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AEC Contract No. AT(11-1)-1505

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Recoil Ranges, Excitation Functions, and Isomer Ratios
for the $^{136}\text{Ba}(^4\text{He},3\text{n})$ and $^{137}\text{Ba}(^3\text{He},3\text{n})$ Reactions *

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Average projected ranges and cross sections for the production of $^{137\text{m}}\text{Ce}$ and $^{137\text{g}}\text{Ce}$ from the $^{136}\text{Ba}(^4\text{He},3\text{n})$ and $^{137}\text{Ba}(^3\text{He},3\text{n})$ reactions have been measured over the energy intervals 27-44 MeV and 14-33 MeV, respectively. The average ranges were found to be consistent with a compound nuclear process over the entire energy interval for both reactions. The isomer ratios were compared with a calculation based on the spin-dependent statistical theory and good agreement was obtained for reasonable values of the parameters of interest. Comparison is made with previous measurements and various discrepancies are discussed.

*Supported by the U. S. Atomic Energy Commission

⁺Submitted in partial fulfillment of the requirements for the Ph.D. degree in the Department of Chemistry, Purdue University

I. Introduction

One of the underlying assumptions of compound nuclear reactions is that the decay of the compound nucleus is independent of its mode of formation. This independence hypothesis was first tested by Ghoshal¹ by means of excitation function measurements for reactions involving the formation of a particular compound nucleus in two different ways. This type of experiment is not particularly sensitive to the details of the de-excitation process since the yield of the observed product is an integral over many such processes. Moreover, recent experiments of this type^{2,3} indicate that angular momentum effects can complicate the interpretation of the results. A more sensitive test of the independence hypothesis involves a comparison of the energy spectra of particles emitted by a given compound nucleus formed in different ways. A recent study⁴ confirmed the independence hypothesis on the basis of the energy spectra of protons and α -particles emitted from the compound nucleus ^{75}Br , formed with ^{12}C and ^{16}O ions.

In the present work the independence hypothesis is tested by means of a different experiment than those that have been used heretofore: the angular distribution of the recoil product of a compound nuclear reaction. Such a measurement permits a determination of the average total kinetic energy of the emitted nucleons and photons.⁵ A sensitive test of the independence hypothesis can be performed if this energy partition is determined for a particular de-excitation mode of a compound nucleus formed in two different ways.

The reactions selected for this work were the $^{136}\text{Ba}(^4\text{He},3n)$ and $^{137}\text{Ba}(^3\text{He},3n)$. The product consists of an isomeric pair, $^{137m}\text{Ce}(t_{1/2} = 34.4 \text{ h}, I\pi=11/2^+)$ and $^{137g}\text{Ce}(t_{1/2} = 9.0 \text{ h}, I\pi=3/2^-)$. The use of ^4He and ^3He projectiles minimizes the difference in the angular momenta of the respective compound nuclei. The study of a reaction involving isomeric products simplifies the evaluation of angular momentum effects and is also of intrinsic interest for a more complete understanding of such effects in compound nuclear reactions.

In order to test the independence hypothesis it must first be established that the reactions in question proceed via compound nucleus formation. We have measured the average projected ranges of the reaction products in order to determine the energy interval where the compound nuclear process predominates. In the course of performing these measurements, the excitation functions and isomer ratios were also determined and the latter were compared with the spin-dependent statistical theory. The results of the range, excitation function, and isomer ratio measurements are presented here. The test of the independence hypothesis by means of angular distribution measurements is described in the following paper.⁶

The excitation functions and isomer ratios for the $^{136}\text{Ba}(^4\text{He},3n)$ reaction have previously been measured by Kiefer and Street⁷(KS) and by Matsuo et al.⁸(MM). There were a number of discrepancies between their results. The isomer ratios reported by KS were about 30% lower than those of MM. In addition, a shift of approximately 3 MeV in the bombarding energy scale is necessary to obtain agreement between their cross sections. The report of MM also includes a measurement of the average recoil ranges and that of KS includes the isomer ratios and cross sections for the $^{137}\text{Ba}(^3\text{He},3n)$ reaction.

II. Experimental

The average range measurements were performed in the same manner as reported in previous communications from this laboratory.^{9,10} The target assembly consisted of the conventional stacked-foil arrangement with 6-8 targets and corresponding catchers. The target stack also included additional aluminum foils of various thicknesses to degrade the ^3He or ^4He beam. The energy of the beam at various positions along the target assembly was calculated from the incident beam energy and an appropriate range-energy relationship.¹¹ The target stack was mounted in an evacuated water-cooled target holder which also served as a Faraday cup for measurement of beam current.

The irradiations were performed with the ^3He and ^4He beams of the 60-inch cyclotron at Argonne National Laboratory for periods of 1 to 2 hours. The beam intensity was limited to less than 0.3 μamp because the $\text{Ba}(\text{NO}_3)_2$ targets tended to melt and fuse at higher beam currents.

Enriched ^{136}Ba (92.9%) and ^{137}Ba (89.6%) were obtained from Oak Ridge National Laboratory. The targets were prepared from this material by electrophoresis of a fine suspension of $\text{Ba}(\text{NO}_3)_2$ in acetone onto 0.0025 cm pure Al using a modification of a procedure described by Björnholm.¹² Target thicknesses were determined by weighing a known area and averaged about 1 mg/cm^2 . Catcher foils were 0.0025 cm thick aluminum of high purity (99.999%).

After irradiation the Ce activities were separated using a modification of a previously described chemical procedure.¹³ The targets and catchers were dissolved in a mixture of HCl and HNO_3 containing Ce^{+3}

and La^{+3} carriers. The Ce^{+3} was oxidized to Ce^{+4} and precipitated with 6 M NaOH. The $\text{Ce}(\text{OH})_4$ was washed, dissolved in a mixture of HNO_3 and NaBrO_3 , extracted into methyl isobutyl ketone, and then back-extracted into H_2O containing a few drops of H_2O_2 . The Ce^{+3} was precipitated as $\text{Ce}_2(\text{C}_2\text{O}_4)_3 \cdot 9\text{H}_2\text{O}$ and weighed to determine the chemical yield.

The decay of the ^{137}Ce activities was determined with several thin NaI(Tl) detectors having beryllium windows. The detectors were used in conjunction with single channel analyzers set to accept the K-x-rays from La and Ce. The x-ray detectors were calibrated with ^{137}Ce samples that had been standardized with an x-ray detector of known efficiency. Differences in efficiency due to self absorption of the x-rays were found to be negligible for sample thicknesses ($\sim 9 \text{ mg/cm}^2$) used in this work.

The decay scheme¹⁴ of $^{137\text{m,g}}\text{Ce}$ is shown in Figure 1. Cerium K-x-rays from the metastable product result from the 255 keV transition. Taking the internal conversion coefficient¹⁴ and fluorescence yield¹⁴ into account, there are 0.53 K-x-rays per disintegration. In the case $^{137\text{g}}\text{Ce}$, the x-rays result from the decay by electron capture to ^{137}La . Neglecting the x-rays from the internal conversion of the 446 keV γ -ray ($\sim 0.04\%$) and using a value¹⁴ of 0.86 for the fraction of electron-capture transitions occurring as K-capture, the number of K-x-rays per disintegration is 0.76.

The decay curves were analyzed by a least squares program appropriate to the particular parent-daughter system of interest, described in a recent publication from this laboratory.¹⁵ This program also calculated the cross sections and average projected ranges from the disintegration rates and included a correction for decay of $^{137\text{m}}\text{Ce}$ during irradiation.

III Results

The average recoil range projected in the direction of the beam is given by

$$R_P = FW \quad (1)$$

where F is the fraction of the total activity due to a given nuclide found in the catcher foil and W is the target thickness. The application of Eq. 1 is based on the assumption that the production cross section is constant throughout the target. This assumption is valid in view of the negligible energy degradation of the beam in the thin targets used in this experiment. The experimental results for the average projected ranges, cross sections, and isomer ratios for the $^{136}\text{Ba}(^4\text{He}, 3n)$ and $^{137}\text{Ba}(^3\text{He}, 3n)$ reactions are given in Table 1.

The standard deviations of the isomer ratios in Table 1 were obtained from a least squares fit to the decay data. They only represent the statistical uncertainty in the activity measurements and do not reflect possible systematic errors in the decay scheme. The standard deviations from the least squares fit were less than 5% in all cases. The cross section and average range measurements are subject to errors in target thicknesses and gravimetric yields as well as the statistical uncertainties in the activities. Target thicknesses are not expected to vary more than 10% in uniformity. The uncertainties in chemical yields are probably less than 5%. The random errors from all sources for the cross sections and average ranges are estimated to be less than 15%.

Contributions to the ^{137}Ce activities in the ^3He bombardments are possible from the $^{138}\text{Ba}(^3\text{He}, 4n)$ reaction which has a Q value of -19.5 MeV. The enriched ^{137}Ba contained 9.6% ^{138}Ba as compared with 17.4%

in the work of KS.⁷ They estimated a maximum contribution of 5 mb due to ^{138}Ba . The contribution due to ^{138}Ba should consequently be only about half this amount in the present work and it has been neglected.

The total cross sections for the $^{136}\text{Ba} (^4\text{He}, 3n)$ and $^{137}\text{Ba} (^3\text{He}, 3n)$ reactions are plotted and compared with previous measurements in figures 2 and 3. The excitation function for the $(^4\text{He}, 3n)$ reaction has its maximum at about the same energy as that of KS, but at about 3 MeV above that reported by MM. It would appear that the energy calibration of the cyclotrons used by MM differs significantly from that of KS and the present work. The shape of the $(^3\text{He}, 3n)$ excitation function agrees fairly well with the work of KS.

A striking discrepancy between the present work and the earlier reports is the difference in the magnitude of the cross sections. The $(^4\text{He}, 3n)$ excitation function rises to its maximum of about 1300 mb at 39 MeV. This value is about 2.0 and 2.5 times larger than the maximum values reported by MM and KS, respectively. The $(^3\text{He}, 3n)$ excitation function has a maximum cross section of 560 mb at 25 MeV which is about twice the corresponding peak value from the work of KS. These differences can largely be attributed to the different counting techniques and corresponding radiation abundances used in the various studies. We refer to Fig. 1 for a discussion of the various radiations that have been used to detect $^{137\text{m,g}}\text{Ce}$. The radioactivity measurements of MM were based on the L-x-rays of $^{137\text{m,g}}\text{Ce}$ while these of KS involved the 446 keV γ -ray from the decay of $^{137\text{g}}\text{Ce}$.

In order to resolve the difference between the present results and those of KS the disintegration rates of several $^{137\text{m,g}}\text{Ce}$ samples were determined from measurements of both the 446 keV γ -ray and K x-rays.

The intensity of the 446 keV photons was assayed with a calibrated 3 x 3 inch NaI(Tl) detector. The disintegration rates of the ^{137}Ce isomers were found to be 30% lower than those obtained from the K x-ray measurements. In order to bring the γ -ray measurements into agreement with K x-ray results it is necessary to assume a branching ratio of 1.8% for the population of the 446 keV level in ^{137}La instead of the adopted¹⁴ value of 2.3%. Since KS used an even higher branching ratio of 3% in computing their cross sections, most of the discrepancy can be attributed to this difference.

The discrepancy with the results of MM can be attributed to the adopted value of the L-shell fluorescence yield, ω_L . The MM cross sections are inversely proportional to ω_L and there are conflicting values in the literature, $\omega_L^{16} = 0.092$ and $\omega_L^{17} = 0.17$. The work of MM assumed a value of 0.17 for ω_L . Their ($^4\text{He}, 3n$) peak cross section would be approximately the same as the present value if $\omega_L = 0.092$ were used instead.

Another factor suggesting that the present cross sections are valid is that the ($^4\text{He}, 3n$) peak cross sections reported by KS and MM correspond to only 0.26 and 0.35 of the total reaction cross section, respectively. By contrast, the present results indicate that at peak energies this reaction accounts for 65% of the total reaction cross section. In arriving at these estimates the total reaction cross section was computed on the basis of the optical model by use of the ABACUS-2 code.¹⁸ Previous measurements of ($^4\text{He}, 3n$) reaction cross sections in the mass region of interest indicate that at peak energies this reaction accounts for 60-70% of the total reaction cross section.^{19,20}

A comparison of the various isomer ratio measurements is shown in Figure 4. In the case of the ($^4\text{He}, 3n$) reaction, the isomer ratios of MM are from 30% to 50% higher than our values. The values of KS agree fairly well with the present values below about 40 MeV, but become larger at higher energies. There is good agreement between the isomer ratios for the ($^3\text{He}, 3n$) reaction as reported by KS and the present work over the entire energy range.

IV. Discussion

A. Comparison of Average Ranges with Compound Nuclear Values

The average projected ranges for the ($^4\text{He}, 3n$) and ($^3\text{He}, 3n$) reactions are plotted as a function of projectile energy in Figure 5 and may be compared with values based on a compound nuclear mechanism. Reactions of this type involve complete momentum transfer from projectile to compound nucleus. The product nucleus recoils with an average kinetic energy given by the formula

$$E_R = E_B \frac{A_B A_R}{(A_T + A_B)^2} \quad (2)$$

where E_R is the recoil energy, E_B the bombarding energy, and A_T , A_B , and A_R are the masses of the target, bombarding particle, and recoil nucleus, respectively. Theoretical ranges represented by the dashed lines in Figure 5 are based on the stopping theory of Lindhard, Scharff, and Schiøtt (LSS)²¹ and refer to a $\text{Ba}(\text{NO}_3)_2$ stopping medium. The LSS ranges were corrected for the effect of neutron evaporation as described elsewhere²² and are represented by solid lines in Figure 5. The corrections increased the ranges by as much as 6 and 12 per cent for the ^4He and ^3He induced reactions, respectively. The average ranges of both the ($^4\text{He}, 3n$) and ($^3\text{He}, 3n$) reaction products increase with bombarding energy in a manner that parallels the energy dependence of the corrected LSS curves although the actual values are some 10% larger than the latter. If direct interactions made significant contributions to these reactions, the ranges would be substantially lower than the LSS values and would not increase with bombarding energy. Both reactions thus appear to be compound nuclear over the energy range studied. The discrepancy with the LSS theory is comparable in magnitude to that found in previous studies.¹⁵

Also included in Figure 5 are the average projected ranges reported by MM.⁸ Although these data differ by as much as 40% from the present values and scatter pronouncedly, the overall trend is similar to that reported here.

B. Comparison of the Excitation Functions of ^3He and ^4He Induced Reactions.

A comparison of the ($^4\text{He}, 3n$) and ($^3\text{He}, 3n$) reaction cross sections can be used to determine the relative importance of compound nucleus formation in ^3He - and ^4He -induced reactions. Let us assume that the compound nucleus formation cross section, σ_{CN} , is in each case equal to the total reaction cross section, σ_{R} . If this assumption is valid then, according to the independence hypothesis, the cross-section ratios, $\sigma(^4\text{He}, 3n)/\sigma_{\text{R}}(^4\text{He})$ and $\sigma(^3\text{He}, 3n)/\sigma_{\text{R}}(^3\text{He})$, should be equal to each other provided the comparison is made at the same excitation energy of the respective compound nuclei. For the purposes of this comparison it is reasonable to neglect the minor differences expected because of the different angular momentum distributions of the compound nuclei.

The results of this comparison are shown in Figure 6. It is seen that the values of σ/σ_{R} tend to be larger for the ^4He -induced reaction. The peak values of the ratios thus are 0.64 for ^4He and 0.43 for ^3He . This difference is most readily explained on the basis of a greater contribution of direct processes to the ^3He total reaction cross section, thereby making the quantity $\sigma_{\text{CN}}(^3\text{He})/\sigma_{\text{R}}(^3\text{He})$ smaller than $\sigma_{\text{CN}}(^4\text{He})/\sigma_{\text{R}}(^4\text{He})$. This behavior can be understood in view of the

greater likelihood of stripping or pickup reactions for a ^3He projectile. In this we corroborate the results of other studies.^{20,23}

C. Comparison of Isomer Ratios with the Statistical Theory.

In this section the measured isomer ratios are compared with the spin-dependent statistical theory. The calculation is based on the formalism first developed by Vandenbosch and Huizenga²⁴ as modified by Dudey and Sugihara²⁵ to include the effects of charged particle emission and limiting spin.

The calculation involves the determination of the angular momentum distribution of the compound nucleus, and the subsequent modifications introduced in this distribution by particle and photon emission. The angular momentum distribution of the compound nucleus was obtained in straightforward fashion with the aid of optical model transmission coefficients generated by the ABACUS-2 code.¹⁸ The probability for the decay of the compound nucleus by particle emission was calculated by means of the computer code EVAMCO,²⁶ which evaluates the following equation based on the spin-dependent statistical model:

$$P(v, E_f, J_f) = \sum_{J_c} \frac{\Omega_v(E_f, J_f) P(E_c, J_c) \sum_{\epsilon} \sum_{\ell} S_v \ell T_{\ell}(\epsilon_v)}{\sum_{J_c} \sum_{\nu} \sum_{J_f} \sum_{\epsilon} \Omega_v(E_f, J_f) \sum_{\ell} S_v \ell T_{\ell}(\epsilon_v)} \quad (3)$$

where E and J are excitation energy and angular momentum with the subscripts f and c referring to the residual and compound nuclei, respectively; $T_{\ell}(\epsilon_v)$ is the transmission coefficient for particle v with channel energy ϵ_v and orbital angular momentum ℓ , $\Omega(E, J)$ is the level density and S the channel spin. The quantity $P(E_c, J_c)$ is the normalized angular momentum distribution of the compound nucleus.

In the present work we have considered neutrons, protons, and alphas as competing modes of particle emission. Previous calculations^{24,25} assumed that the evaporated particles were emitted with an average kinetic energy given by evaporation theory. In the present calculation both the angular momentum and excitation energy distributions of the residual nucleus are evaluated. However, in order to permit the recursive use of Eq. 3, the distribution of excitation energies is replaced by an average excitation energy. The averaging process takes place after particle emission and is expected to introduce a smaller perturbation in the distribution of J_f values than was the case in previous^{24,25} calculations. The average excitation energy of the residual nucleus was determined by averaging over those nuclei which have enough excitation energy to evaporate an additional neutron. The average excitation energy is thus given by

$$\begin{aligned} E_f &= E_{\max} \\ \bar{E}_f &= \frac{\sum_{J_f} \sum_{E_f = S_n} P(v, E_f, J_f) \cdot E_f}{\sum_{J_f} \sum_{E_f = S_n} P(v, E_f, J_f)} \end{aligned} \quad (4)$$

where $E_{\max}$ is the maximum excitation energy of the residual nucleus, and S_n is the separation energy of a neutron from this nucleus. The angular momentum distribution for a nucleus with average excitation energy $\bar{E}_f$ is then given by

$$\begin{aligned} E_f &= E_{\max} \\ P(v, \bar{E}_f, J_f) &= \sum_{E_f = S_n} P(v, E_f, J_f) \end{aligned} \quad (5)$$

The distribution $P(v, \bar{E}_f, J_f)$ is then substituted for $P(E_c, J_c)$ in Eq. 3 to generate a new distribution $P(v, E_f, J_f)$. This process is repeated until three neutrons have been evaporated to give a final distribution $P(\bar{E}_f, J_f)$. This distribution is next used to calculate the angular momentum distribution following γ -ray emission by use of a program²⁷ based on the Vandenbosch-Huizenga formalism.²⁴ The number of emitted γ -rays is obtained from a relation derived by Strutinsky et al²⁸ and the photon cascade is restricted to dipole radiation. The last γ -ray is assumed to populate the isomeric state which requires the smallest spin change. Transmission coefficients were calculated from the ABACUS-2 computer program.¹⁸ Optical model parameters were taken from Huizenga and Igo²⁹ (α particles) and Hodgson³⁰ (neutrons, protons, and ^3He particles).

The calculation uses a level density expression based on the Fermi gas model and the assumption of random coupling of angular momenta³¹:

$$\Omega(E, J) = \frac{(2J + 1)}{\pi^{1/2} (2\sigma^2)^{3/2}} B(E + t)^{-5/4} \exp[2(aE)^{1/2} - J(J + 1)/2\sigma^2] \quad (6)$$

The excitation energy was corrected for pairing effects and the values of the pairing energy, as well as that of the level density parameter, a , were taken from the compilation of Gilbert and Cameron.³² The nuclear temperature was calculated from the equation of state, $E = at^2 - t$ for $E \geq 10$ MeV. At lower energies t was set equal to a constant value of 0.65 MeV.³² The spin cutoff parameter, σ^2 , is related to the effective moment of inertia as $\sigma^2 = \mathcal{J}t/\hbar^2$. The quantity B in Eq. 6 is a constant.

The moment of inertia can be regarded as an adjustable parameter since its value is expected³³ to be less than the rigid body value $\mathcal{J}_r$ at low excitation energies. We have followed the approach of Dudey and Sugihara²⁵ and treated $\mathcal{J}/\mathcal{J}_r$ as an adjustable parameter for $E \leq 10$ MeV. At higher excitation energies this ratio was set equal to unity.

Equation 6 predicts the occurrence of levels with arbitrarily large J values at a given excitation energy but both theory and experiment indicate that there is a maximum possible J value for a given E . A number of estimates of $J_{\max}$ have been given in the literature and the subject has recently been reviewed by Thomas.³⁴ The expression

$$J_{\max} = \frac{(18 E \hbar^2)^{1/2}}{\pi \hbar} \quad (7)$$

is based on the Fermi gas model and may be readily incorporated in the present calculation. This value of $J_{\max}$ is also nearly equal to the value obtained from the rotational energy formula, used in previous studies.^{16,35} The level density was consequently calculated by Eq. 6 for $J \leq J_{\max}$ while for larger J values $\Omega(E, J)$ was set equal to zero. The sensitivity of the results to the particular choice of $J_{\max}$ was explored by varying the value of this quantity. The introduction of a limiting spin into the calculation also has the effect of introducing competitive γ -ray emission a simple way.

The results of the calculation are summarized in Figure 7. An excellent fit to the experimental isomer ratios is obtained by use of the $\mathcal{I}/\mathcal{I}_r$ values shown in the top half of the figure. The values of $\mathcal{I}/\mathcal{I}_r$ are approximately 0.35 at all bombarding energies and consequently also at all excitation energies from 3 to 10 MeV. It is gratifying to note that the isomer ratios for both the ^3He and ^4He induced reactions can be fit with the same values of $\mathcal{I}/\mathcal{I}_r$.

The values of $\mathcal{I}/\mathcal{I}_r$ from our work are lower than those derived for these same reactions by previous workers. Dudey and Sugihara²⁵ fit the data of Matsuo et al.⁸ for the ($^4\text{He}, 3n$) reaction with $\mathcal{I}/\mathcal{I}_r$ values that ranged from 0.4 at 34 MeV to 0.9 at 40 MeV. It should be pointed out, however, that the present isomer ratios are lower than those of

M and so require smaller values of J . In addition, the values of I/I_r reported by Dudev and Sugihara²⁵ are based on a smaller value of $J_{\max}$ than is used in the present work. As is shown presently, this is equivalent to the use of a larger moment of inertia. Kiefer and Street⁷ found a best fit to their isomer ratios with $I/I_r = 0.5$. However, their calculation was based on a different formalism so that comparison with the present values is probably not very meaningful.

The sensitivity of the calculation to some of the parameters of interest was explored and the results are summarized in Figure 8. The effect of a limiting spin was explored by 1. calculating $J_{\max}$ from Eq. 7; 2. using a value previously employed by Dudev and Sugihara²⁵: $J_{\max}(\text{DS}) = J_{\max}/\sqrt{3}$; 3. calculating the level density by Eq. 6 for all J , thereby neglecting this effect. The calculations were performed for the ($^4\text{He}, 3n$) reaction at 35 MeV for various values of I/I_r . It is seen that the calculated isomer ratios show a pronounced direct dependence on both $J_{\max}$ and I/I_r . A given experimental value can thus be fit by a combination of large I/I_r and small $J_{\max}$ or vice-versa. It is therefore impossible to simultaneously determine the values of both parameters.

The effect of a constant nuclear temperature below 10 MeV was also investigated. Figure 8b compares the results at 35 MeV for temperatures of 0.65 and 0.50 MeV. The latter value was used in a previous calculation.²⁵ The dependence of the isomer ratio on the nuclear temperature is seen to be moderate. An increase in temperature from 0.50 to 0.65 MeV thus requires a corresponding reduction in I/I_r from 0.41 to 0.33 when $J_{\max}$ is obtained from Eq. 7.

In conclusion, we have shown that the $^{136}\text{Ba}(^4\text{He},3\text{n})$ and $^{137}\text{Ba}(^3\text{He},3\text{n})$ reactions are compound nuclear over the energy interval studied, as evidenced by the average range measurements. The excitation functions differed in magnitude from previous measurements,^{7,8} but peaked at approximately the same energy as reported by KS.⁷ The isomer ratios for both reactions agreed quite well with the results of KS.⁷ Comparison of the $(^4\text{He},3\text{n})$ and $(^3\text{He},3\text{n})$ cross sections reveals that the probability of direct interactions in ^3He -induced reactions is larger than in those induced by ^4He . Comparison of the isomer ratios with the spin-dependent statistical theory gives satisfactory agreement for reasonable values of the various parameters.

The cooperation of M. Oselka and the operating crew of the Argonne National Laboratory 60-inch cyclotron is gratefully acknowledged. We wish to thank Dr. L. Glendenin for the use of his calibrated x-ray detector. The help of D. G. Swanson in some phases of this work is acknowledged. We wish to thank Dr. R. Reedy and Professor J. M. Miller for a copy of the EVAMCO code. The LSS ranges were kindly supplied by Dr. H. E. Schiøtt.

TABLE I

Experimental Cross Sections, Average Ranges, and Isomer Ratios
for the $^{136}\text{Ba}(^4\text{He},3\text{n})$ and $^{137}\text{Ba}(^3\text{He},3\text{n})$ Reactions

Bombarding Energy (MeV)	^{137g}Ce		^{137m}Ce		Isomer Ratio σ_m/σ_g
	$\sigma(\text{mb})$	$R_p(\mu\text{gm}/\text{cm}^2)$	$\sigma(\text{mb})$	$R_p(\mu\text{gm}/\text{cm}^2)$	
Bombardment A $^{137}\text{Ba}(^3\text{He},3n)$					
33.4	76	74	262	83	$3.43 \pm .13$
30.2	96	77	310	86	$3.24 \pm .10$
26.8	130	76	373	77	$2.93 \pm .09$
25.0	158	73	382	74	$2.42 \pm .04$
21.7	164	82	266	81	$1.63 \pm .02$
18.1	88	66	92	63	$1.04 \pm .01$
Bombardment B $^{137}\text{Ba}(^3\text{He},3n)$					
28.6	94	68	354	71	$3.75 \pm .15$
23.4	161	58	372	58	$2.31 \pm .04$
20.0	136	53	204	52	$1.50 \pm .04$
18.2	93	50	107	51	$1.15 \pm .01$
16.2	37	47	33	47	$0.89 \pm .01$
14.2	4.0	41	2.8	42	$0.70 \pm .01$
Bombardment C $^{136}\text{Ba}(^4\text{He},3n)$					
44.2	109	131	947	134	$8.71 \pm .32$
41.4	145	137	1048	144	$7.25 \pm .30$
39.0	185	121	1059	127	$5.71 \pm .40$
36.8	203	110	965	116	$4.76 \pm .37$
34.8	168	115	715	118	$4.26 \pm .19$
32.8	143	115	492	116	$3.43 \pm .08$
29.6	48	94	120	90	$2.51 \pm .08$
27.1	42	94	11.3	95	$2.66 \pm .13$

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FIGURE CAPTIONS

- Fig. 1. Decay scheme of ^{137}Ce .
- Fig. 2. Excitation function for the $^{136}\text{Ba}(^4\text{He},3n)^{137m,g}\text{Ce}$ reaction. Circles, squares, and triangles represent cross sections from this work, ref. 8, and ref. 7, respectively.
- Fig. 3. Excitation function for the $^{137}\text{Ba}(^3\text{He},3n)^{137m,g}\text{Ce}$ reaction. The circles are from this work and the triangles from ref. 7.
- Fig. 4. Isomer ratios for the $(^4\text{He},3n)$ and $(^3\text{He},3n)$ reactions are given in (a) and (b), respectively. The circles are from this work, squares from ref. 8, and triangles from ref. 7.
- Fig. 5. Average projected ranges of the $^{136}\text{Ba}(^4\text{He},3n)$ and $^{137}\text{Ba}(^3\text{He},3n)$ reaction products. The circles represent ^{137m}Ce and the triangles ^{137g}Ce . The squares are from ref. 8. The dashed line is the LSS range-energy relation. The solid line is the LSS range corrected for neutron evaporation.
- Fig. 6. Ratio of experimental cross section to the total reaction cross section as a function of compound nucleus excitation energy. The $(^4\text{He},3n)$ reaction is represented by circles; the $(^3\text{He},3n)$ reaction by triangles.
- Fig. 7. Comparison of theoretical and experimental isomer ratios for the (a) ^4He and (b) ^3He -induced reactions. Solid curve represents the calculated isomer ratio and the symbols are the experimental points. The upper portion of the figure gives the values of $J/\epsilon r$ used to calculate the isomer ratios.
- Fig. 8. Theoretical isomer ratios for the $(^4\text{He},3n)$ reaction at 35 MeV as a function of $J/\epsilon r$ for various values of J_{max} . The squares, circles, and triangles refer, respectively, to methods 1, 2, and 3 for calculating J_{max} as described in the text. In (b) the open symbols refer to $t = 0.65$ MeV and the closed ones to $t = 0.50$ MeV. The horizontal line through the figure represents the experimental isomer ratio.

Fig 1

Fig 2.

Fig. 4

Fig 6

Fig 57