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ABSTRACT

Isomeric cross section ratios have been measured at α-particle bombarding energies up to 40 MeV for the formation of ^{254}Es isomers from ^{252}Cf. The high-spin isomer was not observed, and a lower limit of 34 could be set for the cross-section ratio (low spin/high spin). This number is higher than values reported for other isomeric cross-section ratios.

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A number of investigators(1, 2, 3) have studied variation in the ratio of the cross sections of isomeric states in nuclear reactions as a function of the bombarding energy. Since the difference in spins of such states is usually large, it is possible to attempt deductions about the effect of angular momentum on the nuclear reactions involved. Vandenbosch and Huisenga(4) have been able to correlate the experimental ratios for the production of the ^{197}Hg isomeric pair by a variety of reactions likely to proceed via compound-nucleus formation, with ratios calculated by a statistical model in which the effect of angular momentum is considered. Low ratios in the (α, αn) and (d, p) reactions were interpreted as evidence of a direct-interaction mechanism for these reactions.

The (α, pn) reaction has been studied by Silva(5) for a wide range of targets from ^{60}Ni to ^{238}U. The (α, pn) reaction in most cases was shown to proceed by prompt emission of a proton, followed by neutron evaporation. The relative contribution of the (α, d) mechanism to the total cross section for (α, pn) + (α, d) was seen to increase with the atomic number, Z; however, this was due more to a decrease in the (α, pn) cross section than an increase in the (α, d) cross section. For ^{238}U, approximately a third of the total cross section was due to the (α, d) mechanism.

In this investigation, the α-particle bombardment of ^{252}Cf to form the isomeric states of ^{254}Es has been performed in an attempt to study the effect of angular momentum on the reaction mechanism.

EXPERIMENTAL PROCEDURE

The californium target was prepared by electrodeposition as the hydrous oxide. A total of 1.62×10^{-2} μg of californium (42% ^{252}Cf) was plated in an area of 0.05 cm^2 on 0.002-in.-thick gold foil. The target was bombarded in the deflector-channel probe assembly of the 60-in. Crocker Laboratory cyclotron, using the recoil-catcher technique previously described(6). Aluminum absorbers were used to reduce the incident α-particle energies to the desired values.

After bombardment, the thin gold catcher foil (~ 5 mg/cm^2) was removed, dissolved in aqua regia, and the solution passed through a small bed of Dowex-1 anion-exchange resin to remove the gold and some fission products. Separation into individual actinide-element fractions was achieved by elution from Dowex-50 cation-exchange resin with a solution of ammonium alpha-hydroxyisobutyrate(7). The einsteinium fraction was electrodeposited on a platinum counting disc. ^{241}Am was used as a chemical yield tracer in these separation steps.

The amount of ^{254m}Es [$t_{\frac{1}{2}}(\beta^-)$ = 37 hours] was determined by allowing the ^{254}Fm daughter to achieve secular equilibrium and then counting the sample for 7.2 MeV α particles of ^{254}Fm in an ionization grid chamber connected to an α pulse-height analyzer. The alpha decay of ^{254g}Es [$t_{\frac{1}{2}}(\alpha)$ = 480 days] could not be measured at that time, as the ^{253}Es formed in the bombardment prevented observation of its decay. After an interval of 10 to 12 months, the samples were recounted for the ^{254g}Es radiations.

RESULTS

Bombardments were performed at the following energies (with total beam in parentheses): 27.9 MeV (5.5μA hr), 30.0 MeV (14.9 μA hr), 33.6 MeV (3.34 μA hr), 36.8 MeV (5.6 μA hr). Five bombardments with a total beam of 48.9 μA hr were done at 40.0 MeV. Cross sections calculated for the amount of ^{254m}Es observed at each energy agreed closely with the excitation function reported earlier$^{(8)}$. Within the counting statistics, no disintegrations of the 6.64 MeV alpha particles of the ^{254g}Es isomer were observed. From the counting time, it was possible to set an upper limit of 1×10^{-3} cpm for ^{254g}Es in each sample. Lower limits for the isomer cross-section ratios could be calculated for each bombarding energy; however, these ratios are quite dependent on the cross section for ^{254m}Es and the total beam, so that they are not realistic limits. At 40 MeV, both cross section and beam were large and a lower limit of 34 was calculated for the ratio (i.e., $\sigma_m/\sigma_g \geqslant 34$).

DISCUSSION

The cross sections for the formation of the long-lived isomer of ^{211}Po$^{(9)}$, ^{234}Pa$^{(10)}$, and ^{240}Np$^{(11)}$ by the (α, pn) reaction have been reported. Silva has measured the total cross section for the (α, pn) reaction for ^{209}Bi and ^{238}U by a scattering-chamber method$^{(8)}$. For (α, pn) reactions with other nuclei, his cross sections are in acceptable agreement with values reported from radiochemical techniques. Since the trends in the isomer cross-section ratios are the subject of this discussion, and not the absolute values, it is possible to use Silva's data to estimate these ratios. Although the total cross section for the formation of ^{234}Pa has not been reported, the measured value for that of the long-lived state is so large that the cross section for the short-lived state cannot be more than 10 mb and is probably closer to 5 mb.

The spins listed for the isomeric states are "best guess" values based on the present evidence(13). All cross sections given in Table I were measured at an α-bombarding energy of 40 MeV; the values in parentheses are estimated from Silva.

To understand the pattern in the isomer cross-section ratios of Table I, it is useful to calculate the relative density P_j/P_0 of states of spin J by the equation(14): $P_j/P_0 = (2J + 1) \exp[-(J+\frac{1}{2})^{1/2} / 2\sigma^2]$. When a value of $\sigma = 4$, based on reported values for σ over a wide range of mass numbers(4,15), is used, it is possible to calculate that the level density passes through a maximum between J = 3 and J = 4 (Fig. 1). According to Silva, the probable mechanism for the reactions yielding (α, pn) products is emission of high-energy deuterons and protons by direct-interaction processes. When a proton is emitted, evaporation of a neutron follows. In either case, (α, d) or (α, pn), there is little angular momentum transfer—perhaps 1 or 2 units. The residual nucleus after completion of the direct processes would be expected to have spins of approximately 2 for ^{232}Th and ^{238}U. This is intermediate between the spins of the isomeric states in both cases and, since the level density for state of J = 3, 4, or 5 is greater than for those of J = 0 or 1, there will be greater relative population of these states upon deexcitation by neutron evaporation or γ emission. This in turn leads to greater population of the higher spin state than of the lower spin state. In fact, this analysis favors a higher ratio in the isomer cross-sections for ^{240}Np than ^{234}Pa, and the ratio does seem to be higher.

The spin of ^{209}Bi is 9/2, so the excited residual nucleus would have a spin close to 11/2 or 13/2. Since both spin and level density favor the low spin isomer in this case, as expected, the ratio is large. The same situation is true for ^{254}Es. Even though the differences in level densities for states of J = 2 and J = 7 in ^{254}Es are less than for states of J = 9/2 and J = 19/2 in

^{211}Po, the isomer cross-section ratio is larger for ^{254}Es. This indicate that the value of the spin of the excited nucleus must be very close to that of the metastable state (I = 2), so that the latter is greatly favored in the α cascade. It should be emphasized that the value of 34 is quite large compared to reported values of other isomer ratios.

Silva's data indicate that for heavy elements the (α, pn) reaction cross section decreases as Z increases, while the (α, d) reaction cross section remains relatively constant with Z. These trends indicate that for ^{238}U, $\sigma_{\alpha, pn}/\sigma_{\alpha, d)} \sim 2$, while for ^{252}Cf, the (α, d) reaction is the principal contributor to the cross section.

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Table I

Reaction	Total Cross Section (mb)	Product Spins	Isomer Cross Section (mb)	Estimated Ratio $\frac{\text{low spin}}{\text{high spin}}$
^{209}Bi (α, pn) ^{211}Po	18±3	$9/2^{(12)}$	(~ 15)	~ 10
		19/2-25/2	1.5	
^{232}Th(α, pn)^{234}Pa	----	0, 1	(~ 5-10)	$\leqslant 0.5$
		3, 4	21	
^{238}U(α, pn) ^{240}Np	9.6±1.9	1	(~ 3)	~ 0.5
		5	6	
^{252}Cf(α, pn) ^{254}Es	----	2	6	$\geqslant 34$
		7	$\leqslant 0.2$	

FIGURE LEGENDS

1. Level density as a function of J.

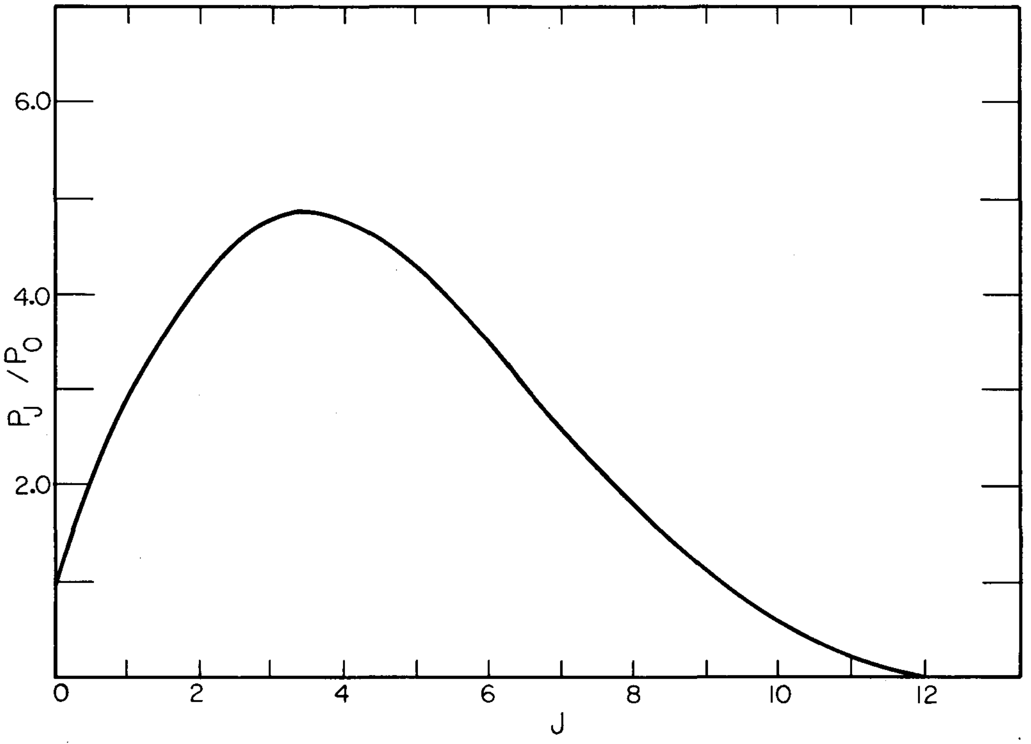

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Fig. 1.