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from the $^{134}\text{Ba}(\alpha, n)$ Reaction

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Angular Distributions of ^{137m}Ce and ^{137g}Ce
from the $^{134}\text{Ba}(\alpha, n)$ Reaction*

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The angular distributions of ^{137m}Ce and ^{137g}Ce nuclei formed in the $^{134}\text{Ba}(\alpha, n)$ reaction have been studied at three different energies in the range between 18 and 25 MeV. The results have been compared to a spin-dependent statistical model calculation. Satisfactory agreement was obtained between theory and experiment at small angles. At large angles the calculated differential cross section was smaller than expected from the experimental data. The discrepancy can be attributed to a small contribution from a direct interaction mechanism. Average properties of the angular distributions were used to obtain the average values of the neutron and photon energies and the difference in the values obtained for the two isomers was interpreted in terms of angular momentum effects. An angular distribution calculation for a hypothetical nucleus suggests that it may be possible to observe striking differences in the angular distribution of (α, n) reaction isomers due to spin fractionation.

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1. Introduction

In an earlier paper¹⁾, the results of a spin-dependent statistical model calculation of the angular distribution of recoil products from (α, n) reactions were presented. The calculation correctly predicted an angular distribution peaking very close to 0° to the beam in the laboratory system. This agreement contrasted with that for earlier spin-independent calculations^{2,3)} which had predicted a spurious peak at large angles. The difference was shown to be due to the effect of competitive gamma ray emission which is not properly included in a spin-independent calculation.

The present study concerns the angular distribution of isomeric (α, n) reaction products. Our calculation indicates that, under favorable conditions, a study of the angular distributions of isomeric (α, n) reaction products can reveal striking evidence of spin fractionation^{4,5)} in the excited residual nucleus. The situation can be understood with reference to fig. 1 which shows a schematic energy spectrum of neutrons emitted in a compound nuclear (α, n) reaction. The bombarding energy is some 4 MeV above the $(\alpha, 2n)$ reaction threshold so that competition between these two reactions will occur.

Consider the de-excitation of compound nuclei with high spin. If a low energy neutron is evaporated, the residual nucleus will be energetically able to de-excite by further neutron emission. It is well known⁶⁾, however, that under these conditions γ -ray emission competes favorably with neutron emission. As shown in fig. 1 the energy spectrum of the (α, n) neutron consequently extends down to very low values and indeed is not very different from that of the first neutron emitted by the compound nucleus. The angular

distribution of the (α, n) reaction product will under these conditions have a normal shape, peaking near 0° to the beam. This then, is the result expected for the high-spin isomer since compound nuclei with large angular momentum will primarily de-excite to this state.

By contrast, neutron emission from low-spin compound nuclei leads to excited nuclei that are much less susceptible to competitive γ -ray emission. The energy spectrum of the (α, n) reaction neutron will not, in this case, extend below a value that would allow subsequent neutron emission. Figure 1 shows that under these conditions the (α, n) neutrons are predominantly emitted with a narrow distribution of kinetic energies. The (α, n) reaction thus involves the formation of two products (neutron and residual nucleus) with practically unique final energies and the angular distribution of the recoil product then peaks at large angles to the beam, as indicated by the kinematics of two-body reactions¹⁾.

In order to determine if this phenomenon could be observed experimentally, and as a further test of the calculation, the angular distributions of ^{137m}Ce and ^{137g}Ce from the $^{134}\text{Ba}(\alpha, n)$ reaction have been measured at 18, 21, and 24 MeV. The results of average range, excitation function, and isomer ratio measurements have been presented in the preceding paper⁷⁾ and indicate that the reaction is compound nuclear at these energies. The experimental procedure is described in Section II and the results presented in Section III. The comparison with calculations is made in Section IV, which also includes an analysis in terms of the average neutron and photon energies associated with the formation of the isomers.

2. Experimental

The experimental procedure followed that of earlier reports from this laboratory^{3,8,9)}. The recoiling nuclei were emitted from a thin target in a forward cone and were stopped in a circular catcher foil located at a known distance from the target. After irradiation the foil was cut into concentric rings each of which corresponded to a particular angular interval, and the radioactivity was assayed.

Targets were irradiated with the external beam of the Argonne National Laboratory 152 cm cyclotron in an evacuated chamber containing a water cooled Faraday cup for measurement of the beam current. The target and catcher foils were mounted on holders whose position relative to the axis of the chamber could be adjusted both horizontally and vertically. The beam was collimated outside the chamber by 0.32 cm or 0.16 cm apertures and inside the chamber by an aperture of the same size located in the water cooled target holder. Degradar foils were located on the upstream side of the first collimator. The target to catcher distance varied between 10 and 13 cm depending on the bombarding energy.

The irradiations had a duration of 3-4 hr at a current of approximately 0.2 μ A. Before each bombardment an alignment experiment was performed to insure that the beam passed through the center of the target and catcher foils. This was accomplished by irradiating mylar foils placed in the target and catcher holders and making appropriate adjustments in the location of the holders based on the position of the beam spot.

In order to minimize the effect of scattering in the target material on the angular distribution, very thin targets were prepared by the molecular plating technique developed by Parker and Falk¹⁰⁾. A teflon cell

with a diameter of two cm was employed. The electrodeposition was carried out using a solution of enriched barium nitrate¹¹⁾ (84.6% ^{134}Ba) in distilled water and spectroscopic grade isopropyl alcohol with the target foil backing as the cathode. A rotating platinum wire served as the anode. A 250 V potential was maintained across the electrodes for ninety minutes, forming a $10\mu\text{g}/\text{cm}^2$ film at the cathode. The target thickness, determined by weighing, was much smaller than the average range of the recoil products in barium nitrate as determined in the preceding paper⁷⁾. The effects of target thickness and collimator size were determined in separate experiments and the results are given in the next section. The target backing and catcher foils consisted of aluminium having a purity of 99.999% and an areal density of $7\text{ mg}/\text{cm}^2$.

The catcher foil had a diameter of 10 cm and was cut into 10 concentric rings of equal width by a die and press. The angular interval subtended by each ring was determined by the target to catcher distance and the intervals were usually in the range from $2-3^\circ$. Cerium was radiochemically separated from each ring according to a procedure developed by Glendenin et al¹²⁾.

$^{137g}\text{Ce}(I\pi = \frac{3}{2}^+)$ decays by electron capture into ^{137}La with a 34.4 h half-life. $^{137m}\text{Ce}(I\pi = \frac{11}{2}^-)$ lies 255 KeV above the ground state and decays to it with a 9.0 h half-life. The counting procedure and decay curve analysis have been described in the preceding paper⁷⁾.

The enriched ^{134}Ba isotope used in the targets contained 4.1% ^{135}Ba . A correction discussed in the preceding paper⁷⁾ was applied for the ^{135}Ba ($\alpha, 2n$) reaction using data from angular distribution measurements performed as a part of this study.

3. Results

The data were analyzed by means of a least squares computer program as outlined in the preceding paper⁷⁾. The angular distribution results are summarized in table 1. For each experiment the table lists the bombarding energy, the minimum, maximum, and mean laboratory angles subtended by each ring, and the differential cross sections, $(\frac{d\sigma}{d\Omega})_m$ and $(\frac{d\sigma}{d\Omega})_g$ for the formation of the metastable and ground-state products, respectively. Where appropriate, the differential cross sections for the $^{135}\text{Ba}(\alpha, 2n)$ reaction are also listed. The disintegration rate of each ring was proportional to $d\sigma/d\theta$. The differential cross sections shown in the table were obtained by multiplication of the disintegration rates by the appropriate solid angle factors:

$$\left(\frac{d\sigma}{d\Omega}\right)_i = \frac{A_i}{\cos\theta_{i_{\min}} - \cos\theta_{i_{\max}}} \quad (1)$$

where A_i is the activity of the i th ring.

The effects of target thickness and collimator size were investigated at 18.8 MeV. The target thickness effect was studied by irradiating 10 $\mu\text{g}/\text{cm}^2$ and 5 $\mu\text{g}/\text{cm}^2$ thick targets using a 0.32 cm collimator. The effect of collimator size was similarly investigated by irradiation of two 10 $\mu\text{g}/\text{cm}^2$ targets with either 0.32 cm or 0.16 cm collimators. In fig. 2, where the angular distributions have been normalized to equal areas, the effects of target thickness and collimator size are shown. The average recoil angles are summarized in Table II. Neither target thickness nor collimator size appear to have any effect on the angular distribution within the limits of experimental error.

The angular distributions are displayed graphically in figs. 3-5. The vertical lines in the figures represent the maximum possible recoil angles obtained from the expression:

$$\theta_{Lmax} = \sin^{-1} \left[\left(\frac{(E_{cm} + Q)(M_T + M_b - M_R)}{E_b M_b} \right)^{\frac{1}{2}} \frac{M_T + M_b}{M_R} \right] \quad (2)$$

where M_T , M_R and M_b are the masses of the target, residual and bombarding nuclei, E_b is the bombarding energy and $E_{cm} + Q$ is the total energy available in the center of mass system. The mass values listed in the compilation by Mattauch et al¹³⁾ were used to compute the Q values. It is seen that the angular distributions of both isomers are quite similar and in all instances peak at or close to 0° . As the bombarding energy increases the curves broaden somewhat. This trend can be seen more clearly in terms of the average recoil angles, summarized in Table III. The noted increase in $\langle \theta_L \rangle$ is a consequence of the faster increase in the recoil velocity resulting from neutron emission than in that of the compound nucleus.

The error bars in the figures indicate the magnitude of all random errors in the experiments. The errors for the ground state isomer are much larger than for the metastable isomer because of the mode of decay. There is an error of less than 5% in the gravimetric chemical yields. Random errors at low energies typically average about 10%. At the higher energies the correction for the $(\alpha, 2n)$ reaction amounts to some 10% and the uncertainty in the results is somewhat larger than 10%.

4. Discussion

A. Comparison with the Statistical Model

The experimental angular distributions do not bear out the expectations described in the Introduction. The curves for both isomers peak near 0° and have very similar shapes. Evidently competitive gamma ray emission is of importance even in processes leading to ^{137}Ce . A calculation of the angular distribution of recoil products was performed in order to obtain quantitative information on this point. The calculation, described in two earlier papers ^{1,7)}, is based on the spin-dependent statistical theory and includes the effects of competitive gamma ray emission. The Monte Carlo technique, in which random numbers are used to select reaction properties, is employed in the program. The effect of parameter variation on the calculation has already been discussed in detail in an earlier report ¹⁾. The original calculation, which was designed to compute angular distributions, has been modified ⁷⁾ to permit evaluation of isomer ratios and angular distributions of isomers. The only modifications required to obtain the angular distributions of the individual isomers involved the assignment of a particular iteration product to either isomer. This was done on the basis of the spin of the nucleus formed after the emission of the penultimate gamma ray as described in the preceding paper ⁷⁾. Enough iterations were performed so that 10^4 (α, n) events were obtained. At the end of the calculation the differential cross section and its standard deviation were computed in one degree intervals.

Figure 3 compares the theoretical and experimental results at 18.8 MeV. In all cases the theoretical curves have been normalized to the same

area as the experimental results. The level density parameter was 15.75 MeV^{-1} and the moment of inertia was $0.49 \mathcal{I}_r$ where $\mathcal{I}_r$ is the rigid body value. This particular choice of $\mathcal{I}$ gave the best fit to the experimental isomer ratio data presented in the preceding paper⁷⁾. The calculation predicts the correct shape for the curves but the angular distribution is too narrow. Previous spin-independent calculations^{2,3} of the angular distribution of (α, n) reaction products predicted a peak at large angles to the beam. The present calculation, by contrast, shows a smooth dropoff from the peak at 0° . In fig. 4 the theoretical and experimental results are shown at 21.2 MeV. The level density parameter was 15.75 MeV^{-1} and the moment of inertia was $0.72 \mathcal{I}_r$. Although the calculation predicts the proper shape for the angular distribution, the distribution is again narrower than the experimental results. The calculation was not performed for comparison with the 24.5 MeV data because of the inordinate amount of computer time required at this energy.

A possible explanation for the discrepancy between experiment and theory at large angles lies in the contribution of a direct interaction process to the (α, n) reaction. Although the average range of the reaction product is consistent with compound nucleus formation⁷⁾, a small contribution from a direct process would not be noticeable in such a measurement. In another paper from this laboratory the angular distribution of the recoil product from a $(^3\text{He}, n)$ reaction proceeding by a direct mechanism has been calculated on the basis of the distorted wave theory⁹⁾. In this reaction the angular distribution was nearly independent of angle up to the kinematic limit. A similar result can be expected for a direct (α, n) reaction. A small contribution from this mechanism could account for

the observed discrepancy at large angles. A chi-square analysis of the discrepancy between theory and experiment was performed at 18.8 MeV and 21.2 MeV. The possibility of a contribution from a direct process was supported by an increase in the discrepancy with energy.

In summary, the calculation is consistent with experiment in predicting similar angular distributions for both isomeric products. The reason for this similarity is that the ground state can be populated by states whose spins can be as large as $7/2$ following the emission of the penultimate gamma ray. The corresponding spins of states prior to the photon cascade can be substantially larger and competitive gamma ray emission predominates.

In order to determine if the effect of spin fractionation can at all be seen in angular distribution measurements of isomeric (α, n) reactions, the calculation was performed for a more favorable case. We chose a hypothetical pair of isomers with metastable and ground-state spins of 2 and 0, respectively. The parameters for the $^{134}\text{Ba}(\alpha, n)$ reaction were used and the bombarding energy was 4 MeV above the $(\alpha, 2n)$ reaction threshold. The results are shown in fig. 6. The angular distributions of the two isomers are now strikingly different showing the dependence of competitive gamma ray emission on the angular momentum of the residual nucleus. We plan to further investigate the possibility of observing this interesting phenomenon experimentally.

B. Average Neutron and Photon Energies

A relation between angular distribution data, the average total kinetic energy of emitted neutrons, T_n , and the average total photon energy, T_γ , has been derived by Kaplan and Subrahmanyam¹⁴⁾ in a

reformulation of an earlier analysis performed by Simonoff and Alexander¹⁵⁾. Kaplan related the mean square tangent of the recoil angle in the laboratory system, $\langle \tan^2 \theta_L \rangle$, to the velocity of the compound nucleus, v_{CN} , and the mean square velocity imparted to the product nucleus during the evaporation process, $\langle v^2 \rangle$. The relation is given below:

$$\langle \tan^2 \theta_L \rangle = \sum_{n=1}^{\infty} \frac{2 \langle v^{2n} \rangle}{(2n + 1) v_{CN}^{2n}} \quad (3)$$

The mean square tangent was computed according to a relation given by Kaplan¹⁴⁾. The value of $\langle v^2 \rangle$ is obtained from this equation by an iterative solution. Once $\langle v^2 \rangle$ is known, T_n can be found from¹⁵⁾

$$T_n = \frac{1}{8} \langle v^2 \rangle (M_T + M_b + M_R)^2 \quad (4)$$

Finally, T_Y is obtained as the difference between the total available energy and T_n :

$$T_Y = (E_{cm} + Q) - T_n \quad (5)$$

The results of this analysis are summarized in Table III and the average neutron and photon energies are plotted as a function of the available energy in fig. 7. The most striking feature of the results is the difference in the values of T_n or T_Y associated with the formation of the two isomers. It is seen that the values of T_Y for reactions leading to ^{137m}Ce are about 0.5 MeV larger than those for ^{137g}Ce . This result is a consequence of the difference in the angular momentum of the compound nuclei leading to the two isomers and of the relation between the photon energy and angular momentum. This relation is based

on the assumption that the classical rotational energy of the compound nucleus, $E_{\text{ROT}} = J_c(J_c + 1)\hbar^2/2\mathcal{I}$, is not available for particle evaporation but is instead dissipated by γ -ray emission. On this basis the expected difference between the values of T_γ for the two isomers is

$$\Delta T_\gamma = E_{\text{ROT}}^m - E_{\text{ROT}}^g \quad (6)$$

where the average rotational energies are those of compound nuclei leading to $^{137\text{m}}\text{Ce}$ or $^{137\text{g}}\text{Ce}$.

The average angular momenta of compound nuclei leading to each isomer were obtained from the spin-dependent statistical theory using the code described in the previous section. These values were in turn used to obtain the difference in rotational energies of the compound nuclei leading to the two isomers. The resulting curve is shown in fig. 8 where it is compared with the experimental values of ΔT_γ . The experimental and theoretical values are seen to be in fairly good agreement confirming the above interpretation of the observed difference.

5. Conclusions

Angular distributions of recoil nuclei from (α, n) reactions have been determined experimentally and compared to the results of a spin-dependent statistical model calculation. The calculation correctly predicts a peak at 0° in the differential cross section in the laboratory system and qualitatively predicts the shape of the angular distribution. The discrepancy between experiment and calculation in the magnitude of the differential cross section at large angles may reflect a small contribution from a direct interaction process. An angular distribution

calculation for a hypothetical nucleus suggests that it may be possible to observe spin fractionation experimentally although the present system is not sufficiently favorable for this purpose. The average neutron and photon energies were calculated and the differences between the values obtained for the two isomers are consistent with the difference in the average angular momenta of the compound nuclei leading to these products.

The cooperation of M. Oselka and the operating crew of the Argonne cyclotron is appreciated.

Table I: Summary of experimental angular distributions

Bombarding Energy (MeV)	$\theta_{\min}$ (degrees)	$\theta_{\max}$ (degrees)	$\langle\theta\rangle$ (degrees)	$^{134}\text{Ba}(\alpha, n)$ $\left(\frac{d\sigma}{d\Omega}\right)_m$ (Arbitrary units)	$^{134}\text{Ba}(\alpha, n)$ $\left(\frac{d\sigma}{d\Omega}\right)_g$ (Arbitrary units)	$^{135}\text{Ba}(\alpha, 2n)$ $\left(\frac{d\sigma}{d\Omega}\right)_m$ Arbitrary units)	$^{135}\text{Ba}(\alpha, 2n)$ $\left(\frac{d\sigma}{d\Omega}\right)_g$ Arbitrary units)
18.8	0.0	2.30	1.15	$1.99 \cdot 10^4$	$3.97 \cdot 10^4$		
	2.30	4.58	3.44	$1.98 \cdot 10^4$	$3.91 \cdot 10^4$		
	4.58	6.86	5.72	$1.64 \cdot 10^4$	$3.10 \cdot 10^4$		
	6.86	9.11	7.99	$1.25 \cdot 10^4$	$2.77 \cdot 10^4$		
	9.11	11.34	10.22	$7.79 \cdot 10^3$	$1.98 \cdot 10^4$		
	11.34	13.53	12.43	$4.79 \cdot 10^3$	$1.31 \cdot 10^4$		
	13.53	15.68	14.60	$2.60 \cdot 10^3$	$7.82 \cdot 10^3$		
	15.68	17.78	16.73	$1.63 \cdot 10^3$	$4.47 \cdot 10^3$		
	17.78	19.84	18.81	$8.08 \cdot 10^2$	$1.87 \cdot 10^3$		
	19.84	21.85	20.85	$6.24 \cdot 10^2$	$1.94 \cdot 10^3$		
21.2	0.0	2.41	1.20	$5.32 \cdot 10^4$	$1.86 \cdot 10^4$	$6.80 \cdot 10^4$	$8.83 \cdot 10^4$
	2.41	4.81	3.61	$4.82 \cdot 10^4$	$3.61 \cdot 10^4$	$6.60 \cdot 10^4$	$8.75 \cdot 10^4$
	4.81	7.19	6.00	$3.90 \cdot 10^4$	$2.45 \cdot 10^4$	$5.12 \cdot 10^4$	$5.78 \cdot 10^4$
	7.19	9.55	8.37	$3.32 \cdot 10^4$	$1.92 \cdot 10^4$	$3.29 \cdot 10^4$	$4.64 \cdot 10^4$
	9.55	11.87	10.71	$2.23 \cdot 10^4$	$1.50 \cdot 10^4$	$2.16 \cdot 10^4$	$3.10 \cdot 10^4$
	11.87	14.16	13.02	$1.30 \cdot 10^4$	$1.51 \cdot 10^4$	$1.20 \cdot 10^4$	$1.85 \cdot 10^4$
	14.16	16.40	15.28	$7.45 \cdot 10^3$	$8.20 \cdot 10^3$	$8.36 \cdot 10^3$	$1.14 \cdot 10^4$
	16.40	18.59	17.50	$3.94 \cdot 10^3$	$5.09 \cdot 10^3$	$4.50 \cdot 10^3$	$8.00 \cdot 10^3$
	18.59	20.73	19.66	$2.21 \cdot 10^3$	$2.56 \cdot 10^3$	$2.20 \cdot 10^3$	$5.01 \cdot 10^3$
	20.73	22.81	21.77	$1.38 \cdot 10^3$	$2.08 \cdot 10^3$	$1.47 \cdot 10^3$	$3.02 \cdot 10^3$

Table I: Summary of experimental angular distributions (continued)

24.5	0.0	2.51	1.26	$4.18 \cdot 10^4$	$4.57 \cdot 10^4$	$6.55 \cdot 10^4$	$8.89 \cdot 10^4$
	2.51	5.01	3.76	$4.22 \cdot 10^4$	$3.81 \cdot 10^4$	$6.36 \cdot 10^4$	$7.80 \cdot 10^4$
	5.01	7.50	6.25	$3.78 \cdot 10^4$	$2.47 \cdot 10^4$	$4.90 \cdot 10^4$	$6.30 \cdot 10^4$
	7.50	9.95	8.72	$2.93 \cdot 10^4$	$2.19 \cdot 10^4$	$3.45 \cdot 10^4$	$4.90 \cdot 10^4$
	9.95	12.37	11.16	$2.53 \cdot 10^4$	$2.11 \cdot 10^4$	$2.30 \cdot 10^4$	$3.40 \cdot 10^4$
	12.37	14.74	13.56	$1.73 \cdot 10^4$	$1.85 \cdot 10^4$	$1.35 \cdot 10^4$	$2.20 \cdot 10^4$
	14.74	17.07	15.91	$1.07 \cdot 10^4$	$1.12 \cdot 10^4$	$8.40 \cdot 10^3$	$1.43 \cdot 10^4$
	17.07	19.33	18.20	$6.58 \cdot 10^3$	$1.11 \cdot 10^4$	$5.00 \cdot 10^3$	$8.40 \cdot 10^3$
	19.33	21.54	20.44	$4.08 \cdot 10^3$	$4.40 \cdot 10^3$	$2.70 \cdot 10^3$	$5.10 \cdot 10^3$
	21.54	23.68	22.61	$2.81 \cdot 10^3$	$2.45 \cdot 10^3$	$1.71 \cdot 10^3$	$3.10 \cdot 10^3$

Table II: Effects of target thickness and collimator size on the
average angle at 18.8 MeV

Bombarding Energy (MeV)	Target Thickness ($\mu\text{g}/\text{cm}^2$)	Collimator size (cm)	$\langle\theta\rangle_{Lm}$ (degrees)	$\langle\theta\rangle_{Lg}$ (degrees)
18.8	12.47	0.32	8.64	9.48
18.8	5.89	0.32	8.82	9.46
18.7	12.96	0.16	9.09	9.17

Table III: Values of some average quantities determined in
angular distribution measurements

Bombarding Energy (MeV)	Measured $\langle \theta_L \rangle$ (degrees)	θ_{Lmax} (degrees)	$\langle \tan^2 \theta_L \rangle$	$E_{cm} + Q$ (MeV)	T_n (MeV)	T_Y (MeV)
^{137m}Ce						
18.8	8.64	21.8	0.0305	9.9	3.3	6.6
21.2	9.33	22.8	0.0352	12.2	4.3	7.9
24.5	10.86	23.7	0.0472	15.4	6.6	8.8
^{137g}Ce						
18.8	9.48	21.8	0.0362	10.1	3.9	6.2
21.2	10.65	22.8	0.0449	12.4	5.4	7.0
24.5	11.19	23.7	0.0492	15.6	6.9	8.7

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Figures

- Figure 1 Schematic neutron energy spectrum illustrating the effect of competition between the (α, n) and $(\alpha, 2n)$ reactions. The maximum excitation energy of the residual nucleus, E_{Rmax} , is greater than S_{n_2} , the separation energy for a second neutron. The solid line represents the energy spectrum for the first neutron emitted. The (--) and (-.-) lines represent the energy spectrum of the (α, n) reaction neutron leading to the metastable and ground state isomers, respectively.
- Figure 2 Effect of target thickness and collimator size on the angular distribution of the $^{134}\text{Ba}(\alpha, n)$ reaction products at 18.8 MeV. O-0.32 cm. collimator, $10 \mu\text{g}/\text{cm}^2$ target; $\square$ -0.32 cm collimator, $5 \mu\text{g}/\text{cm}^2$ target; Δ -0.16 cm collimator, $10 \mu\text{g}/\text{cm}^2$ target. Open points refer to the metastable product and shaded points represent the ground state.
- Figure 3 Comparison of the theoretical and experimental angular distributions at 18.8 MeV. O- experimental points for ^{137m}Ce ; $\bullet$ - experimental points for ^{137g}Ce . The theoretical calculation for the ground and metastable states is represented by the dot-dash (-.-) and dashed line (--), respectively. The experimental and theoretical angular distributions have been normalized to equal areas. There is no significance in the relative positions of the metastable and ground state curves. The vertical line is drawn at the maximum recoil angle.

Figures (continued)

- Figure 4 Angular distribution for the $^{134}\text{Ba}(\alpha, n)$ reaction at 21.3 MeV.
See fig. 3 for details.
- Figure 5 Angular distribution for the $^{134}\text{Ba}(\alpha, n)$ reaction at 24.5 MeV.
See fig. 3 for details.
- Figure 6 Angular distribution for a hypothetical pair of isomers with angular momenta of 2 (—) and 0 (---), formed in an (α, n) reaction.
- Figure 7 Average neutron ($\square$) and photon (O) energies calculated from the experimental angular distributions for the $^{134}\text{Ba}(\alpha, n)$ reaction. Open symbols refer to ^{137g}Ce and closed ones to ^{137m}Ce .
- Figure 8 Difference between T_Y values associated with the formation of ^{137m}Ce and ^{137g}Ce . The solid curve gives the calculated difference between the rotational energies of compound nuclei leading to these two isomers.

Fig 1

$\frac{d\sigma}{d\Omega}$
(arbitrary
units)

Fig 4

Fig 5

Fig 6