Key - words

NUCLEAR REACTIONS $^{63,65}\text{Cu}(\alpha,\text{xnpzp})$.

$E = 10-40$ MeV; measured $\sigma(E)$ for the production of $^{68,67,66}\text{Ga}$, $^{65}\text{Ga} + ^{65}\text{Zn}$, $^{61}\text{Cu}$. Stacked foil technique. Natural target. Analysis of composite activity. Statistical model with and without the inclusion of pre-equilibrium emission of particles.
<table>
<thead>
<tr>
<th>$\gamma$-ray energy $E_\gamma$ (keV)</th>
<th>Absolute Abundance $I_\gamma$ (%)</th>
<th>Normalized relative intensity Present measurement</th>
<th>Literature value (9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual nucleus $^{68}$Ga of $T_2$ = 68.33 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1077</td>
<td>3.0</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Residual nucleus $^{67}$Ga of $T_2$ = 78.26 h</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>184.6</td>
<td>23.56</td>
<td>$62.7^{\pm}6.4$</td>
<td>$62^{\pm}3$</td>
</tr>
<tr>
<td>209.</td>
<td>2.7</td>
<td>$7.3^{\pm}0.2$</td>
<td>$7.1^{\pm}0.4$</td>
</tr>
<tr>
<td>300.2</td>
<td>19.</td>
<td>$50.0^{\pm}0.3$</td>
<td>$50^{\pm}3$</td>
</tr>
<tr>
<td>393.6</td>
<td>5.32</td>
<td>$13.4^{\pm}0.9$</td>
<td>$14^{\pm}1$</td>
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<tr>
<td>Residual nucleus $^{66}$Ga of $T_2$ = 9.45 h</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>833.6</td>
<td>6.1</td>
<td>$14908^{\pm}1465$</td>
<td>$15950^{\pm}160$</td>
</tr>
<tr>
<td>1039.3</td>
<td>38</td>
<td>$1x10^5^{\pm}320$</td>
<td>$1x10^5^{*}$</td>
</tr>
<tr>
<td>1333.4</td>
<td>1.2</td>
<td>$3265^{\pm} 432$</td>
<td>$3260^{\pm}30$</td>
</tr>
<tr>
<td>1419.</td>
<td>0.64</td>
<td>$1791^{\pm} 358$</td>
<td>$1680^{\pm}20$</td>
</tr>
<tr>
<td>Residual nucleus $^{65}$Zn of $T_2$ = 244.1 d</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1116</td>
<td>50.75</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Residual nucleus $^{61}$Cu of $T_2$ = 3.4 h</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>283</td>
<td>13.2</td>
<td>$100^{\pm}0.6$</td>
<td>$100^{\pm}6$</td>
</tr>
<tr>
<td>656</td>
<td>11.7</td>
<td>$89.5^{\pm}7.2$</td>
<td>$88.7^{\pm}3.6$</td>
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<tr>
<td>1185</td>
<td>4.83</td>
<td>$32.7^{\pm}0.7$</td>
<td>$37^{\pm}1.5$</td>
</tr>
</tbody>
</table>

* Normalization has been done with respect to this value of literature.
### Table 2

Measured cross-sections for α-induced reactions

**Target nucleus $^{63}$Cu**

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$\sigma(\alpha,n)$ (mb)</th>
<th>$\sigma(\alpha,2n)+(\alpha,np)$ (mb)</th>
<th>$\sigma(\alpha,2n\alpha)$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$38.2 \pm 1.3$</td>
<td>$3.5 \pm 0.2$</td>
<td>$598.5 \pm 72.2$</td>
<td>$35.7 \pm 0.4$</td>
</tr>
<tr>
<td>$35.5 \pm 1.4$</td>
<td>$5.4 \pm 0.4$</td>
<td>$854.7 \pm 56.1$</td>
<td>$17.0 \pm 0.5$</td>
</tr>
<tr>
<td>$32.6 \pm 1.5$</td>
<td>$6.1 \pm 0.6$</td>
<td>$929.9 \pm 45.8$</td>
<td>$4.5 \pm 0.3$</td>
</tr>
<tr>
<td>$29.6 \pm 1.6$</td>
<td>$16.7 \pm 2.6$</td>
<td>$1158.6 \pm 36.4$</td>
<td>$1.6 \pm 0.2$</td>
</tr>
<tr>
<td>$26.3 \pm 1.7$</td>
<td>$107.8 \pm 0.8$</td>
<td>$1160.9 \pm 47.0$</td>
<td>$0.4 \pm 0.2$</td>
</tr>
<tr>
<td>$22.8 \pm 1.8$</td>
<td>$250.6 \pm 0.8$</td>
<td>$829.8 \pm 81.7$</td>
<td></td>
</tr>
<tr>
<td>$18.9 \pm 2.1$</td>
<td>$500.0 \pm 1.4$</td>
<td>$403.6 \pm 102.1$</td>
<td></td>
</tr>
<tr>
<td>$14.4 \pm 2.4$</td>
<td>$497.1 \pm 1.4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$9.0 \pm 3.0$</td>
<td>$55.1 \pm 1.8$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Target nucleus $^{65}$Cu**

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$\sigma(\alpha,n)$ (mb)</th>
<th>$\sigma(\alpha,2n)$ (mb)</th>
<th>$\sigma(\alpha,3n)$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$38.2 \pm 1.3$</td>
<td>$15.1 \pm 5.5$</td>
<td>$284.9 \pm 3.6$</td>
<td>$338.4 \pm 2.5$</td>
</tr>
<tr>
<td>$35.5 \pm 1.4$</td>
<td>$-1$</td>
<td>$481.7 \pm 3.1$</td>
<td>$248.9 \pm 3.1$</td>
</tr>
<tr>
<td>$32.6 \pm 1.5$</td>
<td>$38.0 \pm 27.6$</td>
<td>$641.1 \pm 3.0$</td>
<td>$107.6 \pm 4.5$</td>
</tr>
<tr>
<td>$29.6 \pm 1.6$</td>
<td>$75.2 \pm 12.2$</td>
<td>$974.4 \pm 19.6$</td>
<td>$72.1 \pm 6.1$</td>
</tr>
<tr>
<td>$26.3 \pm 1.7$</td>
<td>$112.5 \pm 8.6$</td>
<td>$1174.8 \pm 14.5$</td>
<td></td>
</tr>
<tr>
<td>$22.8 \pm 1.8$</td>
<td>$355.0 \pm 60.3$</td>
<td>$724.3 \pm 4.1$</td>
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<tr>
<td>$18.9 \pm 2.1$</td>
<td>$687.7 \pm 127.4$</td>
<td>$301.0 \pm 5.3$</td>
<td></td>
</tr>
<tr>
<td>$14.4 \pm 2.4$</td>
<td>$682.1 \pm 80.4$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$9.0 \pm 3.0$</td>
<td>$87.6 \pm 8.6$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2 Presently measured excitation function and other literature values.
Fig 3 Experimentally measured • and theoretically calculated (—PRE+CN, --- CN) excitation functions.
Fig. 4 Presently measured excitation function and other literature values.
Fig. 5 Presently measured excitation function and other literature values.
Presently measured excitation function and other literature value.
Fig 7 Experimentally measured • and theoretically calculated (—PRE+CN, --- CN) excitation functions.
Fig 8 Experimentally measured • and theoretically calculated (— PRE+CN, --- CN) excitation functions.
Fig 9 Experimentally measured • and theoretically calculated (— PRE+CN, --- CN) excitation functions.

$^{65}\text{Cu} (\alpha, n)^{68}\text{Ga}$

$E_\alpha$ (MeV)

$\sigma$ (mb)
Fig 10 Experimentally measured • and theoretically calculated (—PRE+CN; ---CN) excitation functions.
Fig 11 Experimentally measured • and theoretically calculated (-PRE+CN,-- CN) excitation functions.
Fig. 12 Dependence of the ratio $\frac{\sigma^{Cu(\kappa,3n)}}{\sigma^{Cu(\kappa,n)}}$ on the choice of level density parameter 'a'.
Theoretically calculated excitation functions and literature data.

Fig. 13: 

$^{63}Cu(\alpha, np)^{65}Zn$

$\sigma$ (mb)

$E_\infty$ (MeV)

$\times$ PR 116 (1959) 1193

--- (PRE+CN) Code ACT
Fig. 14. Variation of pre-equilibrium fraction, FR, as a function of incident energy of $\alpha$-particle.
In a programme for measuring the excitation functions for $\alpha$-induced reactions using stacked foil technique, excitation functions for the reactions ($\alpha$,2$n$) and ($\alpha$,n$\alpha$) in $^{59}$Co have been measured in the energy range $\approx 10$-40 MeV. To the best of our knowledge the excitation function for $^{59}$Co ($\alpha$,n$\alpha$) reaction is being reported for the first time.

A stack of ten thin metallic foils (11.1 mg/cm$^2$ thick), fixed individually on Al-sheets having concentric hole at their centres, was irradiated by the $\alpha$-beam of energy $\approx 40$ MeV at VECC, Calcutta. The thickness of the foil gave the energy degradation of 0.6 MeV to 1.3 MeV from first to the last foil. Gamma activities induced in irradiated foils were followed using Ge(Li) detector. Eight $\gamma$-rays, arising from residual nucleus $^{61}$Cu of reaction ($\alpha$,2$n$), were identified and their intensities were used to determine the cross-sections for $^{59}$Co($\alpha$,2$n$) reaction. The reported cross-section at each energy is the weighted average of these individual values. As a check, relative intensities of $\gamma$-rays, arising from $^{61}$Cu, were also measured and in general are found to agree with the literature data. The activity of 811 keV $\gamma$-ray of $^{58}$Co was used to determine the excitation function for $^{59}$Co ($\alpha$,n$\alpha$) reaction.

The experimentally measured excitation functions for ($\alpha$,2$n$) and ($\alpha$,n$\alpha$) reactions in $^{59}$Co have been compared with their literature values, if available, in figs. 1a and 1b. The theoretical excitation functions have been calculated using computer code ACT/1/ based on statistical model with and without the inclusion of pre-equilibrium emission of particles. This code considers successive evaporation of particles with pre-equilibrium emission only at the first evaporation step. Subsequent decay of compound system is inherently
treated on the basis of equilibrium emission of particles. The theoretical excitation functions are also shown in figs. 1a and 1b. As can be seen, the experimental excitation functions are best reproduced taking a mixture of pre-equilibrium and equilibrium decay of the compound system. Both \((\alpha, \alpha n)\) and \((\alpha, n\alpha)\) reactions in \(^{59}\text{Co}\) produce the same residual nucleus. However, the measured excitation function is nearer to the excitation function calculated for \(^{59}\text{Co} (\alpha, n\alpha)\) reaction rather than for the \((\alpha, \alpha n)\). The calculated pre-equilibrium fraction as a function of bombarding energy is shown in fig. 2. In general, the pre-equilibrium emission has been found to become more important as the excitation energy increases.

References:

2/ Table of Isotopes, VII Edn., John Wiley (1978)
EXCITATION FUNCTIONS OF $^{197}$Au($\alpha$, $x\alpha$) REACTIONS BETWEEN 10–40 MeV ENERGY RANGE

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Department of Physics, Aligarh Muslim University, Aligarh, U.P., India.

Received 30 April 1983 and in revised form 3 July 1983.

The stacked foil technique has been used to measure the excitation functions for the reactions $^{197}$Au($\alpha$, $x\alpha$), $x = 1$ to 3. A beam of alpha-particles of energy $= 40$ MeV has been made to bombard a stack of ten gold foils. The thickness of the gold foils was selected so as to obtain an energy degradation of the order of 2 to 4 MeV. The induced activities in each foil were followed using a HPGe system. Theoretical excitation functions for these reactions based on the equilibrium decay model do not agree, in general, with the measured ones towards the high energy tails. Excitation functions have also been calculated simulating the pre-equilibrium emission by a hybrid model. The experimental excitation functions are best reproduced by taking a mixture of both the equilibrium and pre-equilibrium emission.

1. Introduction

The excitation functions for the reactions $^{197}$Au($\alpha$, $x\alpha$)~$^{201}$-Tl have been measured from a few tens to several tens of MeV by different groups [1–5]. Their results differ from each other. Moreover, with the aid of improved detectors of high resolution and better quality beams, one expects to obtain more reliable data. With this view, the excitation functions for $^{197}$Au($\alpha$, $x\alpha$), $x = 1$, 2, 3, reactions have been re-measured in the energy range 15.2–37.9 MeV.

The analysis of these excitation functions, in the past, has been carried out on the basis of the statistical equilibrium model [6,7]. In general, this mechanism for the reaction could not account for the high energy tails of the excitation functions [1–4]. Calboreanu et al. could, however, reproduce the experimental data for $^{122}$Sb, $^{197}$Au($\alpha$, $x\alpha$), $x = 1$, 2, reactions between 11.5 and 27 MeV by including the gamma competition with neutron emission in their statistical model calculations and adjusting the level density and $\gamma$-strength parameters.

In recent years, there is increasing interest to look into the nuclear interaction mechanism via pre-equilibrium emission of particles followed by the equilibrium decay. The present analysis has been done to investigate the relative importance of equilibrium and pre-equilibrium processes and to study the dependence of the pre-equilibrium fraction on incident ion energy. This is a part of a larger project of measurements currently under way.

2. Experimental technique

The experimental measurements were made at the Variable Energy Cyclotron Centre (VECC) Calcutta (India) using an $\alpha$-beam of energy $= 40$ MeV. The stack foil method was used in the present measurements. A stack of ten gold foils, fixed individually on brass sheel or heat conduction, was irradiated by an alpha particle beam of $= 400$ nA. The thickness of these foils, 30.96 mg/cm$^2$, corresponded to an energy degradation of $\approx 2$ to 4 MeV from first to last foil. The energy loss in each foil was obtained from the stopping power tables of Northcliffe and Schilling [8].

The induced activities in each foil were followed using a high purity germanium (HPGe) coaxial detector joined to a multichannel analyser. Various gamma-rays of the $^{132}$Eu source (half-life 13.1 a) were used for the efficiency and the energy calibration of the counting unit. The energy resolution of the detector was $= 2$ keV for 1.33 MeV $^{60}$Co $\gamma$-ray. Four to six photopeaks were identified for each reaction. The spectroscopic data of various identified $\gamma$-rays are given in table 1. To check the identification of $\gamma$-rays, the relative intensities of detected $\gamma$-rays have been calculated. It can be seen in table 1 that the presently measured relative intensities are in good agreement with their respective literature values.

The reaction cross-section, $\sigma(E)$, has been calcu-
Table 1
Spectroscopic data and measured relative intensities of $\gamma$-rays

<table>
<thead>
<tr>
<th>$E_\gamma$ (keV)</th>
<th>Absolute abundance $I_1$</th>
<th>Normalized relative intensity</th>
<th>Literature value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{197}$Au(n, n)$^{198}$Th, $T_{1/2}$ of product nucleus = 26.1 h</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>368</td>
<td>0.85</td>
<td>$100.0 \pm 2.9$</td>
<td>100</td>
</tr>
<tr>
<td>579</td>
<td>0.14</td>
<td>$17.8 \pm 1.2$</td>
<td>13.8</td>
</tr>
<tr>
<td>828.3</td>
<td>0.1105</td>
<td>$12.6 \pm 1.3$</td>
<td>12.47</td>
</tr>
<tr>
<td>1205.7</td>
<td>0.305</td>
<td>$33.2 \pm 1.3$</td>
<td>34.4</td>
</tr>
</tbody>
</table>

| $^{197}$Au(n, 2n)$^{198}$Th, $T_{1/2}$ of product nucleus = 7.4 h |
| 158.6           | 0.068                    | $37.7 \pm 1.4$                | 40               |
| 208.2           | 0.1188                   | $95.9 \pm 3.3$                | 99               |
| 297.3           | 0.09                     | $70.2 \pm 4.5$                | 75               |
| 284.1           | 0.0214                   | $17.3 \pm 1.8$                | 17.8             |
| 403.5           | 0.0167                   | $15.6 \pm 1.8$                | 13.9             |
| 455             | 0.12                     | $100.0 \pm 4.9$               | 100              |

| $^{197}$Au(n, 3n)$^{199}$Th, $T_{1/2}$ of product nucleus = 5.3 h |
| $^{4}$$^2$      | 0.78                     | $697.9 \pm 3.1$               | 750              |
| 637.7           | 0.0965                   | $100.0 \pm 4.3$               | 92.8             |
| 675.8           | 0.104                    | $100.0 \pm 2.2$               | 100              |
| 1200.6          | 0.09                      | $75.0 \pm 3.2$                | 88.6             |
| 1420.6          | 0.073                     | $66.7 \pm 3.9$                | 73.3             |


The activation cross section for the same reaction has been calculated from the intensities of the various identified $\gamma$-rays emitted from the same residual nucleus. The final experimental value has been taken as the weighted average of these individual values. The statistical error shown in the results is the larger of the internal and external errors. These errors are found to be less than 5% except for the case of (n, n) reaction at lowest energy point where the errors are up to 17%. As such, the measured cross section values are given in Table 2.

Table 2
Measured cross sections for $\alpha$-induced reactions in $^{197}$Au

<table>
<thead>
<tr>
<th>$E_\alpha$ (MeV)</th>
<th>$\sigma(\alpha, n)$ (mb)</th>
<th>$\sigma(\alpha, 2n)$ (mb)</th>
<th>$\sigma(\alpha, 3n)$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37.9 ± 1.1</td>
<td>6.24 ± 0.1</td>
<td>141.99 ± 7.75</td>
<td>954.6 ± 21.9</td>
</tr>
<tr>
<td>35.65 ± 1.15</td>
<td>8.06 ± 0.09</td>
<td>195.63 ± 11.13</td>
<td>785.99 ± 17.5</td>
</tr>
<tr>
<td>33.3 ± 1.2</td>
<td>8.25 ± 0.16</td>
<td>313.58 ± 6.65</td>
<td>518.2 ± 5.99</td>
</tr>
<tr>
<td>30.85 ± 1.25</td>
<td>9.27 ± 0.15</td>
<td>585.7 ± 6.22</td>
<td>234.9 ± 2.13</td>
</tr>
<tr>
<td>28.25 ± 1.35</td>
<td>12.08 ± 0.14</td>
<td>710.14 ± 2.07</td>
<td>21.5 ± 0.25</td>
</tr>
<tr>
<td>25.5 ± 1.4</td>
<td>19.74 ± 0.36</td>
<td>425.97 ± 1.6</td>
<td>16 ± 0.07</td>
</tr>
<tr>
<td>22.6 ± 1.5</td>
<td>31.62 ± 0.54</td>
<td>128.62 ± 2.07</td>
<td>3.97 ± 0.05</td>
</tr>
<tr>
<td>19.3 ± 1.8</td>
<td>7.18 ± 0.14</td>
<td>3.97 ± 0.05</td>
<td>0.073 ± 0.012</td>
</tr>
</tbody>
</table>

The expression used for calculating the cross section is:

$$
\sigma(E) = \frac{\alpha \lambda \exp(\lambda t_1)}{N_0 \phi(G\alpha) \theta K [1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_2)]}
$$

where $K = [1 - \exp(-\mu d)]/\mu d$ is the correction for self-absorption of a $\gamma$-ray of absorption coefficient $\mu$ (cm$^2$/gm) in a sample of thickness $d$ (gm/cm$^2$), $A$ is the area under the $\alpha$-peak, $\lambda$ is the decay constant of the product nucleus, $t_1$ is the irradiation time, $t_2$ is the time lapsed between stop of beam and the start of counting, $t_3$ is the counting time, $N_0$ is the number of nuclei in the sample, $\phi$ is the incident flux, $(G\alpha)$ is the geometry dependent efficiency of the detecting unit and $\theta$ being the branching ratio of the identified gamma.
3. Results and Discussion

The measured excitation functions for the reaction $^{197}$Au($\alpha$, $\alpha n$), $x = 1-3$, have been shown in figs. 1a, b and c with closed circles. The size of the circles include the magnitude of statistical errors, if no error bar is plotted. The energy spread, shown in these figures, refers to the energy loss in the foils. In the present analysis of experimental data, the $7^+$ isomeric state of $^{197}$Ti (half-life 1.8 h), expected from the ($\alpha$, $3n$) reaction, has not been observed due to the large time gap between the stop of irradiation and the start of counting. We have measured the cross section for the production of the $^{197}$Ti reaction. In general, the presently measured excitation functions for the three reactions are in good agreement with the literature data [2-5], except for the ($\alpha$, $3n$) reaction.

The excitation functions have also been calculated theoretically using the statistical model with and without the inclusion of pre-equilibrium emission of particles. For the equilibrium part of analysis, the statistical model of Hauser-Feshbach [6] has been used. The contribution from pre-equilibrium process has been included only at the first step of evaporation. The hybrid model formalism has been used for the pre-equilibrium part [10,11]. A computer code ACT [12] has been developed on the lines of the code STAPRE and is used for these calculations. A detailed description of the parent code is given in report no. IRK 76/01 published by the NEA data bank [13]. The level density expression of Lang [14], in the framework of the back-shifted Fermi-gas model [15] has been used to describe the excited states of all nuclei in the region of continuum. The level density parameters have been taken from the tables of Dilg et al. [16] with effective moment of inertia equal to the rigid body value. The transmission coefficients for entrance and exit channels have been generated from another computer code TLK developed on the basis of the code MB2 [17].

In the pre-equilibrium formulations, the configuration of the composite system is defined by its exciton number $n$ ($p, h$). In these calculations, no distinction has been made between neutrons and protons. The calculated value of pre-equilibrium contribution has been found to be very much sensitive to (i) the square of absolute value of average effective matrix element for

![Figure 1a](image-url)  
**Fig. 1a.** Experimental and calculated excitation function for the reaction $^{197}$Au($\alpha$, $n$). The full line represents inclusion of pre-equilibrium emission whereas broken and dotted lines are from pure equilibrium calculations with and without adjusted level density parameters.
Fig. 1b. Experimental and calculated excitation function for the reaction $^{197}$Au(a, 2n). The full line represents inclusion of pre-equilibrium emission whereas broken and dotted lines are from pure equilibrium calculations with and without adjusted level density parameters.

Fig. 1c. Experimental and calculated excitation function for the reaction $^{197}$Au(a, 3n). The full line represents inclusion of pre-equilibrium emission whereas broken and dotted lines are from pure equilibrium calculations with and without adjusted level density parameters.

two body residual interactions, $|M|^2$, and (ii) to the choice of the initial configuration, $n_0$, of the composite system. The following relation due to Kalbach–Clube [18] has been used to estimate the value of effective matrix element,

$$|M|^2 = F^2 M A^{-1} E^{-1}.$$  

Here, $A$ and $E$ are the mass number and the excitation energy of the composite system, respectively. In general, $FM$ (MeV$^2$) is treated as an adjustable parameter and values between 95 and 7000 MeV$^2$ have been proposed for it in the literature [19].

In an earlier study of (n, p) reactions [12], the best value of $FM$ was found to be 430 MeV$^2$. In the present analysis we have also adopted the same value of $FM$ (430 MeV$^2$). The theoretical cross-section calculations have been done by taking different values of the excitation number of the initial configuration. It has been found that the initial configuration (5p, 1h) gives the best fit to the experimental data for a-induced reactions.

From figs. 1a, b and c, it can be seen that the experimental excitation functions for all the three reactions can be best reproduced by including the pre-equilibrium emission.
librium emission, as shown by full lines in these graphs. However, some adjustments in the values of level density parameters have been made to fit all the three excitation functions simultaneously. These parameters have been varied within ±10% of the values given by Dilg et al. [16]. These variations are justified keeping in view the fact that Dilg et al. parameters are good for the energy range 10 to 20 MeV [16]. To show the effect of the pre-equilibrium emission, theoretically calculated excitation functions with the pure equilibrium model are also shown on the same diagrams, (broken lines - with adjusted level density parameters and dotted lines - the level density parameters are consistently equal to the values given by Dilg et al. [16]).

In these calculations, the pre-equilibrium fraction is inherently energy dependent. This dependence is derived from consideration of the internal transition rates and the continuum decay rates. The pre-equilibrium fraction has been taken to be proportional to the cumulative sum of the probability of finding the particle in the continuum for every possible configuration during the process of equilibration. The calculated pre-equilibrium fraction as a function of bombarding energy is shown in fig. 2.

4. Conclusions

The experimental excitation functions for \( ^{14}A (a, xn) \) reactions have high energy tails. The high energy tails, in general, cannot be accounted for by pure compound reaction mechanism and can be attributed predominantly to pre-equilibrium decay of composite system. Proper admixture of equilibrium and pre-equilibrium processes is needed to reproduce the experimental data. The initial configuration (5p, 1h) of the composite system for \( a \)-induced reactions favours the projectile independent value of the average effective matrix element. Nearly linear increase in the pre-equilibrium fraction as a function of excitation energy has been found.

Acknowledgements

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References

Pre-equilibrium emission effect in \((n,p)\) reaction cross-sections at 14.8 MeV

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Abstract. The influence of pre-equilibrium emission on \((n,p)\) reaction cross-sections at 14.8 MeV has been studied. Cross-sections for \((n,p)\) reactions have been measured by the activation technique at 14.8 ± 0.5 MeV neutron energy. The experimental cross-section values have been compared with the calculated values at 14.8 MeV with and without considering the pre-equilibrium emission. Equilibrium calculations have been performed according to the statistical model of Hauser and Feshbach while the hybrid model has been used to include the pre-equilibrium contribution. Pre-equilibrium emission has been considered only in the first emission step. The comparison of experimental and calculated values clearly indicates the presence of pre-equilibrium emission.

Keywords. \((n,p)\) reactions; measured values; equilibrium and pre-equilibrium calculations.

PACS No. 25-40

1. Introduction

Pre-equilibrium processes play an important role in nuclear reactions induced by neutrons of few MeV (< 50 MeV). Taking into account pre-equilibrium decay, it is possible in general to achieve a better understanding and description of these processes.

Since a large number of experimental measurements of \((n,p)\) reaction cross-sections have been performed around 14 MeV incident neutron energy, it has been observed that there is a large discrepancy between the cross-section values of the same reaction reported by different groups of workers. It has also been observed that unless reliable cross-section measurements using the same technique and the standard reaction are available for a large number of target nuclei, it is not possible to study the trends in the values of reaction cross-sections. With this view a programme of cross-section measurements by the activation technique has been undertaken. The cross-section values have also been calculated theoretically using equilibrium and pre-equilibrium emission models. Experimental and calculated \((n,p)\) reaction cross-sections at 14.8 MeV have been compared. It has been observed that the inclusion of pre-equilibrium emission in the calculations gives better agreement with the experimental ones.

2. Experimental procedure

Reaction cross-sections for 18 nuclei have been measured using the activation technique. The 130 keV deuteron beam of the Cockcroft Walton accelerator of our
laboratory bombarded a thin tritium target to obtain 14.8 MeV neutrons. The samples have been prepared in thin perspex rings sandwiched between two cellulose tapes using spectrascopically pure substances of chemical purity more than 99.9%. By following activities induced in samples due to neutron bombardment, cross-sections responsible for these activities can be determined. In actual irradiation, various activities due to different reactions were induced in the samples. The residual nuclei of different reactions generally decay with different half-lives. The decay of the irradiated samples were, therefore, followed for sufficiently long times to obtain complete decay curves. Separated decay curves have been extrapolated to get the counting rates ($C_t = 0$) at zero time after the irradiation. From the observed counting rates at zero time, cross-sections for different reactions ($\sigma_r$) have been calculated using the following expression (Gupta 1983).

$$\sigma_r = \frac{C_t = 0}{G \times \phi \times \epsilon \times N_0 \times (1 - \exp(-\lambda t_e))}$$

where, $G$ is the geometrical efficiency of detection, $\epsilon$ is the efficiency of the detector system, $\phi$ is the incident neutron flux, $N_0$ is the number of target nuclei in the sample and $t_e$ is the time of irradiation. $\lambda$ being the decay constant of the induced activity.

The incident neutron flux has not been determined directly, but instead the value of the effective neutron flux ($\phi \times G$) has been determined in each case from the intensity of the activity induced in the standard iron samples due to $^{56}$Fe $(n, p)$ $^{56}$Mn reaction. The cross-section for the standard $^{56}$Fe $(n, p)$ $^{56}$Mn reaction has been taken as 102 mb. This value is the weighted average of many reported values (Terrel and Halm 1958; Kern et al 1959; Bornemann et al 1962; Banozzola et al 1964; Santry and Butler 1964; Liskien and Paulsen 1965; Hemingway et al 1966; Barrell et al 1969; Cuzzocrea et al 1971; Molla and Qaim 1977). In general, two standard iron samples, one on each side of the unknown sample, have been irradiated simultaneously. All the three samples were then studied by the same detector in identical geometry to keep the geometrical efficiency of irradiation and counting same for all cases including those of the standard samples. Iron as a standard has many advantages. It has a flat excitation function around 14 MeV. As the cross-section for the reaction $^{56}$Fe $(n, p)$ $^{56}$Mn around 14 MeV is quite large, it gives strong activity even for irradiations of short duration. Moreover, the reaction produces a nearly pure activity of 2.56 hr which could be studied both by the $\beta$-particle and $\gamma$-ray counting. Thus measurements have been done for all cases in which the residual nucleus of the reaction decays by either the beta and/or $\gamma$-emission using the same standard reaction. Activities induced in various samples have been followed by the end-window $\beta$-counter and/or by $\gamma$-ray scintillation spectrometer. In cases where the residual nucleus decays through $\beta$-particles of different energies, the detection efficiency, $\epsilon$, can be calculated by the relation

$$\epsilon = a \exp(-\mu_1 d) + b \exp(-\mu_2 d) + c \exp(-\mu_3 d) + \ldots$$

where, $a$, $b$, $c$, etc. are the fractions of $\beta$-particles of end-point energies $E_1$, $E_2$, $E_3$ . . . etc., $\mu_1$, $\mu_2$, $\mu_3$ . . . , etc. are respectively their mass absorption coefficients and $d$ the average thickness (in mg/cm$^2$) which the $\beta$-particle has to travel before entering the counter. In the $\gamma$-ray spectrometer, the efficiency is given by the multiplication of the photo-peak efficiency, detection efficiency and the absorption correction. The decay data have been taken from the literature (Lederer et al 1978; Nuclear Data Sheets).
Pre-equilibrium emission on (n, p) reaction cross-sections

3. Results and discussion

The investigated (n, p) reactions, their Q-values and the measured cross-section values are given in table 1. Cross-sections for these reactions have been measured by many workers and the values reported by different groups differ much from each other. To give an idea of the dispersion in the measured values, the maximum and the minimum reported cross-section values for each reaction are listed in table 1. As has been stated, these discrepancies may partly be due to the different techniques adopted by different workers.

The (n, p) cross-sections for the cases presently measured have also been calculated theoretically using two options: (a) pure compound reaction mechanism (denoted by $\sigma_{\text{cal, } \text{CN}}$) and (b) with the compound plus pre-compound according to the hybrid model (denoted by $\sigma_{\text{cal, } \text{CN} + \text{pre}}$).

The pure compound calculations have been performed according to the statistical model of Hauser and Feshbach (1952). For the pre-compound emission the hybrid model (Blann 1971; Blann and Mignerey 1972) option has been chosen. Pre-equilibrium emission has been considered only in the first emission step where the excitation energy is sufficiently large. In these calculations conservation of the parity and angular momentum has been explicitly considered at each step of de-excitation. A computer code on lines of STAPRE (Uhl and Strohmaier 1976, private communication)

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Q-value (MeV)</th>
<th>Measured $\sigma_{\text{n,p}}$ (mb)</th>
<th>$\sigma_{\text{cal, } \text{CN}}$ (mb)</th>
<th>$\sigma_{\text{cal, } \text{CN} + \text{pre}}$ (mb)</th>
<th>$\sigma_{\text{max}}$ (mb)</th>
<th>$\sigma_{\text{min}}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{24}\text{Mg} (n, p)^{24}\text{Na}$</td>
<td>$-4.74$</td>
<td>$180 \pm 20$</td>
<td>$205.0$</td>
<td>$188.0$</td>
<td>$191 \pm 40^a$</td>
<td>$110 \pm 16^a$</td>
</tr>
<tr>
<td>$^{25}\text{Mg} (n, p)^{25}\text{Na}$</td>
<td>$-3.023$</td>
<td>$45 \pm 8$</td>
<td>$187.7$</td>
<td>$42.6$</td>
<td>$43 \pm 10^a$</td>
<td>$40 \pm 4^a$</td>
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<tr>
<td>$^{27}\text{Al} (n, p)^{27}\text{Mg}$</td>
<td>$-1.798$</td>
<td>$76 \pm 12$</td>
<td>$38.3$</td>
<td>$70.0$</td>
<td>$132 \pm 10^a$</td>
<td>$52 \pm 10^a$</td>
</tr>
<tr>
<td>$^{34}\text{S} (n, p)^{34}\text{P}$</td>
<td>$-4.31$</td>
<td>$75 \pm 8$</td>
<td>$70.5$</td>
<td>$70.5$</td>
<td>$85 \pm 40^a$</td>
<td>$73 \pm 8^a$</td>
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<tr>
<td>$^{37}\text{Cl} (n, p)^{37}\text{S}$</td>
<td>$-4.087$</td>
<td>$28 \pm 5$</td>
<td>$11.4$</td>
<td>$24.4$</td>
<td>$41 \pm 4^a$</td>
<td>$21.3 \pm 3^a$</td>
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<td>$^{41}\text{K} (n, p)^{41}\text{Ar}$</td>
<td>$-1.74$</td>
<td>$53 \pm 4$</td>
<td>$42.0$</td>
<td>$51.0$</td>
<td>$88 \pm 14^a$</td>
<td>$48 \pm 10^a$</td>
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<tr>
<td>$^{48}\text{Ti} (n, p)^{48}\text{Sc}$</td>
<td>$-3.19$</td>
<td>$60 \pm 5$</td>
<td>$47.0$</td>
<td>$59.0$</td>
<td>$93 \pm 33^a$</td>
<td>$53 \pm 6^a$</td>
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<td>$^{50}\text{Ti} (n, p)^{50}\text{Sc}$</td>
<td>$-1.23$</td>
<td>$40 \pm 7$</td>
<td>$19.5$</td>
<td>$33.5$</td>
<td>$97 \pm 16^a$</td>
<td>$23 \pm 5^a$</td>
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<tr>
<td>$^{50}\text{Ti} (n, p)^{50}\text{Sc}$</td>
<td>$-5.65$</td>
<td>$20 \pm 5$</td>
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<td>$147 \pm 14^a$</td>
<td>$9 \pm 3^a$</td>
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<td>$^{51}\text{V} (n, p)^{51}\text{Ti}$</td>
<td>$-1.68$</td>
<td>$38 \pm 4$</td>
<td>$14.5$</td>
<td>$37.0$</td>
<td>$55 \pm 12^a$</td>
<td>$20 \pm 3^a$</td>
</tr>
<tr>
<td>$^{52}\text{Cr} (n, p)^{52}\text{V}$</td>
<td>$-3.19$</td>
<td>$88 \pm 6$</td>
<td>$144.0$</td>
<td>$112.0$</td>
<td>$118 \pm 16^a$</td>
<td>$74 \pm 10^a$</td>
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<tr>
<td>$^{56}\text{Fe} (n, p)^{56}\text{Mn}$</td>
<td>$-2.92$</td>
<td>$100 \pm 6$</td>
<td>$86.0$</td>
<td>$97.0$</td>
<td>$109 \pm 10^a$</td>
<td>$82 \pm 7^a$</td>
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<tr>
<td>$^{65}\text{Cu} (n, p)^{65}\text{Ni}$</td>
<td>$-1.35$</td>
<td>$21 \pm 2$</td>
<td>$15.0$</td>
<td>$22.2$</td>
<td>$31 \pm 13^a$</td>
<td>$11 \pm 1^a$</td>
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<tr>
<td>$^{64}\text{Zn} (n, p)^{64}\text{Cu}$</td>
<td>$+0.21$</td>
<td>$171 \pm 13$</td>
<td>$220.2$</td>
<td>$151.0$</td>
<td>$386 \pm 60^a$</td>
<td>$160 \pm 12^a$</td>
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<tr>
<td>$^{66}\text{Zn} (n, p)^{66}\text{Cu}$</td>
<td>$-1.84$</td>
<td>$74 \pm 6$</td>
<td>$51.0$</td>
<td>$68.0$</td>
<td>$101 \pm 17^a$</td>
<td>$35 \pm 4^a$</td>
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<tr>
<td>$^{71}\text{As} (n, p)^{71}\text{Ge}$</td>
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<td>$35 \pm 3$</td>
<td>$12.2$</td>
<td>$29.0$</td>
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<td>$12 \pm 2^a$</td>
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<tr>
<td>$^{88}\text{Sr} (n, p)^{88}\text{Rh}$</td>
<td>$-4.41$</td>
<td>$15 \pm 2$</td>
<td>$1.1$</td>
<td>$16.3$</td>
<td>$30 \pm 2^a$</td>
<td>$13.5 \pm 1.5^a$</td>
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<tr>
<td>$^{109}\text{Ag} (n, p)^{109}\text{Pd}$</td>
<td>$-0.369$</td>
<td>$14 \pm 2$</td>
<td>$5.5$</td>
<td>$15.3$</td>
<td>$15 \pm 2^a$</td>
<td>$10.5 \pm 2^a$</td>
</tr>
</tbody>
</table>

* Paul and Clarke (1953); † Allan (1961); ‡ Borman et al (1967); ‡ Khurana and Hans (1959); ‡ Khurana and Govil (1965); ‡ Mitra and Ghose (1966); ‡ Bramlitt and Fink (1963); ‡ Bormann and Lammers (1969); ‡ Molla and Qaim (1977); ‡ Koehler and Alford (1964); ‡ Dyer and Hamilton (1972); ‡ Scalans and Fink (1958); ‡ Butler and Santry (1961); ‡ Strohal et al (1962); ‡ Levkovskii et al (1969); ‡ Drantiev et al (1957).
has been developed for these calculations. The code is designed to calculate energy-averaged cross-sections for particle induced reactions. This is based on the statistical compound nucleus model with the consideration of angular momentum and parity conservation. The code considers the evaporation of up to six particles in sequence and intermediary $\gamma$-ray cascades. The code also includes the process of pre-equilibrium decay at the first evaporation step. The hybrid model has been used for the description of pre-equilibrium emission of particles. A detailed description of the parent code is given in report no. IRK 76/01 published by NEA data bank.

The results of calculations depend on many parameters. In the pure compound calculations the value of level density parameter $a$ and the fictive ground state energy $\Delta$ for all nuclei have been taken to be consistently equal to that given by Dilg et al (1973). It has been observed that the calculated $(n, p)$ cross-section values fail to reproduce measured values with pure compound calculations. As such, there is need to include some other reaction mechanisms for a better agreement between theory and experiment. Pre-equilibrium process is then added to compound nucleus process. In the pre-compound calculations the value of the average squared matrix element $|M|^2$ is

![Figure 1. Comparison between experimental and calculated $(n, p)$ cross-sections $[(\sigma(n, p)_{exp})/(\sigma(n, p)_{the})]$ vs atomic mass number of the target nucleus at 14.8 MeV. a. Calculations based on equilibrium statistical theory only. b. Calculations include pre-equilibrium emission.](image-url)
It is required, it depends sensitively on details of the employed model. The expression

$$|M|^2 = FM A^{-3} E^{-1}$$

proposed by Cline (1973) has been used. In the present calculations \( FM \) has been kept as an adjustable parameter to get a better agreement between calculated and measured values of \((n, p)\) reaction cross-sections. In literature, \( FM \) values vary from 95 to 7000 MeV\(^3\) (Gudima et al. 1983). In the present analysis, the best value of \( FM \) has been found to be 430 MeV\(^3\), which reproduces the experimental data.

The calculated \( \sigma(n, p)_{\text{cal.} CN} \) and \( \sigma(n, p)_{\text{cal.} CN + \text{Pre}} \) for 18 nuclei have been listed in columns 4 and 5 of table 1. The ratio

$$\frac{\sigma(n, p)_{\exp}}{\sigma(n, p)_{\text{cal.} CN}} \quad \text{and} \quad \frac{\sigma(n, p)_{\exp}}{\sigma(n, p)_{\text{cal.} CN + \text{Pre}}}$$

have been plotted against atomic mass number \( A \) and asymmetry parameter \((N - Z)/A\) (figures 1 and 2). It is interesting to see from these figures, except for \(^{24}\text{Mg}\), \(^{52}\text{Cr}\) and \(^{64}\text{Zn}\), that the measured cross-sections are higher than their values calculated without consideration of pre-equilibrium emission (figures 1a and 2a). The higher values of the provided.
ratio \( \frac{\langle n, p \rangle_{\text{exp}}}{\langle n, p \rangle_{\text{cal CN}}} \) suggest the presence of some reaction mechanisms, from the compound nucleus process, through which the emission of proton is taking place, the ratio \( \frac{\langle n, p \rangle_{\text{exp}}}{\langle n, p \rangle_{\text{cal CN}} + \langle n, p \rangle_{\text{pre}}} \) is also plotted in figures 1 and 2 against \( A \) and \( \frac{N - Z}{A} \) (figures 1b and 2b). As can be seen now the points in these figures lie quite close to unity. This better agreement between the experimental and calculated cross-section values in the latter case strengthens the presence of pre-equilibrium emission process.

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Report IRK 76(0) 1981 NEA Data Bank, Cendex France
INTERNATIONAL CONFERENCE ON NUCLEAR PHYSICS

On the Occasion of
The Golden Jubilee of the
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BOOK OF ABSTRACTS

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PRE-EQUILIBRIUM DECAY ANALYSIS OF $^{232}$Th(p,p'f) REACTION

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In an earlier work, the fission probability distribution $P_f$ was measured for the reaction $^{232}$Th(p,p'f) at $E \approx 52.5$ MeV and the effective fission barrier heights $E_f$ were deduced for the various $^{232}$Th-isotopes. In this statistical model analysis it was assumed that fission competes with the emission of neutrons and the level density parameter for fission, $a_f$, was taken equal to $a_m$, the value corresponding to equilibrium deformation. The effective fission barrier heights, thus deduced, were found relatively higher than their literature values. Because of the different natures of saddle point deformation and the equilibrium deformation, it is desirable to have different values for $a_f$ and $a_m$. In the present analysis, the $P_f$ has been calculated for different values of the ratio $a_f/a_m$ (greater than unity). An upper limit of 1.05 for this ratio has been found to reproduce the experimental $P_f$ distribution. Further, the choice of ratio $a_f/a_m$, greater than unity required still higher values of effective fission barrier heights for reproducing the measured $P_f$ distribution. An attempt has been made to see if these higher barrier heights can be attributed to the pre-equilibrium emission of neutrons. The pre-equilibrium effects have been included in these calculations by taking an effective nuclear temperature corresponding to the neutron emission relatively higher than its equilibrium statistical value. It has been observed that relatively lower effective fission barrier heights than those previously deduced can now reproduce the experimental data of $P_f$.

The excitation function for the reactions $^{197}$Au ($\alpha$, xn), x = 1 to 3 have been experimentally measured using stack foil technique. A stack of ten Gold foils has been irradiated by a beam of alpha-particles of energy 40 MeV at VBLRC, Calcutta (India). The thickness of Gold Foils corresponded to an energy degradation of the order of 2 to 3 MeV. The induced activities in each foil have been followed using HPGe system. Because of considerable discrepancy in the measured excitation functions for these reactions, reported in part, several $\gamma$-rays, apart from the prominent ones, have also been used to identify the residual nuclei from three different reactions. The relative intensities of these $\gamma$-rays corresponding to each product nucleus, have been experimentally determined and found to be in good agreement with the literature values of the branching ratios. At each energy, the activation cross-sections for the same reaction have been determined from the intensities of the various $\gamma$-rays emitted from the residual nucleus. The final experimental value of the cross-section has been taken as the weighted average of these respective individual values. In general, presently measured excitation functions agree well with their literature values. These excitation functions have been calculated theoretically using the equilibrium decay model. In general, experimental excitation functions do not compare well with the theoretical ones towards the high energy tails. The theoretical calculations of excitation functions have, therefore, also been carried out using computer code ALICE/LIVERMORE 82(1) based on Hybrid model for pre-equilibrium emission of particles. The experimental excitation functions are best reproduced by taking a mixture of both the equilibrium and pre-equilibrium emission. The effect of variation of the nuclear density with the radius of nucleus on the excitation functions have also been investigated in these calculations.

M. Blann and J. Binplinghoff, private communication.
NUCLEAR PHYSICS
AND
SOLID STATE PHYSICS
SYMPOSIUM
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PROGRAMME & ABSTRACTS
Part I : NUCLEAR PHYSICS

MYSORE UNIVERSITY
MYSORE

ORGANISED
UNDER THE AUSPICES OF THE
DEPARTMENT OF ATOMIC ENERGY
GOVERNMENT OF INDIA
In finding out the potential parameters for calculating the single particle shell model states around Pb, it has been shown unlike the previous accepted results that the shape of the spin-orbit potential can be made identical to that of the central one. This feature allows one to minimize the variable number to a considerable extent without hampering the single particle picture near the outer surface. Inclusion of core polarisation has also been done.

**NE5** PRE-EQUILIBRIUM EFFECTS IN (n,p) REACTIONS AT 14.8 MeV.

Physics Department, A.M.U. Aligarh - 202001

The influence of pre-equilibrium emission on (n,p) reactions at 14.8 MeV has been studied. Comparison of measured reaction cross sections with calculated cross section values at 14.8 MeV including pre-equilibrium emission and without consideration of pre-equilibrium emission has been done. A hybrid model has been used to calculate the pre-equilibrium contribution. The comparison of experimental and calculated values clearly indicates the presence of pre-equilibrium emission.

**NE6** PRE-EQUILIBRIUM PARTICLE EMISSION SPECTRA AND MULTIPARTICLE REACTION CROSS-SECTIONS OF NIOBIUM:

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Pre-equilibrium model and multistep Hauser-Feshbach theory have been utilized in the analysis and prediction of neutron induced multiparticle reaction cross sections, particle emission spectra and their angular distributions for niobium at 10, 14.6, 20 and 25.7 MeV. The interaction matrix constant has been extracted to fit the angle integrated total neutron emission spectra at 14.6 MeV. The angular distributions of neutron, proton and alpha particles have been evaluated. Multiparticle reaction cross sections (n,2n), (n,p), (n,pn), (n,p) and (n,4n) have been obtained. It has been observed that the pre-equilibrium emission becomes more predominant with the increasing energy of the incident particle. Gamma emission has been accounted with the giant dipole-radiation model of Brink-Axel.
THE EFFECT OF PRE-COMPOUND NEUTRON EMISSION IN $^{232}$Th(p,p'f) REACTION

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Summary

The relative fission width $P_f$ has been measured for the reaction $^{232}$Th(p,p'f) up to 32 MeV excitation energy. In the excitation energy range of 10 MeV to 50 MeV, $P_f$ has been theoretically calculated using a simple competition between fission and cascade neutron emission. Calculations have been done using the effective fission barrier heights $B_f$. Relatively higher effective fission barrier heights have been obtained from these calculations. The effect of pre-compound neutron emission on $P_f$ has been studied in the present analysis. The inclusion of the pre-compound neutron emission has been found to reduce the fission width to some extent. The effect of variation of the ratio of level density parameter for fission ($\alpha_f$) and for neutron emission ($\alpha_n$) has been discussed.

Introduction

The understanding regarding the fission barrier heights is still not very satisfactory. In a previous experiment, the fission probability for the reaction $^{232}$Th(p,p'f) in the energy range of 10 to 32 MeV was studied. Relatively higher (by about 1 MeV) fission barrier heights were required to fit the experimental fission probability distribution. The details of experimental set up and the method of analysis are given elsewhere. In the present analysis, the effect of pre-equilibrium neutron emission and the variation of ratio $\alpha_f/\alpha_n$ has been investigated to see if it can account for the relatively higher fission barrier heights.

Results and Discussion

At higher excitation energies, it is reasonable to consider the competition of the fission with the emission of neutrons only. Further, it is also reasonable to assume that the probability depends on the highest of the fission barrier in case of the multi-humped barrier and the neutron binding energy in the fissioning nucleus. As such the fission probability $P_f$ at high excitation energy can be given by the following relation:

$$P_f = \frac{\Gamma_f}{\Gamma_f + \Gamma_n} \quad (1)$$

Here $\Gamma_f$ and $\Gamma_n$ are the fission and neutron widths respectively.

The following statistical relation has been used to evaluate the ratio $\Gamma_n/\Gamma_f$ at excitation energy $E^*$ from which $P_f$ at each step of de-excitation of the cascade process has been calculated.

$$\Gamma_n = \frac{4\pi^2}{3\hbar^2} \left[ a_f (2-B_p - \Delta_p) \right] \left[ Ko \frac{\hbar^2}{a_n [2a_f (8 - E_f) + 1]} \right]$$

$$\exp \left[ 2a_f (2-B_p) - 2a_f (2-E_f) \right] \quad (2)$$

where $Ko = \hbar^2/2m_f \gamma_0^2$ is of the order of 10 MeV.

The effective fission barrier height $B_f^*$ is related to actual height $B_f$ by the relation:

$$B_f^* = B_f + \Delta_f \quad (3)$$

$(\alpha_f, \Delta_f)$ and $(\alpha_n, \Delta_n)$ are respectively the level density parameters for the fission mode of decay and the neutron mode of decay in the framework of the back-shifted Fermi gas model. $B_n$ is the neutron binding energy in the residual nucleus.

A computer code HALO has been used for the calculation of $P_f$ from relation (2). In this code the neutron energy at each step of de-excitation was calculated using the Konto-carlo method and assuming a Maxwellian neutron spectra. The earlier calculations were based on the statistical model for the emission of neutrons. However, both the recent experimental measurements and the theoretical developments indicate that the equilibrium assumption of the statistical model goes progressively poorer as the excitation energy increases. Therefore, it is desirable to re-analyze the fission probability distribution with the inclusion of pre-compound emission of neutrons.
Some recent measurements\textsuperscript{10-12} have indicated the presence of large contributions of the pre-compound emission in nuclear reactions at higher excitations. The constant temperature analysis of the emitted particle spectra in these measurements has given the nuclear temperature of the residual nucleus much higher than the one expected from the compound process\textsuperscript{10-12}. This indicates that the pre-compound contribution can be included if the particle spectra be calculated with a temperature greater than the nuclear temperature corresponding to the compound process. Therefore, in this analysis the pre-compound effect has been taken into account in a simple manner by raising the effective nuclear temperature corresponding to the neutron emission from $T_0$ to $3T_0$ in steps of 0.4 $T_0$ where $T_0$ is the temperature corresponding to the compound emission. The results obtained are shown in Figure 1,2,3 for $a_1 = a_0$, $a_1 = 1.01 a_0$ and $a_1 = 1.02 a_0$.

As can be seen from these graphs, in general, $P_f$ decreases with the higher residual nuclear temperature for all values of $a_1$. Thus it is possible to match the calculated and measured $P_f$ distribution for a certain value of residual nuclear temperature and the effective fission barrier heights. By taking a higher residual nuclear temperature lower barrier heights may be used to reproduce the experimental $P_f$ distribution.

In the earlier work\textsuperscript{1}, the level density parameter $a_0$ for fission was taken equal to $a_0$, the value appropriate for neutron emission. However, $a_0$ is expected to be larger than $a_0$ because of the difference in the degrees of freedom for fission and neutron emission\textsuperscript{6}. In general, the ratio $a_1/a_0$ has been estimated to be 20 to 30% larger than unity\textsuperscript{6}. Theoretical estimations of $P_f$ have, therefore, been made for different values of the ratio $a_1/a_0$, e.g. $a_1/a_0 = 1.01 a_0$, $a_1/a_0 = 1.02 a_0$, and $a_1/a_0 = 1.05 a_0$. These results are shown in Figure 4 along with the measured $P_f$ distribution from ref.1. As can be seen from this figure, $a_1/a_0$ should not be greater than 1.02 at higher excitation energies.

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Viglaxm 4. ?|sslon probability distribution $P_e$ as a function of the excitation energy for $a_e$, $a_c=1.02a_e$ and $a_c=1.05a_e$. The experimental distribution is from ref. 1.

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