Title
AN EXPERIMENTAL VERIFICATION OF THE THEORY OF COMPOUND NUCLEUS

Permalink
https://escholarship.org/uc/item/63q5p36f

Author
Ghoshal, Samarendro N.

Publication Date
1950-05-31
TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks.
For a personal retention copy, call Tech. Info. Division, Ext. 5545
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
An Experimental Verification of the Theory of Compound Nucleus

May 31, 1950

by

Samarendra Nath Ghoshal
B.S. (University of Calcutta) 1942
M.S. (University of Calcutta) 1944

UNCLASSIFIED

DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

Physics

in the

GRADUATE DIVISION

of the

UNIVERSITY OF CALIFORNIA

Approved:


Committee in Charge

Deposited in the University Library

Date Librarian

Copy 3
Table of Contents

PART I An Experimental Verification of the Theory of Compound Nucleus

Abstract

Chapter I
Introduction

Chapter II
Experimental Method

Chapter III
Discussion of Results and Conclusions

Acknowledgements

Bibliography

PART II Elastic Scattering of 32 Mev Protons from Gold

Abstract

Chapter I
Theoretical Discourse

Chapter II
Experimental Method

Chapter III
Discussion of Results

Acknowledgements

Bibliography
Part I
An Experimental Verification of the Theory of Compound Nucleus

Abstract

The compound nucleus Zn\(^{64}\) was formed by bombarding Ni\(^{60}\) with \(\alpha\)-particles and Cu\(^{63}\) with protons. The ratios of the cross sections \(\sigma'(\alpha,n): \sigma'(\alpha,2n)\): \(\sigma'(\alpha,pn)\) on Ni\(^{60}\) were found to agree with the ratios \(\sigma'(p,n): \sigma'(p,2n)\): \(\sigma'(p,pn)\) on Cu\(^{63}\), giving a direct verification of the theory of compound nucleus. The observed cross sections of the \((p,n)\), \((p,2n)\), and \((p,pn)\) processes on Cu\(^{63}\) and \((\alpha,n)\), \((\alpha,2n)\) and \((\alpha,pn)\) on Ni\(^{60}\) have been compared with the theoretical cross sections calculated on the basis of statistical model. The observed anomalous behaviour of the \((p,pn)\) and \((\alpha,pn)\) cross sections have been discussed.

Excitation functions for the \((\alpha,n)\), \((\alpha,2n)\) and \((\alpha,3n)\) reactions on Ag\(^{107}\) and \((\alpha,2n)\) and \((\alpha,3n)\) reactions on Ag\(^{109}\) have been measured. The behaviour of the yield vs energy curves confirms the idea of the appearance of competing processes at higher energies. Attempt has been made to assign the new period of 5 hr. to In\(^{109}\). A similar period (3-5 hr.) has been assigned to In\(^{108}\). Attempts have been made to correlate the observed radiations with the various indium isotopes.
Chapter I
Introduction

(A) Historical Background.

Nuclear reaction involving the transformation of one nucleus into another was first observed by Rutherford in 1919. Since then a very large number of types of nuclear reactions have been discovered and quite extensively studied. Attempts have also been made to build up a consistent physical picture to explain the mechanism underlying the different types of nuclear reactions, and to make predictions regarding the behaviour of various measurable quantities.

The first comprehensive picture of the mechanism involved in a nuclear transformation was given by Bohr in his famous compound-nucleus theory. In this picture he proposed that a nuclear reaction proceeds in two independent stages, passing through an intermediate stage. In the first stage an incident light particle 'a' (like a proton or a neutron) is absorbed by a target nucleus 'A' which is generally heavy compared to 'a', to form the intermediate stage 'C' which Bohr calls the 'compound-nucleus'. Because of the comparatively large number of particles within the nucleus, the incident particle has a very short mean-free path. As a result, even though it might come in with a fairly high kinetic energy, that energy will be rapidly dissipated amongst the nuclear constituents by collisions. Thus no one particle may have sufficiently high energy for a considerable length of time to come out of the nucleus again (The minimum energy needed to come out is the binding energy which is about 8 Mev for not too light nuclei). The intermediate stage of the
compound nucleus is thus a remarkably stable configuration. After an interval long compared to the time for a nucleon to cross the nuclear dimension ($\sim 10^{-21} - 10^{-22}$ sec.), enough energy may again be concentrated on any one particle 'b' which will subsequently come out, leaving a residual nucleus 'B'.

The most important feature of the above picture is the comparative stability of the compound nucleus. This makes the process of breaking up of the compound nucleus independent of its formation. This is due to the fact that owing to the long interval of time that has elapsed, the compound nucleus has completely forgotten its past history by the time it is ready to decay. Therefore, if the same compound nucleus is formed by different methods, and observations are made on its decay, the probability of decay into any one particular final state should be the same, irrespective of the way it was formed. Hence, an experiment which would measure the cross section of the occurrence of a nuclear reaction in which the same compound nucleus is produced by different methods, and the residual products are the same, is a most direct test for validity of compound nucleus assumption.

The idea of compound nucleus has played a very vital part in the present theories of nuclear reaction. Hence it was thought desirable to check its validity by an experiment of the type mentioned above. Attempts have also been made, in the present experiment, to compare the measured values of cross sections of different nuclear reactions with the calculated values. The theoretical values can be calculated from the theories of nuclear reactions developed by Weisskopf and Ewing, Weisskopf and others, based on Bohr's picture of compound nucleus. In the next section, we will attempt to give a brief outline of the relevant theoretical considerations.
The present discussion will be restricted to non-resonance processes only. For the excitation energies used in the experiments to be described in the next chapter were fairly high. The levels in this region are very closely spaced and the widths of the levels are quite large compared to their spacing for fairly heavy elements \((z \geq 30)\). Hence there can be no well-defined quantum levels in this region, and no resonance phenomena is therefore expected.

Bohr's assumption regarding the compound nucleus is certainly valid for the case when a single quantum state of the nucleus is excited by the incident particle. In this case, this state of the compound nucleus should be characteristic of the nucleus itself, and should not depend on the way it was excited. It may not, however, be a very good assumption for the case where the excited state consists of the superposition of several stationary states. For in this case, the course of the process would depend upon the relative phases of the states, and is therefore not independent of the process of excitation. However, in the region of fairly high excitation energies, where the density of the states is very high, there is a strong overlapping of the different states. In this case, a great many states can be excited by the incident particle simultaneously, and the phase relations may be random, and the resulting process may be independent of the initial excitation process. Bohr's assumption may thus regain validity in this region.

Ideas regarding the energy-levels in nuclei can be obtained from experiments on the inelastic scattering of neutrons or protons, from the absorption of slow neutrons from nuclear reaction studies at resonance, from \(\gamma\)-ray studies, and other sources. These sources seem to give the following general picture about the nuclear energy levels. For excitation energies up to about
2 or 3 MeV above the ground state, the levels are still widely separated, the separation being of the order of one MeV. There are thus well defined quantum states present in this region. However, the level-density increases rapidly with increasing excitation, and at excitation energies around the binding energy of a neutron or a proton (~8 MeV), the average level spacing is of the order of 100 ev for lighter nuclei, and about 10 ev for heavier nuclei. These levels are quite sharply defined, since the only possible way by which these states can decay is by emitting a $\gamma$-quantum. The estimated lifetime against the decay by $\gamma$-emission is about $10^{-15}$ - $10^{-16}$ sec, which gives a width less than an electron volt.

As the excitation energy increases, the possibility of the decay of the excited state by processes other than $\gamma$-ray emission increases. These consist of the emission of neutrons, protons and other nuclear particles. It is actually found that the probability of decay by $\gamma$-ray emission is quite small in this region, compared to the probability of decay by particle emission. A reasonable estimate of the width of the levels, derived from the probability of particle emission is of the order of several Kev. This corresponds to a lifetime of the state which is small compared to the $\gamma$-decay lifetime, but large compared to the time that a nucleon takes to cross the nucleus (~$10^{-21}$ sec). The level spacing being of the order of several ev, we are here in region of almost complete overlapping of the states. Hence no resonance processes can be expected in this region, and classical considerations can be applied.

As explained above, the compound nucleus idea can be used in this case. Hence the cross section $\sigma(a,b)$ of a process of the type

$$A + a \rightarrow C^* \rightarrow B + b$$ (1)
(or simply $A(a, b) B$) can be divided into two parts. The first part $\sigma_a(\epsilon)$ is the cross section for the formation of the compound nucleus and depends on the kinetic energy $\epsilon$ of the incident particle '$a$'. The second part $\eta_b(E)$ is the relative probability of the emission of a particle $b$ by the compound nucleus $C$ in a state of excitation energy $E$. The two parts are independent of one another, and we may write

$$\sigma(a, b) = \sigma_a(\epsilon) \eta_b(E) \tag{2}$$

where $E = \epsilon + B_a$, $B_a$ being the binding energy of 'a' to the compound nucleus $C$.

$\sigma_a$ can again be written as

$$\sigma_a = S_a(\epsilon) \cdot \xi_a(\epsilon) \tag{3}$$

where $S_a(\epsilon)$ is the cross section for reaching the surface of the nucleus and is equal to the geometrical cross' section $\pi R^2$ for neutrons of energy above 1 Mev, $R$ being the radius of the nucleus. For protons and $\alpha$-particles, this should be reduced because of the problem of penetration through the Coulomb potential barrier.

$\xi_a(\epsilon)$ is what is generally known as the sticking probability. This is usually assumed to be independent of the nature of the particle 'a' and for the energy region considered is almost equal to unity.

The relative probability $\eta_b$ of the emission of the particle 'b' can be written as

$$\eta_b = \Gamma_b \sum_b \Gamma_b' \tag{4}$$

where $\Gamma_b$ is the emission probability per unit time by the compound nucleus. The sum is over all particle $b$ which can be emitted.
Without going further into the exact nature of the quantities defined we will try to deduce certain general conclusions. Suppose a compound nucleus C is formed by two different processes as shown below:

\[ A + a \rightarrow C^* \]
\[ A' + a' \rightarrow C^* \]

where \( C^* \) denotes the same excited state of C. If \( C^* \) now decays into the same final state \( B + b \), the cross sections can be written as

\[ \sigma(a, b) = \sigma_a \gamma_b \quad (E) \]
\[ \sigma(a', b) = \sigma_{a'} \gamma_b \quad (E) \]

\[ \frac{\sigma(a, b)}{\sigma(a', b)} = \frac{\sigma_a}{\sigma_{a'}} = \frac{S_a}{S_{a'}} \quad (6) \]

This shows that this ratio depends only on the relative probabilities of \( a \) and \( a' \) reaching the surface of the nucleus. For fairly high excitation energies these tend to the value \( a R^2 \) even for charged particles, and hence \( \sigma(a, b) \) tends to be equal to \( \sigma(a', b) \).

Suppose now \( C^* \) decays into a different final state \( D + d \), then the cross sections can be written as

\[ \sigma(a, d) = \sigma_a \gamma_d \quad (E) \]
\[ \sigma(a', d) = \sigma_{a'} \gamma_d \quad (E) \]

and from (5) and (7)

\[ \frac{\sigma(a, b)}{\sigma(a', b)} = \frac{\sigma(a', b)}{\sigma(a', d)} \quad (8) \]

Thus if the cross sections are measured at the same excitation energy of the compound nucleus formed by different methods, then a fulfillment of
relationship (8) would provide a direct confirmation of Bohr’s assumptions of compound nucleus.

In the present experiment, the compound nucleus Zn$^{64}$ was formed by the following two methods:

\[
\begin{align*}
\text{Ni}^{60} + \text{He}^4 &\rightarrow \text{Zn}^{64} \\
\text{Cu}^{63} + \text{H}^1 &\rightarrow \text{Zn}^{64}
\end{align*}
\]

and the ratios of the cross sections $\sigma(a, n): \sigma(a, 2n): \sigma(a, pn)$ on Ni$^{60}$ were compared with the ratios $\sigma(p, n): \sigma(p, 2n): \sigma(p, pn)$ on Cu$^{63}$. The results are discussed in Chapter III.

The dependence of the above cross sections on the energy of excitation of the compound nucleus was also studied and compared with theoretical values.

The calculation of the theoretical values of the cross sections depends on finding some suitable expressions for the quantities $\sigma_a$ and $\gamma_b$. The cross section $\sigma_a$ can be expressed as a sum of the partial cross sections

\[
\sigma_a = \sum_{a,l} \sigma_{a\alpha l}
\]

where $\sigma_{a\alpha l}$ is the cross section for the absorption of a particle 'a' of angular momentum 'l' by the target nucleus in state 'a'. This can be related to the probability of the inverse process $\Gamma_{a\alpha l}$. This is the probability of the emission of a particle 'a' of angular momentum 'l' from the compound nucleus of the previous case, leaving the residual nucleus (which is the target nucleus in the previous case) in the state 'a'. This is given by

\[
\Gamma_{a\alpha l} = \frac{\sigma_{a\alpha l}}{2 \pi^2 \chi_a^2} \cdot \frac{1}{\omega_c(E)}
\]

where $\chi_a$ is the De Broglie wave length of the particle 'a'. $\omega_c(E)$ is the

* $\Gamma_{a\alpha}$ is really the partial width and is measured in energy units.
level density of the levels in the compound nucleus at excitation energy E.

It should be noted that the values of $\Gamma_{aa'\ell}$ are averaged over the states of the compound nucleus excited by 'a'.

$\Gamma_{aa'\ell}$ can be expressed as a product

$$\Gamma_{aa'\ell} = K_a G_{aa'\ell} T_{a\ell} (\xi_a)$$  \hspace{1cm} (11)

where $K_a$ is the wave number corresponding to the velocity $v_a$ of the emitted particle at a great distance from the nucleus where the effects of the Coulomb potential and the centrifugal potential are negligible. $T_{a\ell} (\xi_a)$ is a factor depending on the penetrability of the barrier -- both coulomb and centrifugal -- by the outgoing particle 'a'. In case 'a' is a neutron, only centrifugal barrier is present ($l > 0$). $G_{aa'\ell}$ is the effect of the internal situation of the nucleus emitting 'a'.

We are here only interested in charged particle reactions. Values of $\Gamma_{aa'\ell}$ and $\sigma_{aa'\ell}$ have been calculated by Weisskopf for protons and $\alpha$-particles, using suitable approximation methods. For energies above the Coulomb barrier, they will behave almost like neutrons, and will be given by (4)

$$\sigma_{aa'\ell} = \xi (2 l + 1) \pi \lambda^2$$  \hspace{1cm} (12)

where $\xi$ is of the order of unity.

For energies much below the barrier, W. K. B. approximation method may be used. For energies near the barrier, this does not work too well. However, this region is small, and hence the $\sigma$ above the barrier is joined with the $\sigma$ below the barrier, without considering the intermediate region. In the present work, values of $\sigma_a = \sum \sigma_{aa'\ell}$ with a as the ground state of the target nucleus have been obtained by extrapolating from the tables of the calculated values given by Weisskopf.
The probability of the emission of a particle 'b' from the compound nucleus as given in eqn. (4) is \( \gamma_b = \frac{\Gamma_b}{\sum_b \Gamma_b} \), where \( \Gamma_b \) is the partial width for the emission of the different particles. \( \Gamma_b \) can be written as \( \Gamma_b = \sum_{\ell} \Gamma_{b\ell} \), where \( \ell \) is the angular momentum of 'b', and \( \beta \) is the state of the residual nucleus. These are related to the corresponding \( \sigma_{b\ell} \)'s by the eqn. (10)

\[
\Gamma_{b\ell} = \frac{\sigma_{b\ell}}{2 \pi^2 \lambda_b^2} \cdot \frac{1}{\omega_0(E)}
\]

where \( \omega_0(E) \) is the level-density of the compound nucleus from which 'b' has been emitted, \( \lambda_b \) is the De Broglie wave length corresponding to the energy of 'b'.

Since we are considering the region of high level-density, the sum over the partial widths may be replaced by an integral, and we get

\[
\Gamma_b = \frac{1}{2 \pi^2 \omega_0(E)} \int_0^{\xi_m} \frac{2mE}{\xi} \sigma_b(E) \omega_R(\xi - \xi) \, d\xi
\]  

(13)

where \( \Gamma_b \) is a function of \( \xi_m \) only, \( \xi_m \) being the maximum energy that 'b' can get for a given energy of the incident particle. \( m \) is the mass of the particle 'b', and \( \omega_R(\xi_m - \xi) \) is the level-density of the residual nucleus in the state in which it has been left when 'b' is emitted with an energy \( \xi \).

Defining a function

\[
f_b(\xi_m) = \int_0^{\xi_m} \frac{2mE}{\xi^2} \sigma_b(\xi) \omega_R(\xi_m - \xi) \, d\xi,
\]  

(14)

we get

\[
\gamma_b = f_b/\sum_b f_b,
\]  

(15)
The function

\[ I(\varepsilon) \, d\varepsilon = \frac{2m\varepsilon^2}{h^2} \sigma_b(\varepsilon) \, \omega_R(\varepsilon_m - \varepsilon) \, d\varepsilon \]  

(16)

represents the energy-distribution of the emitted particles 'b'. For neutrons above about 1 MeV, this can be approximated to a Maxwellian distribution,

\[ I(\varepsilon) \, d\varepsilon = \text{const.} \, x \varepsilon \exp(-\varepsilon/T) \]  

(17)

This is possible, since \( \sigma_b(\varepsilon) \) is a slowly varying function of energy in this region, while \( \omega_R(\varepsilon_m - \varepsilon) \) can be written as

\[ \omega_R(\varepsilon_m - \varepsilon) = \ell S(\varepsilon_m - \varepsilon) \]  

(18)

where \( S \) is the entropy of the residual nucleus of excitation energy \( (\varepsilon_m - \varepsilon) \).

\[ S(\varepsilon_m - \varepsilon) = S(\varepsilon_m) - \varepsilon \left( \frac{\partial S}{\partial \varepsilon} \right)_{\varepsilon_m} \]  

(18a)

for not too high energy \( \varepsilon \) of the emitted neutron. According to statistical mechanics \( dS/d\varepsilon = 1/T \), where \( T \) is temperature. Hence, we get eqn. (17).

A table of the values of \( T \) are given in Weisskopf's paper 4.

The temperature \( T \) (in MeV) corresponds to the residual nucleus of excitation energy \( E \), and is a function of \( E \). Writing \( E = E(T) \), and noting that both \( E \) and \( dE/dT \) (specific-heat) are zero at \( T = 0 \), we get\(^*\)

\[ E = bT^2 \]  

(19)

neglecting higher terms.

\[ \therefore S = \int \frac{dE}{T} = \sqrt{aE} + \text{const.} \]  

(20)

which gives

\[ \omega(E) = C \ell \sqrt{aE} \text{ for level-density} \]  

(21)

\(^*\)Actually \( E = bT^2 \) where \( \alpha > 2 \). In Debye's specific heat theory \( \alpha = 3 \) at low temperature. Here the simplest case of \( \alpha = 2 \) is chosen.
Because of the lack of our knowledge regarding the level-densities in nuclei, it is not possible to give any accurate values of the constants C and \( q \). However, for sufficiently high atomic weight \((A > 60)\), some rough values have been given. The level densities are expected to depend on the nature of the nuclei. The even-even (even A, even Z) are the most stable ones, and hence should have fewer number of levels, while the odd-odd nuclei should have the highest level-density. A working rule is

\[
C_{\text{even-even}} = \frac{1}{2} 
C_{\text{even-odd}} = \frac{1}{4} C_{\text{odd-odd}}
\]

(22)

The nature of the functions \( f \) defined in eqn. (14) is shown in Fig. 1 for several nuclei as calculated by Weisskopf.4

We will next discuss some specific reactions induced by protons. The \( a \)-induced reactions should have similar characteristics, except for the heavier mass of the \( a \)-particle, and higher Coulomb barrier for it.

We already noted that the cross section for the formation of the compound nucleus has been calculated by Weisskopf. This approaches the value \( n R^2 \) for higher energies (above barrier). In general the values of \( \sigma_p(\epsilon_p) \) are very strongly dependent on the nuclear radius \( R \). This is due to the fact that in the W. K. B. approximation for the calculation for the penetrability of the potential barrier, one has to integrate over a region where the potential energy is higher than the kinetic energy, and the lower limit of this is taken to be the nuclear radius. All experimental determination of the nuclear radius points to the fact that it varies roughly as \( A^{1/3} \), where \( A \) is the mass number of the nucleus. The constant of proportionality \( r_0 \) has been variously determined, and lies between \( 1.3 \times 10^{-13} \) to \( 1.5 \times 10^{-13} \). \( R \) is expressed in cm. In the calculations referred to above both these values of \( r_0 \) have been taken, and two sets of values have been given.
By far the most important reaction at lower energies is expected to be the \((p,n)\) reaction. The important competing process here is the inelastic \((p,p)\) scattering. Both \(\alpha\)-emission and \(\gamma\)-emission will be very small, former because of the high barrier, the latter because of small \(\gamma\)-ray width. Then the value of \(\eta_n = f_n/(f_n + f_p)\) is seen to be generally higher than \(\eta_p = f_p/(f_n + f_p)\) from Fig. 1. However there are some exceptions. The product of a \((p,n)\) reaction is generally positron-active or \(K\)-capturing, which decays into the original target nucleus. The latter is of course the product of \((p,p)\) process. Hence the \((p,n)\) product is heavier than the \((p,p)\) product, so that the threshold for the production of the former is higher than that of the latter by

\[
2m\,c^2 + (M_n - M_p) + \epsilon^+ + h\nu = 1.7\text{ MeV} + \epsilon^+ + h\nu
\]

where \(\epsilon^+ + h\nu\) is the energy released in the decay of the \((p,n)\) product into the original nucleus by the emission of positrons or \(K\)-capture and \(\gamma\)-emission (if there is any). This affects the value of \(f_n\). For a given incident proton energy, the value of \(\epsilon_m\), the upper limit in the integral (14) becomes smaller for \(f_n\) than for \(f_p\). Not only does this pull down the values of \(f_n\) slightly, but there are certain energy regions (between the \(p,p\) and \(p,n\) thresholds and just above) where proton emission becomes more probable than neutron emission. The effect is more pronounced when the energy released \((\epsilon^+ + h\nu)\) is quite high, as in the case of \(\text{Ni}^{62}\)\((p,n)\text{Cu}^{62}\) reaction where the difference in the thresholds is 4.7 MeV.

When the energy of the proton \(\epsilon_p\) is sufficiently high, so that

\[
(\epsilon_p - \epsilon_b) > B_b;
\]

were \(\epsilon_p\) is the energy carried away by the first emitted particle \(b^0\) (neutron or proton) and \(B_b\) is the binding energy for a second particle \(b^0\), the emission of this second particle becomes quite probable, and we begin to see reactions of type \((p,2n)\) or \((p,pn)\).

If we assume that the neutron is the only particle that is emitted as
the first particle then for all neutrons emitted with an energy less than 
\((E_p - B_b)\), a second particle \(b\) will come out. Hence the total cross section 
\(\sigma_{\text{tot}} (p, nb)\) will be given by (\(b\) referring to all the particles that can be emitted):

\[
\sigma_{\text{tot}} (p, nb) = \int_0^{E_p - B_b} I(\varepsilon) \, d\varepsilon \int_0^{E_p - B_n} I(\varepsilon) \, d\varepsilon \, \sigma_p
\]  

where \(I(\varepsilon) \, d\varepsilon\) represents the energy distribution of the first neutron emitted. For the regions of energy considered we can assume a Maxwellian distribution, and (23) becomes

\[
\sigma_{\text{tot}} (p, nb) = \sigma_p \left[ 1 - \left( 1 + \frac{\Delta\varepsilon}{T} \right) e^{-\frac{\Delta\varepsilon}{T}} \right] 
\]  

where \(\Delta\varepsilon = E_p - B_b\) (we neglect the small difference in the thresholds for the different particles \(b\) that can be emitted).

The second particle may be a neutron or a proton. The emission of an \(\alpha\)-particle or a \(\gamma\)-ray is ruled out. The proton emission may be expected to be less probable than the neutron emission. However, as in the case of \((p, n)\) to \((p, p)\), there are regions in which a proton emission may be more probable than the neutron emission.

Let \(P(\varepsilon) \, d\varepsilon\) be the probability of the emission of the first neutron between energies \(\varepsilon\) and \(\varepsilon + d\varepsilon\). The maximum energy available to the second particle \(b\) is \(\varepsilon_m = E_p - E - B_b\), where \(E_p\) is the energy of the incident proton, and \(B_b\) is the binding energy of the second particle, \(b\). Let \(P^b(\varepsilon') \, d\varepsilon\) be the probability for the emission of a second particle \(b\) between energies \(\varepsilon'\) and \(\varepsilon' + d\varepsilon'\). Then the probability for the emission of a second particle \(b\)
after the emission of the first neutron is

$$\int_{E=0}^{E_p - E_B} \int_{E'=0}^{E'_m} P(\varepsilon) P'(\varepsilon') d\varepsilon' d\varepsilon$$

(24)

The integration over $\varepsilon'$ gives the relative probability for the emission of the particle $b$ with the maximum energy $(E_p - E_B)$ and should be given by the expression for $\eta_b (E'_m) = \frac{f_b}{\sum_{b'} f_{b'}}$, where the summation in the denominator should extend over all particles that can follow the emission of the first neutron. Thus we get the expression for the cross section of the process $(p, nb)$ as given below.

$$\sigma(p, nb) = \sigma_p \frac{\int_0^{E_p - E_B} I(\varepsilon) \eta_b (E_p - \varepsilon - E_B) d\varepsilon}{\int_0^{E_p - B_n_1} I(\varepsilon) d\varepsilon}$$

(25)

In calculating $\eta_b$, one must take into account the different values of the binding energy for the different particles that can be emitted.

The cross section for the $(p, n)$ process will of course go down in this region where the two particle emission becomes more and more probable, and will be given by $\sigma_p - \sigma_{tot}(p, nb)$.

In deriving the expressions for $\sigma_{tot}(p, nb)$ or $\sigma(p, nb)$, we assumed that the first particle emitted was a neutron. But as we already saw that this is not always the case. There is a finite chance that the first particle emitted may be a proton. In this case the integral in the denominator of (25) does not give the total number of primary processes possible after the formation of the compound nucleus. To it must be added the total number of protons

* $B_n_1$ is the binding energy of the first neutron to the compound nucleus.
emitted, i.e.,

\[ \sigma(p, nb) = \sigma_p \int_0^{\epsilon_p - B_b} \frac{I_n(\epsilon) \eta_b (\epsilon_p - B_b - \epsilon) \, d\epsilon}{\int_0^{\epsilon_p - B_n} I_n(\epsilon) \, d\epsilon + \int_0^{\epsilon_p} I_p(\epsilon) \, d\epsilon} \]  

(26)

where \( I_n(\epsilon) \) gives the distribution of the first emitted neutrons while \( I_p(\epsilon) \) gives the distribution of the first emitted protons, as given by eqn. (16).

The above expression gives us the cross sections \( \sigma(p, 2n) \) and \( \sigma(p, np) \) when the first particle emitted is a neutron. However we should note that if the first particle emitted is a proton, then for higher excitation energies, it can be followed either by a neutron or a proton emission, and we will get \( (p, pn) \) and \( (p, 2p) \) processes. We have to add the cross section of this \( (p, pn) \) process to the one derived above to get the total \( (p, pn) \) cross section:

\[ \sigma(p, pb) = \sigma_p \int_0^{\epsilon_p - B_b} \frac{I_p(\epsilon) \eta_b (\epsilon_p - B_b - \epsilon) \, d\epsilon}{\int_0^{\epsilon_p - B_n} I_p(\epsilon) \, d\epsilon + \int_0^{\epsilon_p} I_p(\epsilon) \, d\epsilon} \]  

(27)

At still higher energies, three particles may be emitted successively. The cross sections of these processes (like \( p, 3n \)) goes up as the energy goes up. Hence, the cross sections of \( (p, 2n) \) or \( (p, pn) \) processes begins to go down in this region.

In the present experiment cross sections were measured for the various reactions induced by \( \alpha \) particles on \( \text{Ni}^{60}, \text{Ag}^{107}, \text{Ag}^{109} \) and by protons on \( \text{Cu}^{63} \) up to energies where three-particle emission becomes probable. Attempts have been made to correlate the observed values with theoretical values, calculated from the formulas deduced above.
Chapter II
Experimental Method

The source of the α-particles in these experiments was the Berkeley 60-inch cyclotron, while for the proton bombardments, the linear accelerator was used. The former gives about 40 Mev α-particles, while the latter gives about 32 Mev protons.

Stacked foil method was used in determining the different excitation curves, which give the variation of the yield of the given nuclear reaction at different energies of the bombarding particles. As the α-particles or protons go through the stack of foils, they lose energy by ionization, and hence the different foils are bombarded at different energies. The radioactivity of these foils is then measured as function of time by means of thin windowed ionization chamber or thin windowed Geiger counter, with reproducible geometry. The number of foils that can be counted at a time of course depends upon the half-lives studied. The shortest half-life investigated in the present case was the 10.5 min positron activity of Cu⁶².

The foils used in all cases were less than 10mg/cm², which makes the energy of the bombarding α-particles or protons quite well defined, except at very low energies. In these regions much thinner foils were used. The energy of the incident beam was measured by absorption method from the known range-energy curves. The average energy of the particles was derived from this by taking into account the amount of absorber that the particles had traversed before reaching the given foil to which half the thickness of the foil was also added.

The arrangement for the bombardment of the stacked foils in the cyclotron is shown in Fig. 2, which shows the schematic diagram. The method used
was similar to that used by Wilson, and Segre and Kelly. The stacked foils of the material to be bombarded were held in one of the slots in the wheel of Fig. 2, the other slots of which contained aluminum absorbers of gradually increasing thickness. The wheel was enclosed in a chamber at the end of a long curved snout. The front end of the snout was connected to the cyclotron tank, and had an 1/8 in. slit. The beam of the α-particles, which is quite inhomogeneous in energy as it comes out, is somewhat monochromatized by this first slit. The fringing field near the edge of the cyclotron magnet bends the α-particle trajectory, and also spreads out the beam, collimated by the first slit, because of the remaining inhomogeneity of its energy. A second slit at the other end of the snout finally collimates it down to a highly monochromatized and well defined beam. The beam then passes through one of the slots in the foil-wheel and is collected in the Faraday cup. The snout, wheel and cup are insulated from one another.

Beam energy was measured by determining the range in aluminum by bringing the successive slots of the wheel containing aluminum absorbers into the path of the beam by remote control arrangement. The current on the wheel \( i_w \) as well as in the cup \( i_c \) were measured by means of microameters after suitable amplification. The ratio \( i_c/(i_c + i_w) \) was plotted against the absorber thickness and the mean range corresponding to 50 percent transmission into the cup was determined. Then from the range energy curve, the mean energy of the α-particles was determined. The energy of the beam was determined both before and after the bombardment. The energy of the beam remains quite constant throughout the duration of the run if the deflector voltage is held constant within about 2 Kev.

After the energy-determination, the slot with the stacked foils was
brought into the path of the beam, the Faraday cup being now connect to an
Esterline Angus recording milliammeter through an amplifier of high amplification
as described by Vance\textsuperscript{8}. The current was integrated for the duration of
the bombardment.

A somewhat different method was used for proton bombardment in the
linear accelerator. The energy determination was done photographically. The
protons were elastically scattered by a very thin foil of gold at about $45^\circ$
to the incident beam, and made to pass through a thick copper absorber before
reaching the nuclear emulsion C2 type of photographic plate (100 microns thick).
The energy of the protons reaching the surface of the emulsion was about $8$ Mev,
so that the protons would spend their residual range within the emulsion.
The plate was tilted at $17.5^\circ$ to the direction of the scattered beam. A
schematic diagram of the arrangement is shown in Fig. 3(a). After developing
the plates, the residual ranges of the protons were measured by means of a
microscope under high magnification, and the number of the protons with a
residual range greater than $R'$ in the emulsion was plotted as a function of
$R'$. The mean range was taken to that corresponding to the 50 percent diminu-
tion in the number. From the measured range-energy curves for protons in the
material of the emulsion by Lattes et al\textsuperscript{9} and the calculated range-energy
curves in copper\textsuperscript{5} the mean energy of the protons was derived.

The target was held in position within the integrator I in Fig. 3(b)
which consisted of a collecting cup placed behind a permanent magnet to deflect
all secondary electrons. The cup was connected with a condenser of suitable
size (varying from 0.01 to 1.0 micro-farad), and the voltage developed across
the condenser was measured by means of a suitable balancing circuit (slide-
back)\textsuperscript{10}. From this the total charge collected by the integrator could be
found, and hence the total number of protons bombarding the target could be
Preparing the Foils.

Three different elements were studied in the present experiment: nickel, copper, and silver.

In case of nickel, enriched Ni$^{60}$ was used. This was available in the form of NiO and in very limited quantity. The foils of Ni$^{60}$ were made from this by electroplating. NiO was converted into the sulfate, and nickel was plated on copper cathode from the sulfate solution ($\text{pH} = 5$), with boric acid as buffer using a spiral platinum anode which was rotated with the plane of the spiral parallel to the copper cathode. A current density of about 7 milli-amp/cm$^2$ gave a very good deposition.

After deposition of the required amount of nickel, the copper was removed by dissolving it in AgNO$_3$ solution, and finally treating it with conc. HNO$_3$ for a few seconds. The foils were cut by means of a sharp punch to the size of 3/8 in. in diameter, and carefully weighed by means of an assay-balance to determine their thickness.

The copper foils were rolled down from 1 mil to 10 mg/cm$^2$ and cleaned by dil HCl and acetone.

The silver foils were prepared by evaporating silver under high vacuum. The silver was deposited on a clean sheet of mica, bent in the form of a cylindrical arc, and stripped off the mica.

In determining the excitation curves, the activities of the different samples were extrapolated to zero time after the bombardment, and divided by the thickness of the foils. To compare the relative cross sections of the different reactions from the same target nucleus, the correction was also made for the decay during the time of bombardment.
In both these cases the same product nuclei were investigated. The following reactions were studied:

\[
\begin{align*}
\text{Cu}^{63}(p,n) & \rightarrow \text{Zn}^{63} \\
\text{Ni}^{60}(a,n) & \rightarrow \text{Zn}^{62},
\end{align*}
\]

The level schemes of the three end products are well known and the radiations emitted by them quite suitable for comparison of the absolute cross sections of their formation. These characteristics are extremely rare in the whole of Segré's chart and no other single case has the same advantages as in the present case.

\(\text{Zn}^{63}\) decays with a half-life of 38 min. into \(\text{Cu}^{63}\). The major part of the decay goes by the emission of a positron of end point 2.4 Mev (85 percent of the time). There are two other softer \(\beta^+\) of end-points 1.5 Mev (7 percent of the time) and 0.5 Mev (1 percent of the time) respectively. The rest of the decay goes by K-capture (7 percent of the time). There are a few gammas following the betas.

\(\text{Zn}^{62}\) decays predominantly by K-capture into \(\text{Cu}^{62}\) with a half-life of 9.5 hr. The K-capture is about 90 percent of the time while there is a positron of end-point 0.65 Mev (10 percent of the time). There is a \(\gamma\) of about 0.6 Mev.

\(\text{Cu}^{62}\) is the well known isotope which emits a positron of 3.0 Mev end-point and decays with a half-life of 10.5 min. into stable \(\text{Ni}^{62}\). There is a \(\gamma\) of about 0.56 Mev. The half-life of \(\text{Cu}^{62}\) being small compared to that of \(\text{Zn}^{62}\), the latter will be mostly observed to decay with the half-life of 9.5 hr., with the emission of the 3.0 Mev positrons belonging to \(\text{Cu}^{62}\).

Thus when measured with a thin windowed ionization chamber, the absolute
activities of $^{62}$Cu and $^{62}$Zn can be compared easily. This is because of the fact that the x-rays and the $\gamma$-rays emitted by $^{62}$Zn will have a very low efficiency of being counted as compared to the positrons of its decay product $^{62}$Cu. Thus $^{62}$Zn and $^{62}$Cu are assumed to emit identical radiations and the cross sections for their production is thus known on a relative scale just from the counter data. The activity of $^{63}$Zn can also be easily compared to the activities of $^{62}$Zn and $^{62}$Cu, since the former consists of a very high energy (2.4 MeV) positron most of the time. The effect of absorption by the window and of scattering will be very small and could be estimated. Corrections were made for the softer positrons and K-capture in $^{63}$Zn.

Once the relative cross-section curves for the three activities are determined, any one point on any one of these curves can be chosen to establish the absolute value of the cross sections. For this purpose, all the short-lived activities ($^{62}$Cu and $^{63}$Zn) were allowed to die and the absolute number of the 3 Mev positrons from $^{62}$Zn were counted by means of a thin-windowed Geiger counter in an arrangement in which the solid angle could be estimated quite accurately. (See Fig. 4.) Back scattering from the source, which was a thin foil of Ni, was found to be negligible. Absorption in counter window and self-absorption in the source could be accounted for.

Since enriched $^{60}$Ni was used, no chemistry was necessary, and the $^{60}$Ni foils were used as such for counting. A look at Segre's chart shows that the three activities listed above are the only ones that could be expected in this case. Percentage of $^{58}$Ni in the enriched sample was quite low (no exact estimate was available; however, since the characteristic 24 min. activity belonging to $^{60}$Cu produced from $^{58}$Ni by ($a$,pn) reaction was not present, the percentage of $^{58}$Ni must have been quite low; this is also corroborated by the
rough figure available from the mass spectrograph group). Percentage of Ni$^{61}$, whose abundance is quite small compared to that of Ni$^{60}$ in normal nickel, was still further reduced in the present enriched sample. The presence of Ni$^{61}$ will produce some error in the cross section for the production of Zn$^{63}$, specially at higher energies of the $\alpha$-particles. Zn$^{63}$ will be produced by Ni$^{61}$ ($\alpha$,2n) reaction and hence the observed cross section for Ni$^{60}$ ($\alpha$,n)Zn$^{63}$ will include the cross section of the former process also. No estimate could be made of this effect. However, owing to the very small percentage of Ni$^{61}$ present, this effect was neglected. The production of Zn$^{62}$ and Cu$^{62}$ from Ni$^{61}$ is possible only for very high energies of the $\alpha$-particles, as they will be produced by the emission of three particles. Hence this does not bother us in the present experiment.

In case of copper, normal copper consisting of Cu$^{63}$ (69.09 percent) and Cu$^{65}$ (30.91 percent) was used. It will be seen from Segre chart that besides the periods studied, the following activities will also appear: Cu$^{65}$(p,n)Zn$^{65}$ and Cu$^{65}$(p,pn)Cu$^{64}$. The former, however, has a very long half-life of 250 days, and hence its activity (which is predominantly K-capture) will be insignificant for the normally short bombardments used in the course of the present experiment. The other one, viz, Cu$^{64}$ has a half-life of 12.8 hr, and emits both positrons and electrons and also goes partly by K-capture. The $\beta^+$ and $\beta^-$ have energies of about 0.66 MeV and 0.57 MeV respectively. The presence of Cu$^{64}$ distorts the composite decay curve of the activities studied, specially the long-life tail (9.5 hr, Zn$^{62}$). To get rid of its effect, an aluminum absorber of about 300 mg/cm$^2$ was used between the source and the counter, which stopped all the $\beta^+$'s from Cu$^{64}$. Owing to the high energy of the $\beta^-$'s emitted by the nuclei under consideration, radiations
from the latter will still be counted, though reduced in intensity. The excitation curves of the three activities Cu$^{63}(p,n)$Zn$^{63}$, Cu$^{63}(p,2n)$Zn$^{62}$, and Cu$^{65}(p,pn)$Cu$^{52}$ were determined in this way. As explained above the cross sections for the last two will still be found on a relative scale in the present case, since they emit identical radiation.

To get the cross sections for Cu$^{63}(p,n)$Zn$^{63}$ on a scale relative to the other two, it was necessary to precipitate the zinc out chemically and then the decay curve for Zn$^{63}$ and Zn$^{62}$ was followed.

The absolute cross sections were derived by comparing the activities to those produced by the a-bombardment of Ni$^{60}$.

\[ \text{Ag}^{107} + \text{He}^4 \quad \text{and} \quad \text{Ag}^{109} + \text{He}^4. \]

Ordinary silver has two isotopes, Ag$^{107}$ (51.35 percent) and Ag$^{109}$ (48.65 percent). When bombarded with high energy a-particles it is likely to give rise to processes with the emission of neutrons or protons or both. The emission of protons is, however, very unlikely because of the high Coulomb barrier. Both theoretical calculations (based on formulas derived in Chapter I), and experimental results corroborate this. It was found by chemical separation of the indium and calcium fractions from the bombarded silver foil, that more than 98 percent of the activity belonged to the former which proves that proton emission has a very small cross section.

When the present experiment was started the position with regard to the assignment of the various half-lives produced by the a-particle bombardment on silver was rather confused. The two well-known half-lives of 2.7 days (K-capture) and 65 min. (β⁺) were assigned to In$^{112}$ and In$^{110}$ respectively. The former assignment gave rise to a triple isomer for In$^{112}$. Hence it was decided to try proper assignment for the half-lives observed.
Three half-lives were observed when silver was bombarded with α-particles from the Berkeley 60-inch cyclotron, viz., 65 min., 5.2 hr., and 2.7 days. The first and the last were known for a long time, while the 5.2 hr. period was a new one. Subsequently, Tendam and Bradt and Mallary and Pool, have found a similar period. The assignment was done with the help of mass spectrographic analysis, through the courtesy of Dr. Moyer and Dr. Whitson of the mass spectrograph group in the Berkeley Radiation Laboratory. It was found that 65 min. period belongs to In\textsuperscript{110}, 2.7 days period to In\textsuperscript{111} and 5.2 hr. period to In\textsuperscript{109}. These assignments check with the results of other workers. The half life found by Tendam and Bradt for In\textsuperscript{109} was 6.5 hr., while that found by Mallary and Pool was 4.3 hr. Both of these are close to the 5.2 hr. period found in the present experiment.

The excitation curves for these three activities were measured in the same way as in the case of (Ni\textsuperscript{60} + α) case. Thin silver foils were used as targets and were counted as such without chemical separation, since, as mentioned above, most of the activity belongs to indium only. The 20 min. In\textsuperscript{112} produced by Ag\textsuperscript{109}(α,n) reaction was not counted. This was done by allowing it to decay before starting to count the foils.

An attempt to put absolute values to the scale of cross sections in the excitation curves was successful only in the case of the 65 min. In\textsuperscript{110} activity which emits positrons of end point 1.6 Mev. The method used was the same as in the nickel and copper experiments described above. Because of the complexity of the radiations emitted by In\textsuperscript{111} and In\textsuperscript{109}, their activities could not be compared on a scale relative to the In\textsuperscript{110} activity. These points will be discussed in more detail in the next chapter.
Chapter III

Discussion of Results and Conclusions

Cu\(^{63}\) + H\(^{1}\) and Ni\(^{60}\) + He\(^{4}\)

The excitation curves for the production of Zn\(^{63}\), Zn\(^{62}\) and Cu\(^{62}\) by proton bombardment on Cu\(^{63}\) and \(\alpha\)-bombardment on Ni\(^{60}\) are shown in Figs. 5 and 6, respectively. The errors of the individual points are quite high. This is because of the fact that the activities extrapolated to zero time after bombardment had to be obtained from the composite decay curve for these isotopes. The process of subtraction of the long-life tails from the composite decay curves introduced errors into the points which were obtained after subtraction.

It can be seen that within limits of experimental errors, Bohr's theory of compound nucleus is well verified as a result of the present experiment. The ratios of the cross sections \(\sigma(\alpha,n): \sigma(\alpha,2n): \sigma(\alpha,pn)\) on Ni\(^{60}\) agrees well with the ratios \(\sigma(p,n): \sigma(p,2n): \sigma(p,pn)\) on Cu\(^{63}\). For the sake of comparison, all these cross sections are plotted in Fig. 6(a). Since the compound nucleus produced in both cases is the same (Zn\(^{64}\)) it follows from the discussions in Chapter I (eqn. 8), that Bohr's theory of compound nucleus is certainly valid in this region of the periodic table and the mode of decay of the compound nucleus is independent of the mode of its formation. In the subsequent discussion we will speak only of the processes (p,n), (p,2n), and (p,pn) on Cu\(^{63}\) for the formation of Zn\(^{63}\), Zn\(^{62}\), and Cu\(^{62}\) respectively, though all the conclusions derived will apply to the processes (\(\alpha,n\)), (\(\alpha,2n\)) and (\(\alpha,pn\)) on Ni\(^{60}\) for the formation of the same isotopes.

If the above three are the only reactions that take place when Cu\(^{63}\) is bombarded with protons, then the sum of the three cross sections should
give $\sigma_p'$ the cross section for the absorption of the proton by Cu$^{63}$ to form the compound nucleus Zn$^{64}$ as defined by eqn. (3) in Chapter I. The sum of the cross sections are plotted in Fig. 7, and are compared with the theoretical results calculated by Weisskopf. Weisskopf calculates the cross sections $\sigma_p'$ and $\sigma_\alpha$ for nuclei in different parts of the isotope chart (starting from $Z = 20$ up to $Z = 90$ at the interval of 10). The values of $\sigma_p'$ for Cu ($Z = 29$) and $\sigma_\alpha$ for Ni ($Z = 28$) were extrapolated from these. The sum of the $\alpha$ cross sections are plotted in Fig. 8, and are also compared with the theoretical values. The theoretical total cross sections are calculated for the two values of the nuclear radius $R = r_0 A^{1/3}$, with $r_0 = 1.3 \times 10^{-13}$ and $r_0 = 1.5 \times 10^{-13}$ respectively.

The experimental values of $\sigma_p'$ at first increases with energy. It then flattens out between 9 to 15 Mev proton energy, and again rapidly rises at higher energies. The same behaviour is shown by $\sigma_\alpha$ as seen in Fig. 8, though less prominently. It is obvious from the flattening that some reaction is missing at lower energies, which has a rather high cross section between about 9 to 15 Mev proton energies, since the actual $\sigma_p'$ curve should be a smoothly increasing one. It seems reasonable to ascribe this to inelastic $(p,p)$ scattering. As was explained in Chapter I, this may have quite appreciable value when the product of $(p,n)$ reaction has a threshold considerably higher than zero. In the present case, Zn$^{63}$ which is the product of Cu$^{63}(p,n)$ reaction goes into Cu$^{63}$ with the emission of 2.3 Mev positrons. Hence this reaction should have a threshold of about $(2.3 + 1.7)$ or 4.0 Mev. The experimental value of the threshold, as found in the present experiment, is about 3 Mev. However, this is not very accurate because of the straggling in energies. Assuming a threshold of 4 Mev, the cross sections $\sigma'(p,n)$ and
\( \sigma_{\text{inel}}(p,p) \) have been calculated by methods indicated in Chapter I, with two different values of nuclear radius. These are plotted along with the experimental values for \( \sigma(p,n) \) in Fig. 9.

It is evident from Figs. 7 and 9 that the observed values of cross sections do not agree with the calculated values for any one of the two values of \( r_0 \) which have been used in the present calculations. From Fig. 7 it is seen that for \( r_0 = 1.3 \times 10^{-13} \), the total cross section tends to flatten out to a value \( \pi R^2 = 85 \times 10^{-26} \text{ cm}^2 \) at proton energies above about 15 MeV. The experimental values in this region, however, is much higher, and the difference is certainly outside the limits of experimental errors. On the other hand the calculated values of \( \sigma_p \) for \( r_0 = 1.5 \times 10^{-13} \) seem to be higher than the experimental values. This is more easily seen from Fig. 9 where the observed \( \sigma(p,n) \) is compared with the calculated values. The calculated values are higher than the observed ones for \( r_0 = 1.5 \times 10^{-13} \) all the way up to \( E_p = 12 \text{ MeV} \). The calculated \( \sigma(p,n) \) for \( r_0 = 1.3 \times 10^{-13} \) seems to agree at lower energies, though it begins to deviate wildly at higher energies. As the errors, both in theory and in experiment, are rather high, it is not possible to say anything definite as to what value of \( r_0 \) should be taken. However a value of \( r_0 \) somewhat greater than \( r_0 = 1.3 \times 10^{-13} \), but closer to it than to \( r_0 = 1.5 \times 10^{-13} \) would fit with the experimental data better.

As we mentioned before that the results of the present experiment are compatible with Bohr's assumption of compound nucleus idea, in so far as it testifies to the fact that the mode of decay of the compound nucleus is independent of the way it was formed. There is, however, one feature of the excitation curves of Figs. 5 and 6, which, at first sight, might appear to be incompatible with the current theories of nuclear reactions based on compound
nucleus assumption. This is the fact that the cross section \( \sigma(p, pn) \) for the production of Cu\(^{62} \) is large compared to the cross section \( \sigma(p, 2n) \) for the production of Zn\(^{62} \). Similarly \( \sigma(a, pn) \) for the process Ni\(^{60}(a, pn)\)Cu\(^{62} \) is large compared to \( \sigma(a, 2n) \) for the process Ni\(^{60}(a, 2n)\)Zn\(^{62} \). At the peak the cross sections differ by a factor of 4*. One would normally think that the probability for a proton coming out of the nucleus should be small compared to the probability for a neutron coming out, because of the Coulomb barrier.

Calculation of the cross sections \( \sigma(p, pn) \) and \( \sigma(p, 2n) \) were carried out on the basis of the theory developed in Chapter I. The calculated results are shown in Fig. 10. It should be noted that the calculations are extremely rough, and the exact values of the cross sections or their behaviour are not at all accurate. However, the cross section curves reveal one important fact, viz, that in the present case, the cross section \( \sigma(p, pn) \) is comparable to the cross section \( \sigma(p, 2n) \) when calculated on the basis of the statistical theory. There are two important reasons for this. The threshold for the process Cu\(^{63}(p, 2n)\)Zn\(^{62} \) is about 3 Mev higher than that for the process Cu\(^{63}(p, pn)\)Cu\(^{62} \). The exact difference in this threshold could not be determined. However, from the energy release in the disintegration of Zn\(^{62} \) into Cu\(^{62} \), this was estimated to be around 3 Mev. The exact values of the cross sections depend on this difference, and hence the calculated values are quite rough. This difference in the thresholds makes the energy available for the emitted protons in the \( (p, pn) \) process somewhat larger than that for the emitted second neutron in the process \( (p, 2n) \). This essentially results in reducing the barrier effect on the emitted proton. Secondly, the residual nucleus in the process

*Recently, Karl Strauch (private communication) has found a similar ratio for \( \sigma(Y, pn) \) to \( \sigma(Y, 2n) \) by bombarding Zn\(^{64} \) with high energy \( \gamma \)-rays from the synchrotron.
Cu$^{63}$(p, pn) is Cu$^{62}$ which is an odd-odd nucleus, while that in the process Cu$^{63}$(p, 2n) is Zn$^{62}$ which is an even-even nucleus. The former has a level density which is higher than that of the latter. In the present calculations, a factor of 4 in the level-densities for the two cases was assumed, as indicated in Chapter I. This, as can be seen from eqn. (13) in Chapter I, will increase the cross section $\sigma'(p, pn)$ with respect to the cross section $\sigma'(p, 2n)$. The factor 4 is quite arbitrary. There is no definite knowledge regarding the level-densities of the nuclei. The level-densities used in the present case are those given by eqn. (21) in Chapter I. This again indicates how unreliable the calculated values of the cross sections are.

In the light of the above arguments, the large cross section for (p, pn) and (e, pn) processes may not be very surprising. In fact, if a mechanism involving the emission of a deuteron is assumed, in place of the proton and neutron coming out separately in the (p, pn) or (e, pn) processes, there will be a difference of more than 5 Mev in the thresholds of (p, pn) and (p, 2n) processes. This, according to the above reasonings, will further increase the cross section $\sigma'(p, pn)$ with respect to $\sigma'(p, 2n)$. Whether or not this may explain the factor of 4 observed in the ratio of $\sigma'(p, pn)$ to $\sigma'(p, 2n)$, is not possible to decide from the present state of theoretical and experimental materials available, as was explained above. Further, for energies not too high, the residual nucleus will be left in states which are close to the ground state. These states are widely separated, and the application of the statistical method in these regions is not justified.

In our calculations, we neglected the possibility of $\gamma$-ray emission from the excited nucleus. This is definitely not true just below the threshold for particle emission. Hence the above calculations are valid only at energies high above the threshold.
Agl\textsuperscript{107} + He\textsuperscript{4} and Ag\textsuperscript{109} + He\textsuperscript{4}.

The excitation curves for the indium isotopes produced by bombarding silver with α-particles are shown in Figs. 11, 12, 13. Fig. 11 shows the variation of the yield of the 65 min. In\textsuperscript{110} with E_α. The cross section sharply rises above 11 Mev and attains a peak at about 17.5 Mev. It then falls rapidly to a low value, reaching the minimum at about 24 Mev and then rises again up to the maximum α-energy available. The region of the cross section curve from the beginning til about 20 Mev is due to the reaction Ag\textsuperscript{107}(α,n)In\textsuperscript{110}, while the remaining part at higher energies is predominantly due to the reaction Ag\textsuperscript{109}(α,3n)In\textsuperscript{110}. In this latter region, the first process will have a very low cross section, because of the competition of other processes involving the emission of more than one particle. The threshold of the Ag\textsuperscript{109}(α,3n)In\textsuperscript{110} reaction can be roughly extrapolated to a value of somewhere around 22 Mev. The sharp peak at lower energies seems to show the effect of the Coulomb barrier. From the measured (α,2n) reaction threshold, described below, the threshold of the (α,n) reaction should be around 7 Mev, taking 8 Mev to be the average binding energy of a neutron in this region of the isotope chart. The observed threshold at a higher value (11 Mev) must therefore be due to the effect of the Coulomb barrier, which has a height of about 17 Mev.

It should be noted that the rising portion of the curve after about 20 Mev, which has been attributed to Ag\textsuperscript{109}(α,3n)In\textsuperscript{110} reaction, may not represent the excitation curve of this activity alone. The 55 min. β\textsuperscript{+} emitter (E_\text{m} = 2.0 Mev) attributed to In\textsuperscript{108} by Mallary and Pool\textsuperscript{16} may be superposed on it. If their assignment is correct, then this would be produced by (α,3n) reaction on Ag\textsuperscript{107} in the present experiment, and hence its excitation curve will be entirely indistinguishable from that for the production of In\textsuperscript{110} by
by \((a,3n)\) reaction on \(^{109}\text{Ag}\). However, there are serious objections to the assignment of the indium isotope emitting a positron of 2.0 Mev end point to \(^{108}\text{In}\) as has been done by Mallary and Pool. This will be discussed in more detail later.

An attempt was made to find the absolute cross section for the production of \(^{110}\text{In}\) isotope. This was done by bombarding a \(\text{Ag}\) foil at about 13 Mev \(\alpha\)-energy where only \((a,n)\) reaction could take place. After allowing the short lived \(^{112}\text{In}\) formed by \(^{109}\text{Ag} (a,n)\) reaction to die down, the absolute activity of the 65 min. \(^{110}\text{In}\) produced by \(^{107}\text{Ag} (a,n)\) reaction was determined by the arrangement shown in Fig. 4, and already described in page 21. \(^{110}\text{In}\) emits a positron of end-point 1.7 Mev 63 percent of the time and decays by \(K\)-capture the rest of the time. Because of the high energy of the positrons, the effects of absorption and scattering were small, and the situation was very similar to that encountered in the cross section measurements in the previous cases (see page 21).

The cross section was found to be about \(12 \times 10^{-26}\text{ cm}^2\). This would make the cross section at the peak of \(^{107}\text{Ag} (a,n)\) \(^{110}\text{In}\) excitation curve (17.5 Mev) to be \(84 \times 10^{-26}\text{ cm}^2\). The theoretical cross section \(\sigma_a\) for the absorption of the \(\alpha\)-particle by \(^{107}\text{Ag}\) at this energy \(E_a\) is about \(12 \times 10^{-26}\text{ cm}^2\) for \(r_0 = 1.3 \times 10^{-13}\), and \(50 \times 10^{-26}\text{ cm}^2\) for \(r_0 = 1.5 \times 10^{-13}\). Both of these values are small compared to the experimental value. This may seem surprising. However, it should be noted that the cross section was determined at a very steep part of the excitation curve (see Fig. 11). Since the \(\alpha\)-energy is low, there will be some uncertainty in it because of straggling. A small change in \(E_a\) will change the cross section considerably. This may account for the anomaly between theory and experiment.

Fig. 12 shows the excitation curve for the production of \(^{111}\text{In}\) from \(^{109}\text{Ag}\) by \((a,2n)\) reaction. \(^{111}\text{In}\) decays with a period of 2.8 days into \(^{111}\text{Cd}\) by \(K\)-capture, which then emits two \(\gamma\)-rays in coincidence. The energies
of these Y's are 173 and 247 keV respectively (McGinnus\textsuperscript{17}). It was not possible to find the absolute cross section for this reaction in the present experiment. The cross section curve has the normal behaviour of increasing with energy at the beginning and then going down again at higher energies when competing processes begin to appear. The threshold of the reaction is about 14.6 Mev, and the cross section curve has a broad peak at about 25 Mev a-energy. At the highest \( E_a \), the cross section is about 16 percent of its value at its peak.

\textbf{In\textsuperscript{108} and In\textsuperscript{109}.} Fig. 13 shows the excitation curve for the production of the 5.2 hr. indium isotope mentioned in the last chapter. No absolute cross section was found for this case either. As was mentioned, this has been assigned to In\textsuperscript{109} by several authors including the present author. Hence it should be produced by Ag\textsuperscript{107} (a,2n) reaction in the present experiment and its excitation curve should have the same general behaviour as that of Ag\textsuperscript{109}(a,2n)In\textsuperscript{111} shown in Fig. 12. However, a comparison of Fig. 12 and Fig. 13 shows that the two excitation curves, though similar at lower a-energies differ widely at higher \( E_a \). The excitation curve for Ag\textsuperscript{107} (a,2n)In\textsuperscript{109} has a threshold close to that for Ag\textsuperscript{109}(a,2n)In\textsuperscript{111} (\( \sim 13.6 \) Mev). However, instead of the cross section decreasing at higher energies after reaching the peak, the cross section remains almost constant at higher energies. The yield at the maximum energy, \( E_a = 37 \) Mev is around 80 percent of that at its peak value.

This suggests the production of an isotope with a half-life similar to that of In\textsuperscript{109} at higher energies, which is superposed on the Ag\textsuperscript{107}(a,2n)In\textsuperscript{109} curve. Since the activity belongs to indium, it is assigned to In\textsuperscript{108} produced by Ag\textsuperscript{107}(a,3n) process. This point was further studied by means of
β-spectrograph through the courtesy of Dr. Hyward. The results of β-spectrograph studies are summarized below.

Two foils of silver were bombarded, one at 21 Mev and the other at 39 Mev and the spectra of their radiations were investigated. The following table lists the conversion electron peaks observed in these experiments.

Table I

<table>
<thead>
<tr>
<th>$E_\gamma$</th>
<th>110 Kev</th>
<th>170 Kev</th>
<th>203 Kev</th>
<th>240 Kev</th>
<th>660 Kev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-life</td>
<td>3-5 hr.</td>
<td>2.8 d</td>
<td>3-5 hr</td>
<td>2.8 d</td>
<td>3-5 hr</td>
</tr>
<tr>
<td>Assignment</td>
<td>In$^{108}$</td>
<td>In$^{111}$</td>
<td>In$^{109}$</td>
<td>In$^{111}$</td>
<td>In$^{108}$</td>
</tr>
<tr>
<td>Yield at $E_\alpha = 21$ Mev</td>
<td>- 66</td>
<td>100</td>
<td>56</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Yield at $E_\alpha = 37$ Mev</td>
<td>14 16</td>
<td>46</td>
<td>11</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

It should be seen that there are two peaks, one at 0.66 Mev and the other at 0.11 Mev which appear only at $E_\alpha = 37$ Mev and do not appear in any appreciable quantity at $E_\alpha = 21$ Mev. All the other peaks are common at both $\alpha$-energies.

As the next step, rough excitation curves for the peaks at 203 Kev and 660 Kev (assigned in the above table to In$^{109}$ and In$^{108}$ respectively) were determined. These curves are shown in Figs. 14 and 15. It is seen that the excitation curve for the 203 Kev peak behaves in the same way as the $\text{Ag}^{109}(\alpha,2n)\text{In}^{111}$ excitation curve shown in Fig. 12. It increases with increasing $E_\alpha$, reaches a peak at about 25 Mev $\alpha$-energy and then goes down at higher energies. Half life of this peak was found to be between 3-5 hrs.
Since it belongs to indium, and has the characteristics of a process involving the emission of two particles, it seems reasonable to assign it to \( \text{In}^{109} \) produced by \( \text{Ag}^{107} (\alpha,2n) \) reaction.

On the other hand, the excitation curve for the 0.66 Mev peak is seen to start at higher energy and increases with increasing energy, up to the highest \( \alpha \)-energy. Comparing this with the \( \text{Ag}^{109}(\alpha,3n)\text{In}^{110} \) excitation curve in Fig. 11, it seems reasonable to assign it to a process involving three-particle emission. It has a half life of around 3-5 hrs. Unless it is an isomer of the 65 min \( \text{In}^{110} \) it can only be assigned to \( \text{In}^{108} \) produced by \( \text{Ag}^{107}(\alpha,3n) \) reaction.

Besides the conversion peaks discussed, there was continuous positron background in both the samples mentioned above. Kurie plots of these positrons were made and are shown in Figs. 16 and 17. It is seen that the positron spectra at both \( \alpha \)-energies are complex. At \( E_\alpha = 37 \) Mev, the end points of these positrons are 0.90 Mev and 1.7 Mev respectively. At \( E_\alpha = 21 \) Mev, the end-points are 0.94 Mev and 2.2 Mev respectively. The 1.7 Mev positrons in the former of course belongs to the 65 min \( \text{In}^{110} \) isotope produced mostly by \( \text{Ag}^{109}(\alpha,3n) \) reaction and is quite well known. Its cross section, according to Fig. 11, is quite high at this high energy. This positron does not appear in any appreciable quantity at \( E_\alpha = 21 \) Mev, as seen from the Kurie plot in Fig. 17. This is what is expected, for according to the excitation curve for \( \text{In}^{110} \) in Fig. 11, the cross section is very low in this energy region.

The 2.2 Mev positron, on the other hand, appears in appreciable quantity only in the sample bombarded at the lower \( \alpha \) energy, and is almost completely absent in the sample bombarded at the higher \( \alpha \)-energy. This seems to have a half-life of several hours (3-5 hrs.). It thus seems reasonable to ascribe it to an isotope which is the product of a two particle emission. We
assign it to In$^{109}$ produced by Ag$^{107}$ (a,2n) process.

The difference in end-points (0.9 and 0.94 Mev) of the low-energy $\beta^+$ in the two samples is taken to be due to experimental error. It had a half-life of about 3-5 hrs. Its amount in both samples was comparable. We will later give some justification for its assignment to In$^{108}$.

The results discussed above are in contradiction to the results of Mallary and Pool$^{16}$. They, as mentioned above, assign a 55 min. $\beta^+$-activity ($E_m = 2.0$ Mev) to In$^{108}$. A 2.2 Mev $\beta^+$ activite isotope with comparable period has been observed by McGinnus* who observed its growth from a 4.5 hr. tin activity, which was assigned by Mallary and Pool to Sn$^{108}$. He also observed a Y-ray of 285 Kev associated with this activity. Mallary and Pool used enriched cadmium isotopes in their work (bombarded with deuterons) which contained appreciable quantity of all the Cd isotopes. Hence the above assignments of theirs cannot be regarded as final. Their main argument lies in the fact that they observed an one hour positron activity by bombarding both Cd$^{108}$ and Cd$^{110}$ enriched samples with deuterons, -- the activity in the first case being about twice as much as in the second case. This was much more than could be accounted for by taking into consideration the percentage of Cd$^{110}$ in the enriched Cd$^{108}$ sample, which would produce the 65 min. $\beta^+$ active In$^{110}$ by Cd$^{110}$ (d,2n) reaction. If the 55 min. positron activity belonged to In$^{108}$, it would be produced by the Cd$^{108}$(d,2n) reaction. They also bombarded Cd$^{106}$ (enriched) with $\alpha$-particles and did not observe this activity, which could be produced by Cd$^{106}$(a,pn) reaction. Their $\alpha$-energy was not high enough for (a,pn) reaction, but could produce (a,p) reaction giving In$^{109}$ from Cd$^{108}$. Hence they assign the 55 min. $\beta^+$ activity to In$^{108}$ and not to In$^{109}$. However, as was mentioned earlier, the cross section for (a,p ) process in this region of the Segre chart is very small, and hence their reasoning for the above

*Private communciation.
assignment is not very strong. Their assignment of the 4.5 hr. Sn activity to Sn$^{108}$ is based on the observation of the growth of the above 55 min. In activity, and is thus open to the same criticism.

In view of the above arguments, and the results of the present experiments both the 5 hr. activity with a 203 Kev $\gamma$-ray and the 55 min. $\beta^+$ activity are assigned to In$^{109}$ in this work. The proposed level scheme is shown in Fig. 18. It should be noticed that the 55 min. period follows the 5 hr. period, and hence the resultant decay curve will show the latter period only, except for the growth of the former immediately after bombardment. This would however, be masked by the 65 min. activity of In$^{110}$ as also by the decay of the lower state of In$^{109}$ (55 min.), some of which will be produced directly by a bombardment on Ag. If the present scheme is correct, there must be some way of preventing a large amount of this lower state being formed directly by a bombardment on Ag. For the observations seem to indicate that most of the In$^{109}$ is formed in the upper state (5 hr.), Hence we assign a spin of 9/2 to the upper state and a spin of 1/2 to the lower state. This agrees with the multipole characteristic of the 202 Kev $\gamma$-ray emitted by the upper state as is predicted by the calculations of Axel and Dancoff$^{18}$. There is however, one objection to assigning a spin of 1/2 to the ground state of In$^{109}$ as we have done. Both In$^{113}$ and In$^{111}$, will have a spin of 9/2 according to the shell structure of nuclei. One would expect the same to be true for In$^{109}$, since this also contains 49 protons which seems to be responsible for the high value of the spin (being one short of completing the shell). No explanation can be offered to resolve this anomaly.

It must be pointed out here that the present assignment can only be regarded as tentative. An isomeric separation of these two activities (5 hr.
and 55 min.) can be the only convincing argument in favor of the present level scheme.

We mentioned about a 0.92 Mev activity decaying with a half-life of 3-5 hrs. Mallary and Pool found a 0.75 Mev $\beta^+$ (absorption measurement) activity of comparable half-life and assigned it to In$^{109}$. No such positrons were observed in the present experiment. The 0.95 Mev positron activity occurred in comparable quantities in the samples bombarded at both $E_a = 21$ Mev and $E_a = 37$ Mev respectively. Hence it can be assigned to either In$^{108}$ or In$^{109}$. In view of the In$^{109}$ level scheme proposed above, this 0.92 Mev positron activity is assigned to In$^{108}$ tentatively. This would also account for the fact that In$^{108}$ activity is of the same order of magnitude as In$^{109}$ activity, as their excitation curve (Fig. 13) would suggest. If In$^{108}$ were only $K$-capturing with very weakly converted $\gamma$-rays at 0.11 Mev and 0.66 Mev (see Table I), it would be only a very small fraction of In$^{109}$ activity which has conversion electrons and positrons in it.
Acknowledgements

I am highly indebted to Professor Emilio Segrè for his constant guidance and continued encouragement during the progress of the work. It is a great pleasure for me to express my deep obligation to him. Thanks are also due to Professor A. C. Helmholtz for many helpful discussions and suggestions. It is a pleasure to thank Dr. J. G. Hamilton, Mr. Thomas Putnam and Mr. B. Rossi of the 60-inch cyclotron for their kind cooperation in making the bombardments.

This work was sponsored under the auspices of the Atomic Energy Commission.
Bibliography

1. Rutherford, E., Phil. Mag. 37, 581 (1919)
3. Weisskopf and Ewing, Phys. Rev. 57, 472 (1940)
5. Aron, Hoffman, and Williams, Collection of Range Vs Energy Curves, (1948)
6. Wilson, R. R., Phys. Rev. 60, 749 (1941)
10. Amodt, Lee: Private communication.
12. Hayward, R., Ph.D. Thesis
13. Seaborg and Perlman, Rev. Mod. Phys. 20, 585 (1948)
15. Tendam and Bradt, Phys. Rev. 72, 1118 (1947)
FIG. 1

THE FUNCTIONS $f_n$, $f_p$ AND $f_\gamma$ ARE GIVEN AS FUNCTIONS OF ENERGY OF THE COMPOUND NUCLEI Cu, Zr, AND Sn. MU 30 8
FIG. 2
ARRANGEMENT FOR $\alpha$-BOMBARDMENT IN THE 60" CYCLOTRON

MU 286
FIG. 3(a)

ARRANGEMENT FOR THE ENERGY DETERMINATION OF THE LINEAR ACCELERATOR PROTON BEAM.
FIG. 3 (b)

ARRANGEMENT FOR PROTON - BOMBARDMENT INSIDE THE LINEAR ACCELERATOR BEAM INTEGRATOR

MU 289
APPARATUS FOR MEASURING THE ABSOLUTE NUMBER OF $\beta$-RAYS. SOLID ANGLE SUBTENDED BY THE COUNTER WINDOW AT THE SOURCE $R$ CAN BE EASILY COMPUTED. SOURCE HOLDER $R$ IS A THIN WIRE RING HELD BY THREE THIN RODS TO S. BAFFLES WERE USED TO PREVENT SCATTERED ELECTRONS FROM GETTING INTO THE COUNTER.
Fig. 5
Cross-sections for \((p,n)\), \((p,2n)\) and \((p,pn)\) processes on Cu\textsuperscript{63}

\[
\text{CROSS SECTION IN } 10^{-26} \text{ CM}^2
\]

\[
\text{ENERGY OF PROTONS IN MEV}
\]

\[
\text{Cu}\textsuperscript{63}(p,n)\text{Cu}\textsuperscript{62}
\]

\[
\text{Cu}\textsuperscript{63}(p,n)\text{Zn}\textsuperscript{63}
\]

\[
\text{Cu}\textsuperscript{63}(p,2n)\text{Zn}\textsuperscript{62}
\]
FIG. 6
CROSS SECTIONS FOR (a,n), (a,2n) AND (a, pn) PROCESSES ON Ni$^{60}$
MU 293
CROSS SECTIONS FOR (p,n), (p,2n), (p,3n) REACTIONS ON Cu$^{63}$ AND FOR (α,n), (α,2n), (α,3n) REACTIONS ON Ni$^{58}$ PLOTTED TOGETHER. THE SCALE OF $E_p$ IS DISPLACED BY 7 MEV WITH RESPECT TO THE SCALE OF $E_{\alpha}$.
TOTAL CROSS SECTION WHICH IS THE SUM OF \((p,n)\), \((p,2n)\) AND \((p,n)\) CROSS SECTIONS ON Cu\(^{63}\) AS DETERMINED EXPERIMENTALLY IS COMARED WITH THEORETICAL \(\sigma_p\) WHICH IS THE CROSS SECTION FOR THE ABSORPTION OF A PROTON BY Cu\(^{63}\) NUCLEUS.
TOTAL CROSS-SECTION WHICH IS THE SUM OF \((p,n),(p,2n)\) \((p, pn)\) CROSS-SECTIONS ON Cu\(^{63}\) AS DETERMINED EXPERIMENTALLY IS COMPARED WITH THEORETICAL \(\sigma_p\) WHICH IS THE CROSS-SECTION FOR THE ABSORPTION OF AN \(\alpha\)-PARTICLE BY Ni\(^{60}\) NUCLEUS.

MU 295

FIG. 8
FIG. 9

COMPARISON OF THE MEASURED (p,n) CROSS-SECTION ON Cu$^{63}$ WITH THEORETICAL VALUES, CALCULATED ON THE BASIS OF STATISTICAL THEORY. THE SOLID LINE IS THE EXPERIMENTAL CROSS SECTIION CURVE.
FIG. 10
THEORETICAL CROSS SECTIONS FOR THE $(p, 2n)$, $(p, pn)$ AND $(p, 2p)$ PROCESSES ON Cu$^{63}$, CALCULATED ON THE BASIS OF STATISTICAL THEORY.
EXCITATION FUNCTION FOR THE FORMATION OF $\text{In}^{110}$
BY $\text{Ag}^{107}(\alpha, n)$ AND $\text{Ag}^{109}(\alpha, 3n)$ REACTIONS

FIG. II
Excitation function for the formation of In^{III} by Ag^{109} (α, 2n) reaction.

Fig. 12
FIG. 13
EXCITATION FUNCTION FOR THE 5 HR PERIOD ISOTOPE OF $^{115}$In
PRODUCED BY $\alpha$-BOMBARDMENT ON $^{209}$Ag  MU 300

O & $\triangle$ REPRESENT POINTS FROM DIFFERENT RUNS
EXCITATION FUNCTION FOR THE 203 KEV \( \gamma \)-RAY IN INDIUM
PRODUCED BY \( \alpha \)-BOMBARDMENT ON Ag, DETERMINED BY \( \beta \)-RAY SPECTROMETER
FIG. 14
Excitation function for the 770 keV γ-ray in indium produced by α-bombardment on Ag, determined by β-ray spectrometer.

Fig. 15
KURIE PLOT FOR THE POSITRONS FROM INDIUM PRODUCED BY BOMBARDING Ag WITH \( \pi \)-PARTICLES OF ENERGY 37 MEV

FIG. 16
MU. 303
FIG. 17
KURIE PLOT FOR THE POSITRONS FROM INDIUM PRODUCED BY BOMBARDING Ag WITH
α-PARTICLES OF ENERGY 21 MEV.
FIG. 18
PROPOSED LEVEL-SCHEMIE FOR THE DECAY OF In$^{109}$ TO Cd$^{109}$, WHEN In$^{109}$ IS FORMED BY THE Ag$^{107}$ (α,2n) REACTION.

MU 305
Part II

Elastic Scattering of 32 Mev Protons from Gold.

Abstract

32 Mev protons from the Berkeley Linear Accelerator were scattered from a thin (10 mg/cm²) gold target and the elastically scattered protons were detected photographically. A plot of the ratio of observed scattering cross section to the cross section calculated from Rutherford scattering formula against angle of scattering shows a definite departure from the classical Rutherford scattering at all angles except at very small angles. Comparison is made with theoretical results with nuclear radius $R = 1.3 \times 10^{-3} \text{ A}^{1/3}$. There is qualitative agreement, but very little quantitative agreement.
Chapter I
Theoretical Discourse

When a nuclear particle like a neutron or a proton hits a nucleus, it can either be absorbed by the target nucleus to form a semi-stable compound nucleus or can be elastically reflected from the surface of the nucleus. This latter process is known as elastic scattering, and after the particle has been scattered, the target nucleus is left in the same state in which it originally existed. The formation of the compound nucleus by the absorption of the incident particle can be followed by its disintegration through one of the many possible channels, like the formation of a new nucleus through the emission of a particle or a photon, or the emission of the same particle with a different energy. The latter process is the inelastic scattering of the incident particle, and the original target nucleus is left in a different quantum state after this process. The second group of processes is known as nuclear reaction. It is highly unlikely that the incident particle will come out of the compound nucleus with its original energy, leaving the residual nucleus in the same state in which it initially existed. The last process would be identical with the elastic scattering process.

The elastic scattering takes place through the reflection at the nuclear surface where there is an abrupt change in the interaction potential between the incident particle and the target nucleus. In case of neutrons there is no interaction outside the nuclear surface, while inside there is a strong binding. In case of charged particles like protons and α-particles, there is the repulsive Coulomb interaction outside the nucleus, while inside there in again a strong binding. Such sharp changes in potential, as is well-known from quantum mechanics, give rise to large probability of reflection. The
transmission coefficient through the plane where this change occurs is
\[ T = 4 \frac{kE}{(k + K)^2} \]  
where \( k \) is the wave number of the incident particle outside the nucleus, and \( K \) is that inside the nucleus.

An incident charged particle of energy \( E \) encounters difficulty in approaching the nuclear surface when the repulsive Coulomb potential becomes comparable to \( E \). This gives rise to the well-known classical Rutherford scattering with its \( 1/\csc^2 \theta/2 \) dependence of the scattered intensity on scattering angle. However, when the particle is sufficiently energetic, it begins to approach closer and closer to nucleus. When the impact parameter \( b \) (which is the least-distance of approach to the nuclear center) of the incident particle becomes comparable to the nuclear radius \( R' \) of the target nucleus, we should expect deviations to occur from classical Rutherford scattering, as the particle now begins to feel the presence of nuclear interaction. The impact parameter is given by:

\[ b = \frac{Z^2\hbar^2}{Mv^2} \cot \theta/2 \]  

for an incident particle of charge \( z'e \), and target nucleus of charge \( Ze \). \( \theta \) is the scattering angle, \( M \) is the mass of the incident particle and \( v \) its velocity. For \( b = R' \),

\[ \cot \theta/2 = \frac{2ER}{Z^2\hbar^2} \]  

where \( E \) is the kinetic energy of the incident particle. For angles larger than this angle we should expect to see deviations from Rutherford scattering. Thus a study of the scattering in this transition region should give an idea

* See *viz.* Atomic Physics, Born, pages 291-292
regarding the nuclear radius. Measurement of nuclear radius forms an important part in the study of the properties of the nucleus, and various estimates exist. The measured value of the nuclear radius will of course be dependent on the type of particles used in the experiment, viz., neutrons or protons. For in each of these cases, a suitable model has to be chosen for the nucleus. Measurement of the elastic scattering of charged particles is therefore a step forward in this direction.

Some experiments of a preliminary nature were done by Rutherford in the early days with natural α-particles. Since the energy was not sufficiently high, only light nuclei could be investigated. For as can be seen from equation (2.8), the angle θ at which deviations from Rutherford scattering occurs will be very high for low energy particles scattered from heavier elements. With the new source of high energy protons (32 Mev) available in Berkeley Radiation Laboratory in the form of the linear accelerator, it is possible now to study these deviations for heavier elements. For gold as target nucleus (A = 197, R = r_o A^{1/3}, where r_o = 1.5 x 10^{-13}), the critical angle is 25.5° for 32 Mev protons.

The exact nature of scattering will depend strongly on two parameters, viz., the nuclear radius R and the effect of nuclear forces in changing the wave-number of the incident particle from k outside to K inside. This is given by K_o where K^2 = k^2 + K_o^2, K_o being given by

\[ K_o^2 = 2M/\hbar^2 \left[ \epsilon_\beta + 4\pi^2 (3A/16\pi V)^{2/3} \right] \]

where A = nuclear mass number, V = nuclear volume. \( \epsilon_\beta \) is a small quantity which gives the contribution of the kinetic energy to binding energy.

The partial wave method of calculation of the cross sections gives
\[ \sigma_k^{(c)} = (1 - \eta)^2 \left( \pi/k^2 \right) (2l + 1) \]  

\[ \sigma_k^{(el)} = \left| 1 - \eta e^{i\delta} \right|^2 \left( \pi/k^2 \right) (2l + 1) \]

\( \sigma_k^{(c)} \) is the cross section for the absorption of particle of angular momentum \( l \) to form the compound nucleus, \( \sigma_k^{(el)} \) is the cross section for elastic scattering of the particle of angular momentum \( l \). \( \eta \) gives the fraction of the incident wave-amplitude that has been absorbed, \( \delta \) is the phase shift of the outgoing wave. Total absorption and elastic scattering cross sections are respectively

\[ \sigma_o = \sum_l \sigma_k^{(c)} \]

\[ \sigma_{el} = \sum_l \sigma_k^{(el)} \]

The calculation of these cross sections requires the choice of some suitable model to calculate \( \eta \) and \( \delta \).

Akhiser and Pomeranchuk have used some approximations which would permit the evaluation of the above summation expressions for the total cross sections in terms of simple integrals. If \( l_o \) is the limiting value of the angular momentum of the incident protons for which its kinetic energy at the surface of the nucleus passes from positive to negative value, \( l_o \) will be given by

\[ l_o = R/\lambda \sqrt{1 - Ze^2/RE} \]

where \( R \) = radius of the target nucleus, \( 2\pi\lambda \) is the wave-length of the incident particle at a great distance from the nucleus and \( E \) its energy. \( Ze \) is the atomic number of the target nucleus. According to the above authors, elastic scattering cross section will be given by:
For $\alpha \ll 1$,

$$\frac{\sigma(\theta)}{\sigma_{\text{Ruth}}(\theta)} = 1 \quad \text{for} \quad \theta \ll \sqrt{\alpha}/l_o$$

$$\frac{\sigma(\theta)}{\sigma_{\text{Ruth}}(\theta)} = \frac{\alpha^4}{l_o^4/16\alpha^2} \quad \text{for} \quad 1/l_o \gg \theta \gg 2\sqrt{\alpha}/l_o$$

$$\frac{\sigma(\theta)}{\sigma_{\text{Ruth}}(\theta)} = \left| \frac{l_o}{2\alpha} \frac{J_1(l_o \theta)}{J_1} \right|^2, \quad 1 \gg \theta \gg 1/l_o$$

For $\alpha \gg 1$,

$$\frac{\sigma(\theta)}{\sigma_{\text{Ruth}}(\theta)} = 1 \quad \theta \ll \alpha/l_o$$

$$\frac{\sigma(\theta)}{\sigma_{\text{Ruth}}(\theta)} = \left| \frac{l_o}{2\alpha} \frac{J_1(l_o \theta)}{J_1} \right|^2, \quad \alpha/l_o \ll \theta \ll 1$$

where $\alpha = Ze^2/h\nu$, $\nu$ being the velocity of the incident particle. $\sigma_{\text{Ruth}}(\theta)$ is the cross section calculated according to Rutherford scattering formula. $J_1$ is the Bessel function of the first order.

For scattering of 32 Mev protons on gold ($Z = 79$), $\alpha = 2.22$ and $l_o = 8.4$, which would make the range of validity of the above equations too limited.

Hence the above approximations are not very good in the present case. The application of these formulas will be more desirable at higher energies.

Feschbach and Weisskopf have shown a simple method of calculation of the various cross sections for neutrons. Similar method has been employed by Tyson to calculate cross sections of processes induced by charged particles. At the time of writing this paper, no report of this work was available. However, the numerical results calculated by the M. I. T. group for 32 Mev protons on gold was available through courtesy of Professor Weisskopf of the Physics Department of the Massachusetts Institute of Technology. These results will be compared with the results of the present experiment.
Chapter II

Experimental Method

The protons were detected photographically. The scattering chamber used was similar to the one developed by Silverman.\(^6\) A schematic diagram of the arrangement used is shown in Figure 1.

The low energy components of the 32 Mev proton beam from the linear accelerator were eliminated by the use of an analysing magnet, which deflected the beam through 17.5° from the original direction. Before entering the magnet the beam passed through a rectangular slit whose dimensions were adjusted to give the maximum current. After passing through the magnet, the beam was further collimated down by means of a collimator with three carbon slits of gradually increasing diameters, fitted in a brass pipe. This arrangement prevented the protons scattered from the slit from reaching the plates. This slit scattering is particularly disturbing at small angles and increases with the atomic number of the material of the slit. However, most of the protons scattered from the slits were degraded in energy and were prevented from reaching the plates due to absorption in the target-holder plus the copper absorber in front of the plates. (See Figure 2.)

The alignment of the proton beam through the collimator to hit the target at the center was done by means of a telescope.\(^6\)

The target and the plate holders were all assembled on a large 3/4 inch thick plate of dural which constituted the lid of the scattering tank. A photograph of this assembly is shown in Figure 3.

The target (\(\sim 10 \text{ mg/cm}^2\) gold foil) was Scotch taped to a 1/16 in. thick dural plate with a hole of suitable size in the middle, which was covered by

\(^{6}\)I am indebted to Dr. Silverman and Dr. Levinthal for kindly letting me use some of their plate holders.
the gold foil. The size of this hole was so arranged that a proton scattered from the slit would have to pass through the body of the target holder in order to reach the plates and would thus be absorbed out as explained in the last paragraph (see Figure 2).

The position of the lid with respect to the tank could be fixed by means of two pins on the upper rim of the tank which fitted into two holes on the edge of the lid. There were four such positions giving a wide range of possible scattering angles, from $18^\circ$ to $165^\circ$ at intervals of $7.5^\circ$.

The plate holder was held at appropriate height from the inner surface of the lid on five brass rods which fixed its position quite accurately. Four plates could be held by each holder and two plate holders could be used simultaneously, one in the forward direction and one in the backward direction. The exposure time for each plate depended on the angle of scattering. Too much exposure would render the plates black. Hence after the required exposure, each plate had to be removed from the plate holder. This was made possible by using a light tight device to cover the entire assembly of plate holders and target, so that the lid could be taken out into an adjoining dark room to take out the successive plates. This operation took less than five minutes.

The plates were Ilford C-2 of 100 microns thickness. The protons reached them at an angle of $17.5^\circ$ along the mean direction as shown in Figure 2. There was a defining slit ($S_1$ in Figure 2) whose width was $1/16$ inch for the forward direction and $1/8$ inch for the backward direction through which the protons could reach the plate. This defined the angle of scattering to $\pm 3/4^\circ$ and $\pm 1.5^\circ$ respectively in these directions. Behind this slit were the copper absorbers of required thicknesses. They were put in such a way that they were perpendicular to the path of the protons reaching the surface of the plate. These absorbers were used to cut down the energy of the protons such that they
were perpendicular to the path of the protons reaching the surface of the plate. These absorbers were used to cut down the energy of the protons such that they would spend their residual range within the 100 μ thick emulsion. Measurement of the distribution of the ranges of the protons in the emulsion would give the energy of the proton beam (see page 18 in Part I).

Total exposure on each plate was obtained by allowing the main beam, after passing through the scattering chamber, into the integrator which was described on page 18 in part I of this thesis.

After developing the plates, they were scanned under a microscope with either high-dry or oil objectives, and the number of proton tracks on a known area was counted. The area chosen was close to the median line of the plate which was scanned from one end to the other. The solid angle subtended by this area at the center of the target could be easily calculated. It should be noticed that the protons would suffer multiple scattering within the copper absorbers in front of the plates. Thus a proton scattered from the target and after reaching the outer surface of the copper absorber, may not reach the surface of the plate along the same straight line. The track of such a scattered proton would not show the right direction under the microscope. Also, for the same reason, there will be many protons in regions of the plate which are outside the cone of the geometrical shadow of the scattered beam as defined by the front slit, $S_1$, in Figure 2. The effect of this scattering was calculated $^7$ to see if an appreciable number of protons, coming through the defining slit, might miss the surface of the plate owing to scattering. With the present geometry, this was found to be negligible.

Only those tracks were counted which had the right direction on the plate. However, as explained above, some of them may appear to have wrong direction, and yet may be genuine tracks. Thus all tracks were counted which
were within ± 20° of the right direction. This limit was obtained by calculating the mean scattering angle in the copper absorber. The number of tracks missed due to this was less than 1 percent. Then again some protons, owing to straggling, would not end their paths within the emulsion, but would escape into the glass. Some of these may not be genuine tracks, but may be due to some background effect (mostly due to neutrons). Only such of these tracks were counted which had the proper grain density.

For each plate exposed with the target on, a second plate was exposed without the target. An equal area of the second plate was scanned to subtract the background effect. The background effect was practically absent for small angles of scattering. However, for large angles, the exposure was long and the background was quite appreciable.

The criterion for the right direction of a track was that it should start at the surface of the emulsion and should proceed in such a direction that it would appear to come from the direction of the target.
Chapter III
Discussion of Results

The results of the experiment are shown in Figure 4. The main interest of the present experiment lies in its ability to determine the nuclear radius, on which the nature of the scattering is strongly dependent. This is possible when the dependence of the scattering cross section ($\sigma_{el}$) on the angle of scattering is known over a wide range of angles. In the present experiment, results are shown over a range of angles varying from $18^\circ$ to $75^\circ$. Study in the region of larger angles is in progress, the plates being ready.

Before discussing the results, it should be pointed out that all the proton tracks counted in this experiment were regarded as being due to elastically scattered protons only. The basis of this was as follows. The protons scattered inelastically from gold would have a lower energy. The lowest level of gold is $3.3$ Mev above the ground level. Hence the protons scattered inelastically due to this state would have an energy of $(31.5 - 3.3)$ or $27.2$ Mev, $31.5$ Mev being the measured energy of the incident protons. Protons scattered from higher levels in gold will have still lower energy. The thickness of the copper absorber used in front of the plates was $1410$ mg/cm$^2$. This was much greater than the range of $27.2$ Mev protons ($1200$ mg/cm$^2$ of Cu). Thus no inelastically scattered protons could reach the plate, provided there is no level in gold which is less than $1.5$ Mev above the ground state.

The absorber thickness used ($1410$ mg/cm$^2$ of Cu) left a residual range in Cu of $140$ mg/cm$^2$ for the protons when they reached the surface of the plates. This corresponded to an energy of $8$ Mev which had a range of $385$ microns in the emulsion. This insured against any proton not reaching the plate due to straggling in the copper absorber. Measurement of the range distribution showed a flat distribution below $80$ microns residual range.
In Figure 4, the ratio of observed elastic scattering cross section \( \sigma(\theta) \) to the cross section given by the Rutherford formula \( \sigma_{\text{Ruth}}(\theta) \) has been plotted against the scattering angle \( \theta \). This is compared with the theoretical results of Tyson \(^5\) with nuclear radius \( R = r_0 \times A^{1/3} \) with \( r_0 = 1.3 \times 10^{-13} \).

Obviously there is very little agreement between the theoretical and experimental data. Other choice of parameters are needed to make the theory fit with the experiment. To demonstrate this point better, the theoretical results of Tyson for proton energy of 13.6 MeV have been plotted in Figure 5 for two values of \( r_0 \), viz., \( r_0 = 1.3 \times 10^{-13} \) and \( r_0 = 1.5 \times 10^{-13} \) respectively. The strong dependence of \( \sigma(\theta) \) on \( R \) is clearly seen from this figure.

Certain features of the experimental curve, however, have a qualitative agreement with the theoretical curve of Figure 4. The experimental \( \sigma(\theta)/\sigma_{\text{Ruth}}(\theta) \) curve, like the theoretical curve decreases with increasing angle, and attains a minimum, the minimum being located at larger angle (\( \sim 65^\circ \)) for the experimental curve than for the theoretical curve (\( \sim 40^\circ \)). The minimum is much deeper than the theoretical minimum. There is no sharp break in the experimental curve at an impact parameter \( b \) equal to the nuclear radius \( R_0 \) which also seems to agree with the theoretical results. The ratio \( \sigma(\theta)/\sigma_{\text{Ruth}}(\theta) \) continuously decreases with increasing angle of scattering from a value of 1.00 at \( \theta = 0^\circ \) until it reaches a minimum, and then rises again. More theoretical work is needed before any quantitative comparison can be made.
Acknowledgements

It is a pleasure to thank Professor Emilio Segre for his kind encouragement during the progress of the work and also for suggesting the problem. Thanks are also due to Professor Wolfgang K. H. Panofsky for many helpful discussions and suggestions. I am also indebted to the linear accelerator crew headed by Mr. Robert Watt for their very close cooperation in making the runs of this and the other experiment (Part I) possible.

This work was sponsored by the U. S. Atomic Energy Commission.
Bibliography

(1) Feschbach and Weisskopf, Phys. Rev. 76, 1550 (1949)

(2) Rutherford, Chadwick and Ellis, Radiations from Radioactive Substances, Cambridge University Press


(5) Tyson, J. K., Quoted in reference 1

(6) Silverman, Albert, Ph.D. Thesis

(7) Rossi and Greisen, Rev. Mod. Phys. 13, 240 (1941)

(8) Eyges, Leonard, Phys. Rev. 74, 1554 (1948)
FIG. 1
SCHEMATIC DIAGRAM OF SCATTERING CHAMBER AND PLATE HOLDERS
MU 287
FIG. 1
SCHEMATIC DIAGRAM OF SCATTERING CHAMBER AND PLATE HOLDERS

MU 287
FIG. 2
DETAILS OF THE PLATE HOLDER
FIG. 3

PLATE HOLDERS IN SCATTERING CHAMBER
FIG. 4
RATIO OF OBSERVED SCATTERING CROSS-SECTION TO RUTHERFORD SCATTERING CROSS-SECTION FOR GOLD PLOTTED AGAINST SCATTERING ANGLE. THE THEORETICAL CURVE IS FOR A VALUE OF NUCLEAR RADIUS \( r = 1.3 \times 10^{-13} \) \( \text{A} \frac{1}{3} \) AND BARRIER HEIGHT \( v_0 = 28 \) MEV.

\( o \) EXPERIMENT
\( \times \) THEORETICAL
\( (r_0 = 1.3 \times 10^{-13}, v_0 = 28 \text{ MEV}) \)
THEORETICAL RATIO OF $\sigma(\theta) / \sigma_{\text{RUTH}}(\theta)$ FOR TWO VALUES OF THE NUCLEAR RADIUS FOR PROTON ENERGY OF 13.6 MEV.

MU 307