INTERACTION OF 14.8 Mev NEUTRONS WITH ALUMINIUM

R. K. MOHINDRA AND H. S. HANS

DEPARTMENT OF PHYSICS, MUSLIM UNIVERSITY, ALIGARH

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ABSTRACT The spectra of charged particles and neutrons from Al^{27} have been calculated on the basis of the compound nucleus theory using various level density formulae and taking into account the effect of volume direct interaction. The comparisons between the experimental and calculated spectra are presented in the form of actual particle spectra. The shapes of the calculated spectra for the various level density formulae are in rough agreement with the experimental results, but there are deviations in the absolute yield. Level density formulae due to Lang & LeCouteur and Newton give better agreement with the experimental results than the simple formulae based on Fermi gas model and the constant temperature. Yield of (n, np) calculated on the basis of simple Fermi gas model formula, assuming the parameter a to be constant, is too high. All the calculated proton spectra are deficient in the high energy protons compared to the experimental values even after taking into account the contribution of the volume direct interaction.

INTRODUCTION

Recent comparison of Colli *et al.* (1959), Allan (1957), (1958); Kumabe *et al.* (1957); Graves and Rosen (1953); Paul and Clarke (1953) between experimental data on the various interaction cross-sections and the predictions of the compound nucleus theory have suggested that the theory is inadequate. In the experimental spectra there is excess of high and low energy particles. The excess of high energy particles has been explained partly by various authors [Brown and Muirhead (1957), Austern *et al.* (1953)] by taking into account direct interactions. On the other hand, several attempts have been made to explain to some extent the preponderance of low energy particles by taking into account (i) the evaporation of secondary particles from the residual nucleus, (ii) assuming the density distribution of the nucleus to be round edged Kikuchi (1957), (iii) the velocity dependent potential, (iv) the oscillations of the compound nucleus Nemeth (1958); (v) the particles are evaporated from an excited nucleus and the potential and transmission coefficients for an excited nucleus differ from those of a nucleus in ground state Nemeth (1960).

The present calculations were undertaken as an attempt to delineate the extent to which various level density formulae of the statistical theory and the theory of volume direct interaction can provide a valid description of the spectra of emitted particles due to the interaction of 14.8 Mev neutron with Al^{27}. We have made calculations on the basis of compound nucleus for the spectra of emitted particles in (n, p), (n, n') and (n, α) reactions making use of (i) the simple Fermi gas model level density formula due to Weisskopf (1952), (ii) the constant temperature formula, (iii) the level density formula due to Lang and LeCouteur (1954) and (iv) Newton's shell dependent formula (1956). It may be noted that the direct comparisons of calculated and the observed actual particle spectra provide a better test for the validity of the statistical theory rather than the comparisons in the form of level densities. Earlier, Mani and Nair (1960) reported similar calculations for the proton spectrum and using the simple Fermi gas model formula only.

THEORY

In the interaction of 14.8 Mev neutrons with Al^{27},

(i) the proton spectrum is mainly due to the following reactions:

$$[(n, p\gamma)+(n, pn)]_{comp+dir}+[(n, np)]_{comp+dir}$$

The contribution due to $(n, \alpha p)$ reaction has been found to be less than one millibarn and (n, pp') is not energetically possible because of the large separation energy of proton in ${}_{12}Mg^{27}$.

(ii) the neutron spectra is mainly due to

$$[(n, n'\gamma)+(n, n'n'')+(n, n'p)+(n, n'\alpha)]_{comp+dir}+[(n, \alpha n')]_{comp}+[n, pn']_{comp+dir}$$

(iii) the alpha particle spectra are mainly due to

$$[(n, \alpha\gamma)+(n, \alpha n')+(n, \alpha p)]_{comp}+[(n, n'\alpha)]_{comp+dir}$$

The primary particles are emitted both due to the evaporation process and direct interaction, while the secondary particles are mainly emitted due to evaporation.

COMPOUND NUCLEUS THEORY

The energy spectra of the (l, i) reaction due to incident particle l with energy E_l(14.8 Mev in the present case) is given by

$$\frac{\partial^2\sigma_c(l, i)}{\partial E_i \partial\Omega} = \frac{\sigma_c(E_l)}{4\pi} \cdot \frac{2M_i}{\hbar^2} \cdot \frac{E_i\sigma_c{}^i(E_i)\omega_R(E_0-E_i)dE_i}{\sum\limits_K F_K(E_0)} \qquad \dots \quad (1)$$

where F_K is a quantity proportional to partial width for the disintegration with the emission of any particle K and is given by Blatt and Weisskopf (1952) as

$$F_K(E_0) = \frac{2M_K}{\hbar^2}\int^{E_0} E_K\sigma_c{}^K(E_K)\omega_R(E_0-E_K)dE_K \qquad \dots \quad (2)$$

where E_0 is the maximum available energy = the incident energy + Q value of the reaction. $\sigma_c{}^K(E_K)$ is the cross-section for the inverse reaction, ω_R is the level density of the residual nucleus, M_K is the mass of the emitted particle, and $\sum_K F_K(E_0)$ is extended over all kinds of partial widths

When the first particle i is emitted with small kinetic energy, the intermediate nucleus is often so highly excited that a second particle j can be evaporated if

$$E_i < E_0 - S_{ij}$$

where S_{ij} is the separation energy of the secondary particle j in the intermediate nucleus left after the evaporation of i.

The energy spectrum of secondary particles emitted after evaporation of the particle i as given by Hayakawa *et al.* (1955) is

$$\frac{\partial^2 \sigma_c(l, i, j)}{\partial E_j \partial \Omega} = \frac{\sigma_c(E_l)}{4\pi} \cdot \frac{1}{\sum_K F_K} \int_0^{E_0 - S_{ij} - E_j} \frac{2M_i}{\hbar^2} \cdot E_i \sigma_c'(E_i) \omega_R'(E_0 - E_i) \times$$

$$\frac{2M_j}{\hbar^2} \frac{E_j \sigma_c'(E_j) \omega_R''(E_0 - E_i - S_{ij} - E_j)}{\sum F_m(E_0 - E_i - S_{im})} \, dE_i \quad . \quad (3)$$

DIRECT INTERACTION

These formulae are the same as derived by Hayakawa *et al* (1955) and Brown and Muirhead (1957) assuming the nucleus to be composed of two non-interacting Fermi gases and taking into account the Pauli exclusion principle. The direct collisions with the individual nucleons in the nucleus give rise to these reactions.

The energy spectrum of protons due to direct interaction is given by

$$\left[\frac{d\sigma_{np}}{d\epsilon_p}\right]_{dir} = \sigma_1 \frac{\left(\frac{d\sigma}{d\epsilon_0}\right)^p_{np} X_{np}\phi(\epsilon_p)}{[\rho_p \alpha_{np} X_{np} + \rho_n \alpha_{nn} X_{nn}]} \quad \ldots \quad (4)$$

The neutrons can be emitted either due to the collision of the incident neutrons with the protons or the neutrons of the target nucleus.

The energy spectrum of neutrons due to (n, p) collisions is given by

$$\left[\frac{d\sigma_{np}}{d\epsilon_n}\right]_{dir} = \sigma_1 \frac{\rho_p \left(\frac{d\sigma}{d\epsilon_0}\right)^n_{np} X_{np}\phi(\epsilon_n)}{[\rho_p \alpha_{np} X_{np} + \rho_n \alpha_{nn} X_{nn}]} \quad \ldots \quad (5)$$

The part due to (n, n) collisions is given by

$$\left[\frac{d\sigma_{nn}}{d\epsilon_n}\right]_{dir} = \sigma_1 \frac{2\rho_n \left(\frac{d\sigma}{d\epsilon_0}\right)^n_{nn} X_{nn}\phi(\epsilon_n)}{[\rho_p \alpha_{np} X_{np} + \rho_n \alpha_{nn} X_{nn}]} \quad \ldots \quad (6)$$

where $\left(\frac{d\sigma}{d\epsilon_n}\right)_{np}$ is the cross-section for the production of a proton with energy ϵ_0 in a single collision between the neutron and proton inside the nucleus and α is a factor which reduces the magnitude of X_{np} and X_{nn} due to Pauli exclusion principle. The values of $\left(\frac{d\sigma}{d\epsilon_0}\right)$ and α have been evaluated by the method of Mani and Nair (1960). ρ is the density of nucleons inside the nucleus, σ is the interaction cross-section. X_{np} and X_{nn} are free (n, p) and (n, n) collision cross-sections at 14 Mev. $\phi(\epsilon)$ is the total probability of escape for a particle with energy ϵ is given by

$$\phi(\epsilon) = P(\epsilon)\exp-\left[\frac{0.75R}{\lambda(\epsilon_0)}\right] + [1-P(\epsilon)]\exp\left[\frac{1.33R}{\lambda(\epsilon_0)}\right]$$

$\lambda(\epsilon_0)$ is the mean free path of the nucleon inside the nucleus, P is the penetrability factor and for a square well potential is given by Mani and Nair (1960)

$$P(\epsilon) = \frac{\sigma_c(\epsilon)}{[\pi(R+\bar{\lambda})^2]}$$

where $R = 1.5A^{1/3} \times 10^{-13}$ cms, $\bar{\lambda} = \lambda/2\pi$ is the wavelength of the particle with energy ϵ and $\sigma_c(\epsilon)$ is the cross-section for the formation of the compound nucleus. For the case of a diffuse nuclear model an expression for P has been given by Kikuchi (1957) but we used only a square well potential.

Spectrum of secondary particles. The spectrum of the secondary particles j boiling off the intermediate nucleus left after protons have been knocked out due to direct collisions is given by (Hayakawa *et al.* 1955)

$$\frac{\partial^2\sigma_{n,p,j}}{dE_j d\Omega} = \frac{1}{4\pi}\int_0^{E_0-S_{ij}-E_j}\left(\frac{d\sigma_{np}}{d\epsilon_p}\right)_{dir}[1-\phi(\epsilon_n)]\,\frac{2M_j}{\hbar^2}\cdot\frac{E_j\sigma_c{}^j(E_j)\omega_R{}^{ij}(E_0-S_{ij}-E_i-E_j)dE_i}{\sum_m F_m(E_0-E_i-S_{im})} \quad \dots (7)$$

Similarly, the spectra of particles boiling off the residual nucleus left after the first neutron has been knocked out

$$\frac{\partial^2\sigma(n;n',j)}{\partial E_j\partial\Omega} = \frac{1}{4\pi}\int_0^{E_0-S_{ij}-E_j}\left\{\left(\frac{d\sigma_{np}}{d\epsilon_n}\right)_{dir}[1-\phi(\epsilon_p)]+\left(\frac{d\sigma_{nn}}{d\epsilon_n}\right)_{dir}[1-(\phi)\epsilon'_n)]\right\}$$

$$\times\frac{2M_j}{\hbar^2}\cdot\frac{E_j\sigma_c{}^j(E_j)\,w_R{}^{ij}(E_0-E_i-S_{ij}-E_j)}{\sum_m F_m(E_0-E_i-S_{im})}\,dE_i \quad \dots (8)$$

Differential cross-section of protons emitted due to direct interaction.

A calculation of the differential cross-section has been given by Hayakawa *et al.* (1955) and Brown and Muirhead (1957) for the production of a proton with energy ϵ and in a direction θ in the centre of mass system and their result is

$$\left[\frac{\partial^2\sigma}{\partial\epsilon\partial\Omega}\right]^{\theta}_{dir} = \frac{\sigma_1\phi(\epsilon_p)}{[\rho_p\alpha_{np}X_{np}+\rho_n\alpha_{nn}X_{nn}]}\left[\rho_p\left(\frac{\partial^2\sigma}{\partial\epsilon_0\,\partial\Omega}\right)_{np}\right] \quad \ldots \quad (9)$$

where

$$\left(\frac{\partial^2\sigma}{\partial\epsilon_0\partial\Omega}\right)_{np} = \frac{3PP_1X_{np}(P_1)M_p}{4\pi\, q\, P_F^3}\log_e\frac{(\rho_2^4+2b\rho_2^2+c)^{\frac{1}{2}}+\rho_2^2+b}{(\rho_1^4+2b\rho_1^2+c)^{\frac{1}{2}}+\rho_1^2+b}$$

Where P_1 and P represent the momentum of the incident neutron and the emitted proton inside the nucleus, P_F is the Fermi momentum for the proton,

$$b = z_0^2+q^2-P^2, \quad c = (P^2+q^2-z_0^2)^2, \quad \rho_2^2 = P_F^2-z_0^2,$$

$$\rho_1^2 = P_F^2-2Q+P^2-Z_0^2-P_1^2, \quad Z_0 = \frac{1}{2q}(P^2+q^2-P_1^2), \text{ and } q = |\vec{P}-\vec{P}_1|.$$

CALCULATIONS FOR THE EVAPORATION PROCESS

In order to carry out the calculations we have to consider the following quantities.

(i) cross-section for the formation of the compound nucleus. For protons and alphas calculated values of σ_c for square well potential have been listed by Blatt and Weisskopf (1952) for various $Z > 10$. For neutrons, values of σ_{cn} have been plotted in Fast Neutron Data Report (1951) for various A. We simply used the interpolated values.

(ii) Separation energies for various nuclei involved were calculated from the mass differences and beta disintegration energies given by King (1954) and Mattauch and Everling (1957).

The values used are given below.

Nucleus	Sp in Mev	Sn in Mev
$_{13}Al^{27}$	8 3	13 0
$_{13}Al^{26}$	6 3	11.3
$_{12}Mg^{27}$	14 3	6 5
$_{12}Mg^{26}$	14 0	11 1
$_{11}Na^{24}$	10 6	7 0
$_{11}Na^{23}$	8 8	12 5

Γ 42 Mev

X_{np} 740mbs $X_{nn} \simeq 200$ mbs (Hess. 1958)

σ_I $\sigma_{I\gamma}$ 900 mbs (Celli et al. 1959)

$[\sigma(n, \alpha)]_{comp}$ 92 mb (Kumabe et al. 1957)

S_n in $_{13}Al^{27}$ -- 8 Mev (Kumabe, 1958)

$[\sigma(n, p\gamma + n\ pn)]_{comp}$ 89 mbs (Glover et al 1961)

(iii) Level densities :--The four formulae for level density have been employed. The evaluation of verious parameters of the particular formula used along with its results is discussed below separately.

Simple Fermi gas model level density formula

This formula was first given by Blatt and Weisskoff and is frequently used for statistical theory calcultions

$$\omega(U) = C \exp(2a^{\frac{1}{2}}U^{\frac{1}{2}}) \quad .. \quad (10)$$

where U is the residual energy in the C.M. system. The parameters a and C of the above formula are not known. We eliminate the constant C and use 'a' equal to 3 Mev^{-1} and 5 Mev^{-1}. From formula (1) we know.

$$\sigma(n\ p\gamma + n\ pn)|_{comp} = \frac{\sigma_c(E_l) \cdot C \frac{2M_p}{h^2} \int_0^{E_0} E_p\sigma_c(E_p) \exp(2a^{\frac{1}{2}}U^{\frac{1}{2}})}{\sum_K F_K(E_0)} dE_p.$$

using experimental value of $[\sigma(n, p\gamma) + \sigma(n, p\,n)]_{comp}$ we can write the energy spectrum of protons as

$$\left[\frac{\partial^2\sigma_{np}}{\partial E_p \partial\Omega}\right] = \frac{[\sigma(n, p\gamma + n, pn)]_{comp}}{4\pi} \frac{E_p\sigma_c(E_p) \exp(2a^{\frac{1}{2}}U^{\frac{1}{2}})dE_p}{\int_0^{E_0} E_p\sigma_c(E_p) \exp(2a^{\frac{1}{2}}U^{\frac{1}{2}})dE_p} \quad \ldots \quad (11)$$

Similarly, $(n\ n')$ spectrum can be found if we use

$$[\sigma(n, n')]_{comp} = \sigma_{nonel} - [\sigma(n, p\gamma + n\ pn)]_{comp+dir} - [\sigma(n, \alpha\gamma + n, \alpha n)]_{comp} - [\sigma(n, n')]_{dir}$$

where $[\sigma(n, n')]_{dir}$ and $[\sigma(n, p\gamma + n, pn)]_{dir}$ were found by formulae (4), (5) and (6). The value of estimated $\sigma(n, n')$ may introduce large errors and the result were checked by using another form

$$\frac{\partial^2\sigma_{nn'}}{\partial E_n \partial\Omega} = \frac{[\sigma_c(E_l) - \sigma(n, \alpha)]}{4\pi} \frac{E_n\sigma_{cn}(E_n)\omega(E_0 - E_n)dE_n}{F_p(E_0) + F_n(E_0)} \quad \ldots \quad (12)$$

This expression is quite insensitive to the value of $\sigma(n, \alpha)$ as this value is quite mall as compared to $\sigma_c(E_l)$

The spectrum of (n, np) was evaluated with the help of formula (3) and (8) and ΣF_m was taken over (n, np) and $(n, 2n)$ only because we do not know C for $_{11}Na^{23}$ nucleus in $(n, n'\alpha)$ reaction. The neglect of $(n, n'\alpha)$ introduces small error which may be estimated from the case where spectra have been calculated on the basis of Lang and LeCouteur formula and has been found to be of the order of 3% for 1.5 Mev, 6% for 2.5 Mev, 8% for 3.5 Mev and 15% for 4.5 Mev secondary protons. The value of C was used according to the odd-even character of the nucleus from the relation, Moore (1960)

$$\tfrac{1}{2}C_{odd-odd} = C_{even-odd} = C_{odd-even} = 5C_{even-even}$$

Lang and LeCouteur level density formula

For a nucleus of atomic weight A and excitation energy U, the level spacing is

$$D_0 = \frac{1}{\omega_0} = 0.14A^2(U+t)^2 \exp-\left[2\left(\frac{AU}{11}\right)^{\frac{1}{2}} + \frac{3}{32}(11U)^{2/3}\right] \quad \ldots \quad (13)$$

where nuclear temperature

$$t = \left[\frac{10.5U}{A}\right]^{\frac{1}{2}} - \frac{7.9}{A}$$

The effect of the pairing energy was not taken into account as it appears as a fictitious negative Q value and the high energy end of the spectrum is cut off. This will make the comparison with experiment difficult as in the high energy region we want to see the effect of volume direct interaction. Instead of it we performed the calculations with and without taking into account the odd-even characteristic of residual nuclei by the method suggested by Brown and Muirhead (1957).

Newton's level density formula

This shell dependent level spacing formula depends upon the densities of single particle orbits near the Fermi level in the nucleon gas. For a nucleus of excitation energy U, with Z protons and N neutrons,

$$D_0 = \frac{1}{\omega_0} = A^{5/3}(2\hat{j}_N+1)^{\frac{1}{2}}(2\hat{j}_Z+1)^{\frac{1}{2}}(2U+3t)^2 \times$$

$$\exp\{8.75-0.4982(\hat{j}_N+\hat{j}_Z+1)^{\frac{1}{2}}A^{1/3}U^{\frac{1}{2}}\} \quad \ldots \quad (14)$$

D is in ev, U and t in Mev

Here $\hat{j}_N, \hat{j}_Z$ are effective values of j and are tabulated by Newton (1956).

Nuclear temperature $t = [6\pi^{-2}G^{-1}U]^{\frac{1}{2}}$ where $G = 2\alpha(\hat{j}_N+\hat{j}_Z+1)A^{2/3}$

$\alpha = 0.03772$

The level spacing approaches infinity at zero excitation energy which is the unattractive feature of the Newton's formula in our calculations. This may introduce some error in the calculations as we simply extrapolated the curves to zero excitation energy. Cameron (1958) has given an improved formula which does go smoothly to zero excitation energy but it is too complicated. Again, the effect of pairing energy was not taken into account.

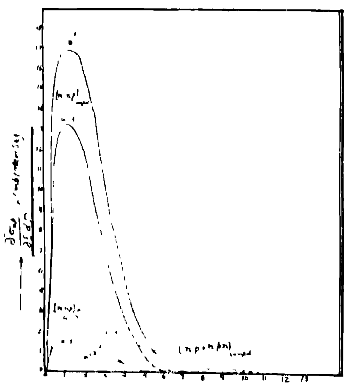
Constant temperature level density formula

Here,
$$\omega(E_i) = C \exp-\left(\frac{E_i}{\theta}\right) \quad \ldots \quad (15)$$

where C is a constant and θ is the nuclear temperature. Calculations were made for the primary neutron and proton spectra using $\theta = 0.5$ Mev, 1 Mev, 1.3 Mev and 1.6 Mev. The shape of the spectrum depends more sensitively upon the value of θ as compared to the parameter 'a' in Weisskopf's formula. As θ is not known precisely in the case of (n, np) and $(n, 2n)$ processes, calculations were not carried out for secondary processes.

DISCUSSION AND RESULTS

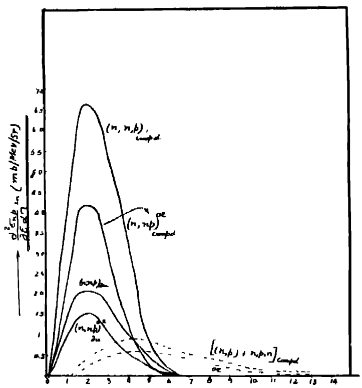
Proton spectra The calculated proton spectra are shown in fig 1, 2 and 3. After adding the differential cross-section at 40° to the above curves the resultant curves are shown in fig 1 along with the smoothed experimental curve of Glover and Weigold (1961) for the sake of comparison. The following points are worth mentioning



→Proton energy in Mev.

Level density formula : $\omega(U) = Ce^{2\sqrt{aU}}$.

Figure (1) Energy spectra of protons for (n, p) and (n, np) reactions Curves correspond to two different values of 'a' in the simple Fermi gas model formula.



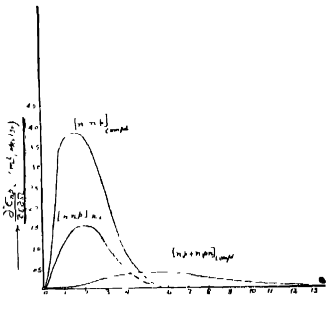
→Proton energy in Mev.

Level density formula . Lang and LeCouteur.

Figure (2) Energy spectra of protons for (n, p) and (n, np) reactions calculated with Lang and Le Couteur formula. Oe denotes curves obtained with odd even effec and the remaining curves are without odd even effect.

(i) In the case of simple Fermi gas model formula (10), we used the experimental value of σ $(n, p\gamma + n, pn)$ rather than $\sigma(n, p\gamma)$ found by activation technique to eliminate the unknown constant C and put the limits of the integral from zero to E_0 as in formula (11). The value of the calculated $\sigma(n, p\gamma + n, pn)$ obtained by using $\sigma(n, p\gamma)$ is too high. This suggests that there may be competition between proton and γ-ray emission even if $E_p < E_0 - S_n$, where S_n is the separation energy of neutron in the residual nucleus left after the evaporation of proton.

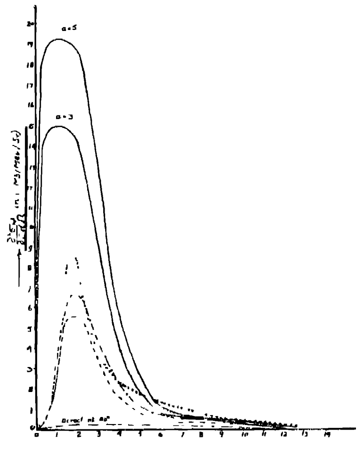
(ii) The calculated value of the spectra on the basis of the above formula is too high on the low energy region which is mainly due to (n, np). This is probably because we used the same value of the parameter 'a' for the calculation of $\sigma(n, n')$, $\sigma(n, np)$ and $\sigma(n, 2n)$ as for $\sigma(n, p)$. By choosing suitable value of 'a' for each reaction, one may get better fit with the experiment. If we use the



→Proton energy in Mev

Level density formula Newton

Figure (3) Energy spectra of protons for (n, p) and (n, np) reactions calculated on the basis of Newton's formula.



→Proton energy C. M. S. (Mev.)

— — — Newton

--●—●—● Lang Lecuteur with odd even effect.

× × × Exptal points.

.. Lang Lecuteur without odd even effect

Figure (4) Resultant differential energy spectra of protons due to evaporation and direct interaction along with the experimental curve. The spectra shown here are calculated for θ = 10°, to compare with experimental curve obtained at the same angle.

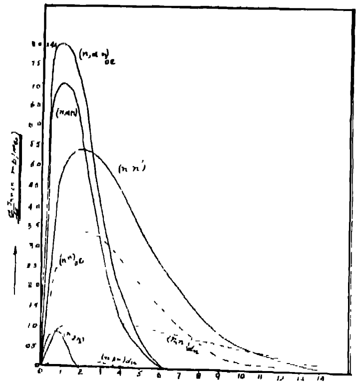
same value of $a = 3$ Mev^{-1} for (n, n') and (n, p), the (n, n') spectrum is exaggerated in the low energy region and hence the (n, np) spectrum.

(iii) Curves of Fig. 2 show the various partial cross-sections calculated on the basis of Lang and LeCouteur formula with and without odd even effects. The *oe*-curve fits quite well with experimental values taking into account the uncertainties involved in the experimental points. It is evident that one should take into account the odd even effects.

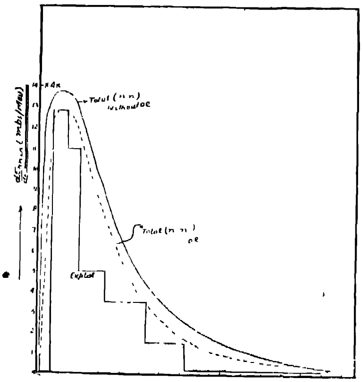
(iv) Curves of fig. (3) give the various partial cross-sections calculated on the basis of Newton's shell-dependent level density formula. Fig. 4 shows that Newton's formula behaves nearly in the same way as that of Lang and Le-Couteur with odd even effects.

(v) All the calculated spectra are deficient in the high energy protons compared to the experimental spectra This can be partly due to the deuteron contamination in the experiment and partly due to the fact that the theory of volume direct interaction may not take fully into account all the instantaneous emissions.

Neutron spectra. The calculated neutron energy spectra on the basis of Newton's and Lang and LeCouteur's formulae are shown in Fig 5 and 7.



→Newtron energy in Mev.
Level density formula Lang & LeCouteur.
Figure (5) Energy spectra of neutrons for (n, n'_s) and $(n, \alpha\ n)$ calculated on the basis of Lang and LeCouteur formula. *oe* denotes curves obtained with odd even effects and the remaining curves are without odd even effects. The ordinate is to be multiplied by 4π to get absolute value



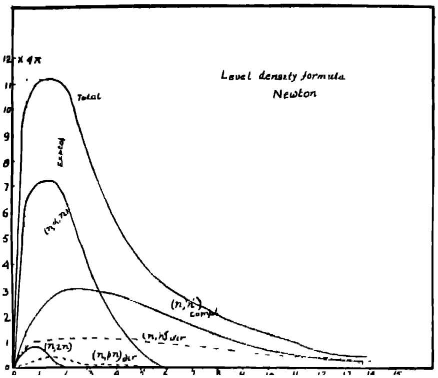
→Newtron energy in Mev.
Level density formula : Lang & LeCouteur.
Figure (6) Energy spectra of neutrons due to the sum of various curves in fig (5). The dotted curve is with odd even effect and has been normalised with respect to the peak of the experimental histogram. The ordinate should be multiplied by 4π to get absolute value.

(i) Calculated $(n, \alpha n)$ contribution is quite significant in the low energy region and the contribution of $(n, 2n)$ is quite small.

(ii) Lang and LeCouteur's formula with odd-even effects and Newton's formula behave nearly in the same manner for the case of various partial cross-sections viz. $\sigma(n, \alpha n)$, $\sigma(n, n')$.

(iii) Calculated value of direct interaction cross-section for n, n' is about four times as compared to the n, p direct interaction cross-section. The higher value in the case of (n, n') is expected because of the collisions between identical particles.

(iv) The resultant neutron spectra are compared with the experimental curve of Stelson and Goodman (1951) The experimental curve has been normalized corresponding to the peak of the calculated spectra for the sake of comparison. The various spectra are shown in Figs. (6) and (7). The shapes are in rough agreement, but nothing can be concluded regarding the absolute yields.



→Neutron energy in Mev.
Level density formula : Newton

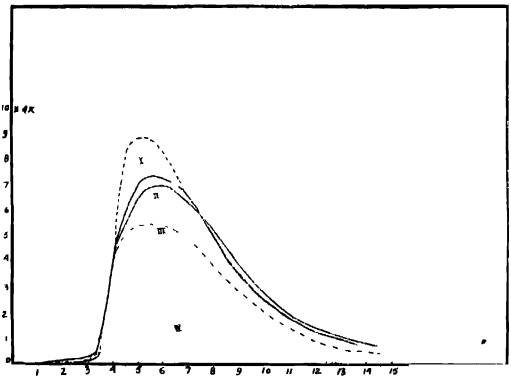
Figure (7). Energy spectra of neutrons for $(n, n' x)$ and $(n, \alpha\, n)$ calculated on the basis of Newton's formula. The ordinate should be multiplied by 4π to get absolute value.

(v) The neutron spectrum was not calculated by using simple Fermi gas model formula (10) because we cannot eliminate C for calculating $\sigma(n, \alpha n)$ by the procedure used in the case of (n, np). This is because C is assumed to be the same for isobaric nuclei. For the same reasons, we did not calculate the alpha particle spectrum by using the formula (10).

Alpha particle spectra. The alpha particle spectra calculated on the basis of Lang and LeCouteur formula with and without odd-even effects and Newton's formula are shown in Fig 8. The following points may be noted :

(i) As in the case of (n, p) and (n, n') the above two formulae due to Lang and LeCouteur with odd-even effects and Newton's behave nearly in the same manner and calculated total $\sigma(n, \alpha)$ is of the same order of magnitude in each case.

(ii) The calculated value of $\sigma(n, \alpha)$ is about five times higher than the experimental value. It is surprising that the above two formulae which give favourable results in case of (n, n') and (n, p) give too high a value in the case of (n, α) reac-



$\rightarrow E_\alpha$ C. M. S. (Mev).

- - - - Lang and LeCouteur with odd even effect.

———·——— Newton.

—.—.—. Lang & LeCouteur without odd even effect.

. .. .. Experimental.

Figure (8) Calculated energy spectra of alphas along with the experimental curve. Dotted portion of curve (I) shows the calculated $(n, n' \alpha)$ contribution on the basis of Lang-LeCouteur formula. The ordinate should be multiplied by 4π to get absolute value.

tion which is supposed to be mainly due to the compound nucleus formation. The calculated curves have been compared with the experiment of Kumabe *et al.* (1957) in figure (8). The dotted part of curve I shows the contribution of $\sigma(n, n\alpha)$ calculated on the basis of Lang and LeCouteur formula.

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