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Decay of the ^{210}Po Compound Nucleus

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Test of the Independence Hypothesis in the

Decay of the ^{210}Po Compound Nucleus

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Abstract: The angular distributions, cross-sections, and recoil ranges of ^{207}Po from the $^{206}\text{Pb}(^4\text{He},3\text{n})$ and $^{207}\text{Pb}(^3\text{He},3\text{n})$ reactions have been measured over the energy intervals 32-44 MeV and 21-33 MeV, respectively. The compound nuclear nature of these reactions was established by comparison of the average ranges with values expected for this mechanism. The angular distributions were used to derive values of the average total kinetic energy of the neutrons and photons emitted in these reactions. The partition of the excitation energy between these two decay modes was found to be equal for the two reactions to within at most 1.5 MeV. The expected difference in energy partition arising from angular momentum differences is approximately 0.5 MeV.

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I. INTRODUCTION

One of the most basic features of compound nuclear reactions is that the excited compound nucleus lives sufficiently long prior to its decay that all correlations between the entrance and exit channels are lost. Only those invariants associated with the conservation laws, such as energy and angular momentum, are preserved during the lifetime of the compound nucleus. The separability of entrance and exit channels is embodied in the independence hypothesis. The first test of this hypothesis was performed by Ghoshal¹ on the basis of excitation function measurements for reactions involving the formation of a particular compound nucleus in two different ways. Experiments of this type are not particularly sensitive to the details of the deexcitation process since the measured cross-section represents an integral over many decay paths. More recent experiments of this type^{2,3} indicate, furthermore, that angular momentum effects can complicate the interpretation of the results. More sensitive verifications of the independence hypothesis and of the role of angular momentum differences have been obtained from measurements of the angular distributions and energy spectra of evaporated particles.⁴⁻⁶

More recently, a different method for testing the independence hypothesis has been described by Montgomery and Porile⁷. These workers measured the angular distribution of $^{137m,g}\text{Ce}$ formed in the $^{136}\text{Ba}(^4\text{He},3n)$ and $^{137}\text{Ba}(^3\text{He},3n)$ reactions. The compound nuclear nature of these reactions was first established by means

of average range measurements. The angular distributions were then analyzed to yield the values of the average total kinetic energy of the emitted neutrons, T_n , and that of the emitted photons, T_γ . The independence hypothesis requires that this energy partition be independent of the specific mode of formation of the ^{140}Ce compound nucleus provided the comparison is made at the same excitation energy and angular momentum of the compound nucleus. The choice of an isomeric reaction product provided a method for determining the effect of angular momentum differences on the energy partition. The above study confirmed that the energy partition of the compound nucleus between neutrons and photons was independent of its mode of formation to within at most 2.5 MeV and indicated that angular momentum differences between the ^3He - and ^4He -induced reactions could affect this partition by about 0.4 MeV.

A similar test of the independence hypothesis is given in the present report for a different mass region than that investigated by Montgomery and Porile.⁷ The reactions of interest are $^{206}\text{Pb}(^4\text{He},3n)$ and $^{207}\text{Pb}(^3\text{He},3n)$, involving the formation and subsequent decay of the ^{210}Po compound nucleus. In order to first establish the compound nuclear character of these reactions the average ranges and excitation functions were determined. The angular distributions were then measured and analyzed to yield the average neutron and photon energies.

2. EXPERIMENTAL

2.1 Cross-Sections and Range Measurements

Targets for these experiments were prepared by electrodeposition of lead to a thickness of 1 mg/cm^2 onto thin nickel foil. The target

material consisted of highly enriched $^{206}\text{Pb}(97.4\%)$ and $^{207}\text{Pb}(92.4\%)^+$.

The recoil catchers were prepared of very pure (99.999%) aluminium foil having a surface density of 5 mg/cm^2 . Stacks consisting of six target-catcher pairs were mounted in a target holder which also served as a Faraday cup for determination of the beam intensity. The catchers were always placed on the downstream side of the lead targets in order to stop the forwardly emitted recoil products.

The irradiations were performed with the deflected ^3He and ^4He beams of the Argonne National Laboratory 152 cm cyclotron. The beam intensity was kept below $0.1 \text{ }\mu\text{A}$ and the bombardments had a duration of about 1h. The target holder was water cooled and additional cooling was provided by maintaining a flow of helium gas across the foils. Under these conditions no difficulties were encountered with target melting or diffusion of polonium products. The bombarding energies were determined from the incident beam energies and the energy loss tables of Williamson et al.⁸.

Following irradiation, polonium was chemically separated from the target and catcher foils by spontaneous deposition on silver⁹. The various foils were dissolved in acid, the solutions adjusted to 0.5 N in HCl , and 50 mg hydrazine dihydrochloride were added. The solution was warmed to 60°C , stirred continuously, and a silver foil was suspended in it for a period of two hours. Under these conditions over 99% of the polonium was deposited on the silver for both the target and catcher foil solutions.

⁺ Obtained from Oak Ridge National Laboratory

The radioactivity of the ^{207}Po product was assayed with thin NaI(Tl) X-ray detectors. The detectors were calibrated by comparison of the ^{207}Po X-ray counting rate with that of the ^{207}Po 0.992 MeV γ -ray, as measured with a calibrated Ge(Li) spectrometer. This radiation occurs in 58% of the decays¹⁰. The decay curves were analyzed with the CLSQ least squares program¹¹.

2.2 Angular Distribution Measurements

The experimental procedure used to perform these measurements has been described in previous reports from this laboratory^{12-14,7}. Briefly, the technique involves the irradiation of thin targets in an evacuated chamber. Product nuclei recoil out of the target in a forward cone and are stopped by a circular catcher foil placed a known distance from the target. Following irradiation, the catcher is cut into concentric rings each of which corresponds to a particular angular interval. The radioactivity of each ring is assayed after chemical separation of the product of interest.

The targets consisted of enriched lead isotopes evaporated to a thickness of $2\text{--}12\text{ }\mu\text{g}/\text{cm}^2$ on 99.999% pure aluminium. Before striking the target, the incident beam was degraded to the desired energy and then collimated by a 0.47 cm aperture located outside the chamber. Further collimation was achieved at the water-cooled target with a 0.32 cm aperture. The 10 cm diameter catcher foil consisted of the same pure aluminium as the target backing. Irradiation lasted for 1-3h at beam intensities of 0.1-0.3 μA . Before each irradiation a lineup experi-

ment was performed to ensure the passage of the beam through the centres of the target and catcher foils. After bombardment, the catcher foil was cut into ten concentric rings with a precision steel cutter and polonium was separated and assayed in the manner described in the previous subsection.

The effect of target thickness on the angular distribution was investigated in a separate series of experiments and the results are given in the next section. The effect of collimator size on the angular distribution has been investigated previously^{7,14} and found to be negligible for the present experimental conditions. The possible contribution to the polonium activities from activation of impurities in either the target backing or catcher was checked in a separate experiment and found to be completely negligible.

3. RESULTS

The results of the cross-section and recoil range measurements are summarized in table 1. The average recoil ranges of ^{207}Po in lead were obtained by means of the relation $R = \bar{F}W$, where $\bar{F}$ is the fraction of the total activity of ^{207}Po found in the catcher and W is the target thickness. This relation is based on the assumption of a constant production cross section throughout a given target. This assumption introduces a negligible error in view of the very small energy loss in the thin targets used in this experiment. The random errors in both the cross-section and range values are estimated as 10-15%, being comprised primarily of the uncertainty in target thickness.

The angular distribution data were used to obtain the average laboratory recoil angle, $\langle\theta_L\rangle$, and the mean-squared tangent of the recoil angle, $\langle\tan^2\theta_L\rangle$. These quantities were obtained from the measured activities by means of the following relations:

$$\langle\theta_L\rangle = \frac{\sum_i A_i \Delta\theta_i \langle\theta_i\rangle}{\sum_i A_i \Delta\theta_i} \quad (1)$$

$$\langle\tan^2\theta_L\rangle = \frac{\sum_i A_i \Delta\theta_i \langle\tan^2\theta_i\rangle}{\sum_i A_i \Delta\theta_i} \quad (2)$$

where A_i , $\Delta\theta_i$, $\langle\theta_i\rangle$, and $\langle\tan^2\theta_i\rangle$ are respectively the activity, width, mean angle, and mean squared tangent of the i^{th} ring.

The dependence of $\langle\theta_L\rangle$ and $\langle\tan^2\theta_L\rangle$ on target thickness was investigated in a series of experiments whose results are summarized in table 2. It is apparent that scattering in the target broadens the angular distribution. This type of effect has not been found for very thin targets of lower mass number^{12,14,7} but had been observed earlier¹⁵ for bismuth targets of comparable thickness. The experimentally determined values of $\langle\theta_L\rangle$ and $\langle\tan^2\theta_L\rangle$ were corrected for this effect on the basis of a linear extrapolation to zero thickness of the data in table 2. The same correction function was used for each projectile over the relatively narrow energy range covered in this experiment. The measured values of $\langle\tan^2\theta_L\rangle$ were thus reduced by 2-10% as a result of this correction.

The corrected values of $\langle\theta_L\rangle$ and $\langle\tan^2\theta_L\rangle$ are summarized in table 3. The uncertainties in the $\langle\theta_L\rangle$ values are approximately 0.2° - 0.3° and arise from the extrapolation to zero target thickness as well as from the statistical uncertainty in the activity measurements and the accuracy of the alignment procedure. The mean angles are plotted as

a function of the energy available for the emission of three neutrons, $E_{cm} + Q$, in fig. 1. The Q - values were obtained from the mass table of Mattauch et al.¹⁶ and E_{cm} is the center-of-mass bombarding energy. The two most noticeable features of these data are the gradual increase of $\langle \theta_L \rangle$ with energy and the fact that the values obtained from ^3He bombardment are some 4° larger than those for ^4He . The first feature arises from the fact that the recoil velocity due to neutron emission increases more rapidly with energy than the velocity of the compound nucleus. The second result merely reflects the larger forward momentum imparted to the compound nucleus in ^4He bombardment.

4. DISCUSSION

4.1 Comparison of Ranges with Compound Nuclear Values

Compound nucleus formation involves complete momentum transfer from projectile to compound nucleus. The reaction product recoils with an average kinetic energy given by

$$E_R = \frac{E_B A_B A_R}{(A_T + A_B)^2} \quad (3)$$

where E_B is the bombarding energy, and A_T , A_B , and A_R are the masses of the target, projectile, and recoil product, respectively. The stopping theory of Lindhard et al.¹⁷ was used to obtain a range-energy relation for ^{207}Po in lead. The ranges obtained in this fashion were corrected for the effect of neutron evaporation from the compound nucleus in the manner described elsewhere.¹⁷ This correction increased the ranges by some 5%.

The experimental and calculated ranges are compared in fig. 2

and, within the limits of error, are in good agreement with each other. If direct interactions made a major contribution to these reactions, the measured ranges would be some 30-100% smaller than the predicted values⁷, depending on the details of the mechanism.

4.2 Comparison of the $^{206}\text{Pb}(^4\text{He},3\text{n})$ and $^{207}\text{Pb}(^3\text{He},3\text{n})$ Excitation Functions

A comparison of the cross sections of the $(^4\text{He},3\text{n})$ and $(^3\text{He},3\text{n})$ reactions can be used to determine the relative importance of compound nucleus formation in ^4He - and ^3He -induced reactions of lead. Let us assume that, for each projectile, the compound nucleus formation cross section, σ_{CN} , is equal to the total reaction cross section, σ_{R} . If this assumption is valid then, according to the independence hypothesis, the cross-section ratios, $\sigma(^4\text{He},3\text{n})/\sigma_{\text{R}}(^4\text{He})$ and $\sigma(^3\text{He},3\text{n})/\sigma_{\text{R}}(^3\text{He})$, should be equal to each other provided the comparison is made at the same excitation energy of the ^{210}Po compound nucleus. For the purposes of this comparison it is reasonable to neglect the minor differences expected from the different angular momentum distributions of the respective compound nuclei.

The values of q_{R} were calculated with the ABACUS-2 code.¹⁹ Optical model parameters were taken from the compilation by Huizenga and Igo²⁰ in the case of ^4He , and from Bassel²¹ for ^3He . The results of this comparison are shown in fig. 3. It is apparent that the $(^4\text{He},3\text{n})$ reaction accounts for a substantially larger fraction of the interactions than the $(^3\text{He},3\text{n})$ reaction does. The peak values of σ/σ_{R}

thus are 0.67 for ${}^4\text{He}$ and 0.32 for ${}^3\text{He}$. This difference is most readily explained on the basis of a greater contribution of direct interactions to the ${}^3\text{He}$ total reaction cross section. Similar results have previously been obtained in other mass regions.^{22,23,7}

4.3 Comparison of Average Neutron and Photon Energies

The experimentally determined values of $\langle \tan^2 \theta_L \rangle$ may be used to determine the mean neutron and photon energies, T_n and T_γ , associated with the reactions of interest. On the assumption of isotropic neutron evaporation, these quantities are obtained from the relations

$$T_n = 1/8 \langle V^2 \rangle (A_T + A_B + A_R)^2 \quad (4)$$

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

where the mean-squared evaporation velocity $\langle V^2 \rangle$ is obtained from $\langle \tan^2 \theta_L \rangle$ and the known velocity of the compound nucleus, v_{cn} , by an iterative solution of the equation:²⁵

$$\langle \tan^2 \theta_L \rangle = \sum_{n=1}^{\infty} \frac{2 \langle V^{2n} \rangle}{(2n+1) v_{cn}^{2n}} \quad (6)$$

Three terms in this expansion permitted the determination of $\langle V^2 \rangle$ with 1% accuracy.

The values of T_n and T_γ obtained in this fashion are summarized in table 3 and plotted in fig. 4. The uncertainties are estimated at approximately 0.5 MeV on the basis of the magnitudes of the various experimental errors. This estimate is also consistent with the scatter of the data. The T_γ for both reactions are seen to increase with the available energy but even the largest values of this quantity are

still smaller than the neutron separation energy. Evidently γ -ray emission does not compete with neutron evaporation in reactions induced by helium ions at intermediate energies. This result confirms similar findings in other mass regions^{7,12}.

The independence hypothesis demands that the T_γ values for the $^{206}\text{Pb}(^4\text{He},3n)$ and $^{207}\text{Pb}(^3\text{He},3n)$ reactions be equal at the same excitation energy and angular momentum of the compound nucleus. The T_γ values plotted in fig. 4 meet the first of these conditions but not the second. Since the effect of angular momentum difference is expected to be small, a rather simple correction may be made. The procedure is based on the notion that the angular momentum of the compound nucleus is associated with a rotational energy which is entirely dissipated by photon emission. Moreover, the rotational energy is assumed to be the only source of electromagnetic radiation.

The average angular momenta of the compound nuclei were obtained by use of the ABACUS-2 code¹⁹ and are plotted as a function of the available energy in fig. 5. An implicit and possibly erroneous assumption in this calculation is that the distributions of orbital angular momenta in the entrance channel for direct and compound nuclear processes are similar. The values of $\langle J \rangle$ increase linearly with energy but the difference between the two compound nuclei remains nearly constant at $6\hbar$ units. This difference in angular momentum may be converted to an expected difference in photon energy by means of the rotational energy formula:

$$\Delta T_\gamma = \frac{1}{2I_r} [\langle J_{^4\text{He}} \rangle (\langle J_{^4\text{He}} \rangle + 1) - \langle J_{^3\text{He}} \rangle (\langle J_{^3\text{He}} \rangle + 1)] \quad (7)$$

where I_r is the rigid body moment of inertia.

The expected difference in T_Y values is plotted in fig. 6 where a comparison is made with the experimental values of ΔT_Y . The latter were obtained by assuming a linear variation with energy of T_Y for ^3He between adjacent points and subtracting an interpolated value from the measured T_Y for ^4He . It is seen that the measured T_Y values from ^4He bombardment are about 0.5 MeV larger than those for ^3He as expected from the greater orbital angular momentum transferred to the compound nucleus in ^4He bombardment. Within the rather large uncertainty introduced by the subtraction of the T_Y values, the results are in agreement with the rotational formula. In order to detect a discrepancy from the calculated line it is apparent that the experimental values would have to differ from it by at least 1 MeV. The present work thus shows that the partition of the excitation energy of the compound nucleus between neutrons and photons is independent of its mode of formation to within at most 1.5 MeV.

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Table 1.
Cross sections and average recoil ranges for
 $^{206}\text{Pb}(^4\text{He},3\text{n})$ and $^{207}\text{Pb}(^3\text{He},3\text{n})$ reactions

Reaction	Bombarding Energy (MeV)	Cross Section (barns)	Average Range (mg/cm ²)
$(^4\text{He},3\text{n})$	32.3	0.19	0.100
	33.7	0.41	0.092
	34.4	0.58	0.097
	35.8	0.74	0.105
	36.4	0.86	0.107
	37.8	0.90	0.112
	38.3	1.11	0.099
	39.6	1.08	0.110
	40.2	0.98	0.115
	41.0	1.11	0.116
	41.4	1.16	0.106
	42.0	0.96	0.121
	43.2	0.95	0.109
	43.7	0.84	0.132
	43.8	0.76	0.112
$(^3\text{He},3\text{n})$	21.1	0.04	0.049
	23.5	0.14	0.056
	24.3	0.20	0.051
	25.6	0.26	0.058
	26.4	0.30	0.047
	27.7	0.32	0.063
	28.4	0.30	0.053
	30.3	0.22	0.067
	30.4	0.24	0.070
	32.2	0.19	0.050
	33.1	0.18	0.054
	33.2	0.14	—

Table 2. Effect of target thickness on the mean recoil angle

Reaction	Bombarding Energy (MeV)	Target Thickness ($\mu\text{g}/\text{cm}^2$)	$\langle \theta_L \rangle$ (degree)	$\langle \text{Tan}^2 \theta_L \rangle$
$(^4\text{He}, 3n)$	40.6	1.8	8.97	.0359
		4.4	9.10	.0362
		12.4	9.53	.0395
$(^3\text{He}, 3n)$	27.8	2.6	13.16	.0812
		9.7	13.36	.0839

Table 3. Summary of results derived from angular distribution data

Reaction	Bombarding Energy (MeV)	$E_{cm} + Q$ (MeV)	$\langle \theta_L \rangle^a$ (degrees)	$\langle \tan^2 \theta_L \rangle^a$	T_n (MeV)	T_γ (MeV)
$(^4\text{He}, 3n)$	35.3	6.2	7.8	.0257	5.2	1.0
	38.3	9.2	8.5	.0335	7.4	1.8
	40.7	11.5	8.9	.0353	8.2	3.3
	42.9	13.7	9.6	.0400	9.8	3.9
$(^3\text{He}, 3n)$	20.9	6.0	12.9	.0744	6.5	-0.5
	24.3	9.4	13.1	.0779	7.8	1.6
	27.8	12.8	13.1	.0805	9.2	3.6
	30.5	15.5	14.2	.0965	12.0	3.5

^aCorrected to zero target thickness.

FIGURES

- Fig. 1 Energy dependence of the average recoil angles. Triangles- ($^4\text{He}, 3n$) reaction; circles- ($^3\text{He}, 3n$) reaction.
- Fig. 2 Variation of the average projected ranges with bombarding energy; circles- ^3He reaction, triangles- ^4He reaction. Typical experimental uncertainties are indicated. The solid line is the range expected for compound nucleus formation.
- Fig. 3 Ratio of experimental cross section to the total reaction cross section as a function of the energy available for the emission of 3 neutrons. Circles represent the ($^3\text{He}, 3n$) reaction and triangles the ($^4\text{He}, 3n$) reaction.
- Fig. 4 Comparison of T_n and T_γ in the production of ^{207}Po by the ($^4\text{He}, 3n$) and ($^3\text{He}, 3n$) reactions. Circles represent the ^3He reaction and triangles the ^4He reaction. Open points refer to T_n and closed points to T_γ .
- Fig. 5 Calculated average angular momenta of ^{210}Po compound nuclei formed in ^3He and ^4He bombardment. The $\langle J \rangle$ values are in units of $\hbar$.
- Fig. 6 Difference between T_γ values for the ($^4\text{He}, 3n$) and ($^3\text{He}, 3n$) reactions. Symbols represent the experimental points and the solid line is based on the calculation described in the text.

Fig 1

Fig 2

Fig 4

Fig 6