
				σ_{c2}	5	1.53	1.90	5.43	3.89	4.38	4.72
				σ_{c3}	5	1.43	2.16	5.88	4.28	4.78	5.14

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c4}	5	1.54	1.89	5.42	3.88	4.37	4.71
				σ_{c5}	5	1.53	1.89	5.42	3.88	4.36	4.71
				σ_{c6}	5	1.59	1.76	5.20	3.70	4.17	4.51
CsI(n,p)	Bormann & Langkau (1961) Langkau (1963)	16.0	7.0-9.0	σ_{c1}	3	1.33	4.59	8.09	6.66	7.12	7.45
				σ_{c2}	3	1.62	3.08	6.05	4.82	5.22	5.49
				σ_{c3}	3	1.40	4.10	7.44	6.07	6.51	6.82
				σ_{c4}	3	1.56	3.32	6.37	5.11	5.52	5.80
				σ_{c5}	3	1.53	3.47	6.59	5.30	5.72	6.01
				σ_{c6}	3	1.49	3.63	6.80	5.50	5.92	6.21
CsI(n,p)	Bormann & Langkau (1961) Langkau (1963)	18.0	7.0-9.0	σ_{c1}	7	2.21	1.66	3.96	2.98	3.29	3.52
				σ_{c2}	7	2.42	1.38	3.52	2.60	2.90	3.10
				σ_{c3}	7	2.16	1.73	4.07	3.08	3.39	3.62
				σ_{c4}	7	2.55	1.24	3.30	2.41	2.69	2.89
				σ_{c5}	7	2.04	1.94	4.40	3.36	3.69	3.93

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c6}	7	2.38	1.42	3.60	2.67	2.96	3.17
CsI(n,p)	Bormann & Langkau (1961) Langkau (1963)	19.6	7.0-9.0	σ_{c1}	9	3.67	0.60	2.19	1.47	1.70	1.86
				σ_{c2}	9	4.19	0.46	1.92	1.25	1.46	1.61
				σ_{c3}	9	3.68	0.59	2.18	1.47	1.69	1.85
				σ_{c4}	9	4.22	0.45	1.90	1.24	1.45	1.59
				σ_{c5}	9	4.33	0.43	1.85	1.20	1.40	1.55
				σ_{c6}	9	4.55	0.39	1.77	1.14	1.33	1.47
CsI(n,p)	Bormann & Langkau (1961) Langkau (1963)	21.5	7.0-9.0	σ_{c1}	5	3.13	0.81	2.59	1.80	2.05	2.23
				σ_{c2}	5	3.41	0.67	2.35	1.86	1.64	2.02
				σ_{c3}	5	3.11	0.81	2.61	1.82	2.06	2.24
				σ_{c4}	5	3.45	0.66	2.33	1.59	1.82	1.99
				σ_{c5}	5	3.89	0.52	2.06	1.36	1.58	1.74
				σ_{c6}	5	3.31	0.72	2.44	1.68	1.91	2.09

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
Ni(α,p)Cu	Fox & Albert (1961)	9.65 (135°)	0.6-3.9	σ_{c1}	2	0.63	5.05	14.0	10.1	12.3	12.1
				σ_{c2}	2	0.65	4.71	13.3	9.58	10.8	11.6
				σ_{c3}	2	0.61	5.39	14.5	10.5	11.8	12.7
				σ_{c4}	2	0.66	4.57	13.1	9.38	10.6	11.4
				σ_{c5}	3	0.83	2.59	10.0	6.66	7.70	8.45
				σ_{c6}	2	0.65	4.75	13.4	9.64	10.8	11.7
Ni(α,p)Cu	Fox & Albert (1961)	9.65 (135°)	1.1-3.7	σ_{c1}	2	0.61	6.18	14.8	11.1	12.3	13.1
				σ_{c2}	2	0.63	5.71	14.1	10.5	11.6	12.4
				σ_{c3}	2	0.59	6.57	15.4	11.6	12.8	13.7
				σ_{c4}	2	0.64	5.55	13.8	10.3	11.4	12.2
				σ_{c5}	3	0.81	3.49	10.4	7.38	8.33	9.01
				σ_{c6}	2	0.62	6.05	14.6	11.0	12.1	12.9

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
Ni(α,p)Cu	Fox & Albert (1961)	9.65 (135°)	1.5-3.9	σ_{c1}	2	0.61	7.08	15.4	11.9	13.0	13.8
				σ_{c2}	2	0.62	6.69	14.8	11.4	12.5	13.2
				σ_{c3}	2	0.59	7.51	16.0	12.4	13.6	14.4
				σ_{c4}	2	0.62	6.66	14.7	11.3	12.4	13.2
				σ_{c5}	3	0.82	3.61	10.3	7.37	8.28	8.93
				σ_{c6}	2	0.64	6.42	14.4	11.0	12.1	12.9
Ni(α,p)Cu	Fox & Albert (1961)	10.00 (135°)	0.6-3.9	σ_{c1}	2	0.66	4.60	13.2	9.43	10.6	11.4
				σ_{c2}	2	0.70	4.02	12.2	8.59	9.71	10.5
				σ_{c3}	2	0.66	4.58	13.1	9.40	10.6	11.4
				σ_{c4}	2	0.71	3.94	12.0	8.47	9.58	10.4
				σ_{c5}	2	0.88	2.62	9.60	6.47	7.45	8.15
				σ_{c6}	2	0.66	4.55	13.1	9.35	10.5	11.4
Ni(α,p)Cu	Fox & Albert (1961)	10.00 (135°)	1.1-3.7	σ_{c1}	2	0.63	5.70	14.0	10.5	11.6	12.4

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c2}	2	0.68	4.97	12.9	9.47	10.5	11.3
				σ_{c3}	2	0.62	5.77	14.1	10.6	11.7	12.5
				σ_{c4}	2	0.69	4.76	12.5	9.18	10.2	11.0
				σ_{c5}	3	0.84	3.21	9.92	6.97	7.90	8.56
				σ_{c6}	2	0.62	5.81	14.2	10.6	11.8	12.6
Ni(α,p)Cu	Fox & Albert (1961)	10.00 (135°)	1.5-3.9	σ_{c1}	2	0.65	6.16	14.0	10.7	11.7	12.5
				σ_{c2}	2	0.70	5.37	12.8	9.64	10.6	11.4
				σ_{c3}	2	0.65	6.23	14.1	10.8	11.8	12.6
				σ_{c4}	2	0.71	5.13	12.4	9.32	10.3	11.0
				σ_{c5}	2	0.92	3.12	9.16	6.52	7.35	7.94
				σ_{c6}	2	0.65	6.12	13.9	10.6	11.7	12.4
Ni(α,p)Cu	Fox & Albert (1961)	10.35 (135°)	0.6-3.9	σ_{c1}	2	0.65	4.66	13.2	9.51	10.7	11.5
				σ_{c2}	2	0.69	4.14	12.4	8.77	9.90	10.7

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c3}	2	0.66	4.58	13.1	9.40	10.6	11.4
				σ_{c4}	2	0.69	4.12	12.3	8.73	9.86	10.7
				σ_{c5}	2	0.85	2.77	9.89	6.71	7.70	8.42
				σ_{c6}	2	0.64	4.75	13.4	9.64	10.8	11.7
Ni(α,p)Cu	Fox & Albert (1961)	10.35 (135°)	1.1-3.7	σ_{c1}	2	0.63	6.14	14.2	10.8	11.9	12.7
				σ_{c2}	2	0.67	5.45	13.2	9.88	10.9	11.7
				σ_{c3}	2	0.63	6.25	14.4	11.0	12.1	12.8
				σ_{c4}	2	0.68	5.38	13.1	9.79	10.8	11.6
				σ_{c5}	3	0.86	3.35	9.76	6.96	7.84	8.47
				σ_{c6}	2	0.62	6.43	14.7	11.2	12.3	13.1
Ni(α,p)Cu	Fox & Albert (1961)	10.35 (135°)	1.5-3.9	σ_{c1}	2	0.63	6.48	14.5	11.1	12.2	13.0
				σ_{c2}	2	0.67	5.77	13.4	10.2	11.2	11.9

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c3}	2	0.62	6.67	14.8	11.4	12.4	13.2
				σ_{c4}	2	0.67	5.74	13.4	10.1	11.2	11.9
				σ_{c5}	2	0.87	3.46	9.73	7.01	7.87	8.48
				σ_{c6}	2	0.61	6.86	15.1	11.6	12.7	13.5
$Ni(\alpha,p)Cu$	Fox & Albert (1961)	12.80 (135^0)	0.6-3.9								
				σ_{c1}	2	0.73	3.70	11.6	8.11	9.20	9.98
				σ_{c2}	2	0.75	3.52	11.3	7.84	8.91	9.68
				σ_{c3}	2	0.74	3.57	11.4	7.93	9.00	9.77
				σ_{c4}	2	0.75	3.49	11.2	7.81	8.87	9.64
				σ_{c5}	2	0.77	3.34	11.0	7.58	8.63	9.39
				σ_{c6}	2	0.77	3.35	11.0	7.59	8.64	9.40
$Ni(\alpha,p)Cu$	Fox & Albert (1961)	12.8 (135^0)	1.1-3.7								
				σ_{c1}	2	0.75	3.77	11.2	7.97	9.00	9.73
				σ_{c2}	2	0.75	3.74	11.2	7.92	8.94	9.67

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c3}	2	0.71	4.19	11.9	8.57	9.63	10.4
				σ_{c4}	3	0.75	3.79	11.3	8.00	9.03	9.76
				σ_{c5}	2	0.72	4.06	11.7	8.39	9.44	10.2
				σ_{c6}	2	0.73	3.92	11.5	8.19	9.23	9.97
Ni(α,p)Cu	Fox & Albert (1961)	12.80 (135°)	1.5-3.9	σ_{c1}	2	0.70	5.32	12.7	9.57	10.6	11.3
				σ_{c2}	2	0.72	5.00	12.2	9.14	10.1	10.8
				σ_{c3}	2	0.72	4.99	12.2	9.12	10.1	10.8
				σ_{c4}	2	0.73	4.90	12.1	9.01	9.98	10.7
				σ_{c5}	2	0.75	4.66	11.7	8.68	9.63	10.3
				σ_{c6}	2	0.74	4.79	11.9	8.85	9.81	10.5
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	11.9 (90°)	5.8-7.9	σ_{c1}	3	0.48	26.1	35.0	31.5	32.7	33.5
				σ_{c2}	3	0.57	19.0	26.7	23.7	24.7	25.4

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c3}	2	0.54	20.7	28.7	25.5	26.6	27.3
				σ_{c4}	2	0.57	18.5	26.1	23.1	24.0	24.7
				σ_{c5}	3	0.73	11.3	17.5	15.0	15.8	16.4
				σ_{c6}	3	0.50	24.5	33.2	29.8	30.9	31.6
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	16.3 (90^o)	5.8-7.9	σ_{c1}	3	0.84	9.76	15.1	13.0	13.7	14.2
				σ_{c2}	3	0.86	9.15	14.4	12.3	13.0	13.4
				σ_{c3}	3	0.84	9.55	14.9	12.8	13.4	13.9
				σ_{c4}	3	0.86	9.20	14.4	12.3	13.0	13.5
				σ_{c5}	3	0.89	8.63	13.7	11.7	12.3	12.8
				σ_{c6}	3	0.90	8.40	13.4	11.4	12.0	12.5
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	16.3 (90^o)	10.1-11.5	σ_{c1}	4	0.64	26.6	33.3	30.7	31.5	32.1
				σ_{c2}	4	0.69	22.8	29.0	26.6	27.4	27.9
				σ_{c3}	4	0.67	23.6	29.9	27.4	28.3	28.8

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c4}	4	0.71	21.6	27.6	25.3	26.1	26.6
				σ_{c5}	4	0.96	11.7	16.3	14.5	15.1	15.5
				σ_{c6}	5	0.57	33.0	40.4	37.5	38.4	39.1
$Cu^{63}(\alpha,p)An^{66}$	Lassen & Sidorov (1960)	17.8 (90^0)	10.1-11.5	σ_{c1}	5	0.83	15.4	20.6	18.6	19.3	19.7
				σ_{c2}	5	0.90	13.4	18.2	16.3	16.9	17.4
				σ_{c3}	5	0.80	16.7	22.1	20.0	20.7	21.2
				σ_{c4}	5	0.91	13.0	17.8	15.9	16.5	16.9
				σ_{c5}	5	1.02	10.3	14.6	12.9	13.4	13.8
				σ_{c6}	5	0.81	16.3	21.6	19.6	20.2	20.7
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	19.30 (90^0)	10.1-11.5	σ_{c1}	6	1.01	10.6	14.9	13.2	13.8	14.2
				σ_{c2}	6	1.04	9.99	14.2	12.5	13.1	13.5
				σ_{c3}	6	1.02	10.4	14.7	13.0	13.5	13.9

.... continued

TABLE A.1, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	T Mev	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
				σ_{c4}	6	1.02	10.4	14.7	13.0	13.5	13.9
				σ_{c5}	6	1.13	8.52	12.4	10.9	11.4	11.7
				σ_{c6}	6	1.11	8.84	12.8	11.2	11.8	12.1

TABLE A.2 (With Pairing Energy Correction)

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
Ni(α,p)Cu	Fox & Albert (1961)	9.65 (135°)	1.5-3.9	σ_{c1}	5	2.45	16.7	9.87	12.0	13.5
				σ_{c2}	5	2.37	16.5	9.71	11.8	13.3
				σ_{c3}	5	2.59	17.1	10.2	12.3	13.8
				σ_{c4}	5	2.30	16.3	9.57	11.6	13.1
				σ_{c5}	5	1.13	14.8	7.84	9.90	11.4
				σ_{c6}	5	2.24	16.2	9.46	11.5	13.0
Ni(α,p)Cu	Fox & Albert (1961)	10.00 (135°)	1.5-3.9	σ_{c1}	4	2.14	15.9	9.23	11.3	12.7
				σ_{c2}	4	1.87	15.1	8.66	10.6	12.1
				σ_{c3}	4	2.17	16.0	9.31	11.3	12.8
				σ_{c4}	4	1.78	14.9	8.49	10.4	11.9
				σ_{c5}	4	1.10	12.8	6.90	8.66	9.97
				σ_{c6}	4	2.12	15.9	9.21	11.2	12.7

.... continued

TABLE A.2, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
Ni(α,p)Cu	Fox & Albert (1961)	10.35 (135°)	1.5-3.9	σ_{c1}	6	2.22	16.1	9.40	11.4	12.9
				σ_{c2}	6	1.98	15.4	8.90	10.9	12.3
				σ_{c3}	6	2.29	16.3	9.54	11.6	13.1
				σ_{c4}	6	1.95	15.4	8.85	10.8	12.3
				σ_{c5}	6	1.19	13.1	7.11	8.89	10.2
				σ_{c6}	6	2.34	16.4	9.64	11.7	13.2
Ni(α,p)Cu	Fox & Albert (1961)	12.8 (135°)	1.5-3.9	σ_{c1}	5	1.82	15.0	8.56	10.5	11.9
				σ_{c2}	5	1.71	14.7	8.33	10.3	11.7
				σ_{c3}	5	1.71	14.7	8.32	10.2	11.7
				σ_{c4}	5	1.68	14.6	8.26	10.2	11.6
				σ_{c5}	5	1.60	14.4	8.08	9.97	11.4
				σ_{c6}	5	1.64	14.5	8.17	10.1	11.5

.... continued

TABLE A.2, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	11.9 (90°)	5.8-7.9	σ_{c1}	5	15.1	24.6	20.8	22.0	22.9
				σ_{c2}	5	11.0	19.3	15.9	16.0	17.7
				σ_{c3}	5	12.0	20.5	17.0	18.2	18.9
				σ_{c4}	5	10.7	18.8	15.5	16.6	17.3
				σ_{c5}	5	6.58	13.2	10.5	11.3	12.0
				σ_{c6}	5	14.2	23.4	19.7	20.9	21.8
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	16.3 (90°)	5.8-7.9	σ_{c1}	5	6.07	11.8	9.44	10.2	10.7
				σ_{c2}	5	5.70	11.3	8.97	9.71	10.2
				σ_{c3}	5	5.95	11.6	9.29	10.0	10.6
				σ_{c4}	5	5.73	11.3	9.01	9.76	10.3
				σ_{c5}	5	5.38	10.8	8.57	9.30	9.81
				σ_{c6}	5	5.23	10.6	8.38	9.10	9.61

.... continued

TABLE A.2, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	16.30 (90^0)	10.1-11.5	σ_{c1}	5	20.3	27.1	24.4	25.3	25.9
				σ_{c2}	5	17.4	23.7	21.2	22.0	22.6
				σ_{c3}	5	18.0	24.4	21.9	22.7	23.3
				σ_{c4}	5	16.5	22.6	20.2	21.0	21.5
				σ_{c5}	5	8.92	13.6	11.7	12.3	12.8
				σ_{c6}	5	25.1	32.6	29.7	30.7	31.3
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	17.8 (90^0)	10.1-11.5	σ_{c1}	5	11.8	17.1	15.0	15.6	16.1
				σ_{c2}	5	10.2	15.2	13.2	13.8	14.3
				σ_{c3}	5	12.8	18.2	16.1	16.8	17.3
				σ_{c4}	5	9.91	14.8	12.9	13.5	13.9
				σ_{c5}	5	7.83	12.2	10.5	11.0	11.4
				σ_{c6}	5	12.4	17.9	15.7	16.4	16.9

.... continued

TABLE A.2, continued

Reaction	Reference	Incident energy (Mev) and angle of emission	Excitation energy of the residual nucleus (Mev)	σ_c	Error %	a_0 Mev^{-1}	a_1 Mev^{-1}	a_2 Mev^{-1}	a_3 Mev^{-1}	a_4 Mev^{-1}
$Cu^{63}(\alpha,p)Zn^{66}$	Lassen & Sidorov (1960)	19.3 (90^0)	10.1-11.5	σ_{c1}	6	8.10	12.6	10.8	11.4	11.8
				σ_{c2}	6	7.64	12.0	10.2	10.8	11.2
				σ_{c3}	6	7.92	12.3	10.6	11.1	11.5
				σ_{c4}	6	7.12	11.3	9.63	10.2	10.6
				σ_{c5}	6	6.52	10.6	8.92	9.45	9.82
				σ_{c6}	6	6.76	10.9	9.20	9.74	10.1

ACKNOWLEDGEMENTS

The author is greatly indebted to her Supervisor, Dr. M. Irfan, for his constant interest and active guidance in the present research and for his assistance in the preparation of the thesis.

The author is grateful to Dr. S. W. Breckon for his keen interest and helpful discussions throughout in this work.

The author wishes to acknowledge with thanks Mrs. G. Critch and Miss D. Janes for typing the thesis, and Mr. H. R. Breckon for his help in the photographic work.

Financial support received by the author from Memorial University of Newfoundland is also gratefully acknowledged.

BIBLIOGRAPHY

Albert, R. D., Anderson, R. D., and Wong, C., Phys. Rev., 120 (1960), 2149-54.

Alevera, A., Dumitrescu, R., Lukas, I., Magda, M. T., Martalagu, N., Plostinaru, D., Poenaru, D., Trutia, E., Vilcov, I., and Vilcov, N., Nucl. Phys., 58 (1964), 108-112.

Allan, D. L., Proc. Phys. Soc., A70 (1957a), 195.

Allan, D. L., Columbia International Conference on the Neutron Interaction with the Nucleus, New York (1957b), 207-213.

Allan, D. L., Nucl. Phys., 6 (1958), 464.

Allan, D. L., Nucl. Phys., 10 (1959), 348.

Allan, D. L., Nucl. Phys., 24 (1961), 274.

Armstrong, L., and Rosen, A. H., Nucl. Phys., 19 (1960), 40-51.

Bethe, H. A., Rev. Mod. Phys., 9 (1937), 69.

Blatt, J., and Weisskopf, W. F., Theoretical Nuclear Physics, (John Wiley & Sons, Inc., New York, 1952).

Block, B., and Feshbach, H., Ann. Phys., (N.Y.), 23 (1963), 47.

Bodansky, D., Ann. Rev. of Nucl. Sci., Vol. 12 (1962), 107.

Bohr, N., Nature, 137 (1936), 344.

Bormann, M., Z. Naturforsch, 17a (1962), 479-93.

Bormann, M., and Langkau, R., Z. Naturforsch, 16a (1961a), 445.

Bormann, M., and Langkau, R., Rutherford Jubilee Conference, Manchester (1961b), Paper C 5/17, p. 501-2.

Bonner, T. W., and Bramblett, R. L., Nuclear Structure Conference, Kingston, Ontario, 1960, p. 347-9.

Bramblett, R. L., and Bonner, T. W., Nucl. Phys., 20 (1960), 395-407.

Brown, G., Morrison, G. C., Muirhead, H., and Morton, W. T., Phil. Mag., 2 (1957), 785.

Buccino, S. G., Hollandsworth, C. E., Lewis, H. W., and Bevington, P. R., Nucl. Phys., 60 (1964), 17.

Cameron, A. G. W., Can. J. Phys., 36 (1958), 1040.

Campbell, E. J., Feshbach, H., Porter, C. E., and Weisskopf, V. F., MIT Laboratory for Nuclear Science, Technical Report No. 73 (1960).

Cindro, N., Rev. Mod. Phys., 38 (1966), 391.

Colli, L., and Facchini, U., Nuovo Cimento, IV (1956), 671-673.

Colli, L., Facchini, U., and Micheletti, S., Nuovo Cimento, V (1957), 502.

Colli, L., Facchini, U., Iori, I., Marcazzan, G., Sona, A., and Pignanelli, M., Nuovo Cimento, VII (1958a), 400-410.

Colli, L., Pignanelli, M., Rytz, A., and Zurmühle, R., Nuovo Cimento, 9 (1958b), 280-8.

Colli, L., Facchini, U., Iori, I., Marcazzan, M. G., and Sona, A. M., Nuovo Cimento, XIII (1959), 730-760.

Colli, L., Iori, I., Micheletti, S., and Pignanelli, M., Nuovo Cimento, XXI (1961), 966-979.

Debertin, K., Thesis, (Institute fuer Kern Physik, Universität Frankfurt, W. Germany) 1965a.

Debertin, K., and Rössle, E., Nucl. Phys., 70 (1965b), 89-96.

Dixon, W. R., Nucl. Phys., 42 (1963), 27-45.

Eddy, J. K., Thesis, 1967, West Virginia Univ.

Eisberg, R. M., Igo, G., and Wegner, H., Phys. Rev., 100 (1955), 1309-1314.

Emmerich, W. D., and Hofmann, A., Z. Phys., 201 (1967), 241-9.

Ericson, T., Advan. Phys., 9 (1960), 425.

Ericson, T., and Strutinski, V., Nucl. Phys., 8 (1958), 284.

Ericson, T., and Strutinski, V., Nucl. Phys., 9 (1959), 689.

Ewing, D. H., and Weisskopf, V. F., Phys. Rev., 57 (1940), 472, 935.

Fallieros, S., and Ferrell, R. A., Phys. Rev., 154 (1967), 92.

Feshbach, H., Shapiro, M. M., and Weisskopf, V. F., U. S. Atomic Energy Comm. Rept., NYO-3077 (1953) (Unpublished).

Ferrell, R. A., and MacDonald, W. M., Phys. Rev. Letters, 16 (1966), 187.

Fox, R., and Albert, R. D., Phys. Rev., 121 (1961), 587.

Griffin, J. J., Phys. Rev. Letters, 17 (1966), 478.

Holbrow, C. H., and Barschall, H. H., Nucl. Phys., 42 (1963), 264-79.

Huizenga, J. H., and Igo, G., ANL Report, 6373 (1961).

Huizenga, J. R., and Igo, G., Nucl. Phys., 29 (1962), 462.

Hurwitz, H., and Bethe, H., Phys. Rev., 81 (1951), 898.

Hurwitz, C., Spencer, S. J., Estertund, R. A., Pate, B. D., and Raynolds, J. B., Nucl. Phys., 54 (1964), 65-85.

Igo, G., Phys. Rev., 115 (1959), 1665.

Igo, G., and Wegner, H. E., Phys. Rev., 102 (1956), 1364.

Iwatani, K., Iwao Fujita, Masteru Sonoda Akira Katse and Yoshikisi Wakuta, J. Phys. Soc., Japan, 25 (1968), 964-70.

Izumo, K., Progr. Theoret. Phys., (Tyoto), 26 (1961), 807.

Jack, W., and Ward, A., Proc. Phys. Soc., 75 (1959), 833-849.

Kennedy, H. P., and Schrils, R., Intermediate Structure in Nuclear Reaction, Univ. of Kentucky Press, Lexington, Kentucky, 1968.

König, V., Nucl. Phys., 71 (1965), 497-510.

Kondiah, E., and Parthasardhi, K., Nuovo Cimento, 53B (1968), 174.

Kumabe, I., and Fink, R. W., Nucl. Phys., 15 (1960), 316.

Kumabe, I., Komatuzaki, T., Tomita, S., Yamaki, T., and Yamada, Y., J. Phys. Soc., Japan, 17 (1962), 1526.

Lane, A. M., and Parker, K., Nucl. Phys., 16 (1960), 690.

Lang, D. W., Nucl. Phys., 26 (1961), 434.

Lang, J. M. B., and Le Couteur, K. J., Proc. Phys. Soc., (London), A67 (1954), 586.

Lang, D. W., and Le Couteur, K. J., Nucl. Phys., 13 (1959a), 32.

Lang, D. W., and Le Couteur, K. J., Nucl. Phys., 14 (1959b), 21.

Langkau, R., Z. Naturforsch, 18a (1963), 914-926.

Lassen, N. O., and Larsen, C., Nucl. Phys., 42 (1963), 183.

Lassen, N. O., and Sidorov, V. A., Nucl. Phys., 19 (1961), 529.

Lindner, A., Zeitschrift für Physik, 171 (1963), 379-402.

Mani, G. S., Melkanoff, M. A., and Iori, I., Rapport C.E.A. No. 2379 (1963).

March, P. V., and Morton, W. T., Phil. Mag., 143 (1958a), 577.

March, P. V., and Morton, W. T., Phil. Mag., 3 (1958b), 1256.

Marmier, P., and Sheldon, E., Physics of Nuclei and Particles, Vol. II, 1970 (Academic Press, New York and London).

Mattauch, J. H. E., Thiele, W., and Wapstra, A. H., Nucl. Phys., 67 (1965), 1-31.

Mead, J. B., and Cohen, B. L., Phys. Rev., 125 (1962), 947.

Meldner, H., and Lindner, A., Z. Phys., 180 (1964), 362.

Newton, T. D., Can. J. Phys., 34 (1956), 804.

Parthasaradhi, K., and Sastry, D. L., Nuovo Cimento, 63B (1969), 511.

Parthasardhi, K., Rao, J. R., and Roa, V. V., Ind. Journ. of Pure and Appl. Phys., 7 (1969), 205.

Peaslee, D. C., Ann. Rev. Nucl. Sci., 5 (1955), 99-144.

Rama Rao, J., Lakshamana Rao, A., and Parthasaradhi, K., Nuovo Cimento, 68A (1970), 203-205.

Robertson, J. C., Nucl. Phys., 49 (1963), 306-314.

Shapiro, M. M., Phys. Rev., 90 (1953), 171.

Sherr and Brady, Phys. Rev., 124 (1961), 1928-43.

Sidorov, V. A., Nucl. Phys., 35 (1962), 53.

Storey, R. S., Jack, W., and Ward, A., Proc. Phys. Soc., 75 (1960), 526-38.

Swenson, N., and Cindro, N. Phys. Rev., 123 (1961), 910-22.

Swenson, L. W., and Gruhn, C. R., Phys. Rev., 146 (1966), 886-898.

Thomas, T. D., Nucl. Phys., 53 (1964a), 558-576.

Thomas, T. D., Nucl. Phys., 53 (1964b), 577-592.

Thomson, B. D., Phys. Rev., 129 (1963), 1649.

Topping, J., Error of Observation and Their Treatment.

Ureh, S., Jeannet, E., and Rössle, J, Helv. Phys. Acta., 34 (1961), 954-9.

Verbinski, V. V., Hurlimann, T., Stephens, W. E., and Winhold, E. J., Phys. Rev., 108 (1957), 779-82.

Weisskopf, V., Phys. Rev., 52 (1937), 295.

West, R. W., Phys. Rev., 141 (1966), 1033-1052.

Williams, C. D., and Thomas, T. D., Nucl. Phys., A92 (1967), 1-29.

Williams, C. S., and Thomas, T. D., Nucl. Phys., A107 (1968), 552-568.

Wolfenstein, L. Phys. Rev., 82 (1951), 690.

Wong, C., Anderson, J. D., McClure, J. W., and Walker, B. D., Nucl. Phys., 57 (1964), 515-525.

Wood, R. M., Borchers, R. R., and Barschall, H. H., Nucl. Phys., 71 (1964), 529-545.

Wood, R. D., and Saxon, D. S., Phys. Rev., 95 (1954), 577.