Angular momentum saturation in the ^{209}Bi(α, 2n) reaction

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The measured yield of the $\frac{39}{2}^-$ isomer in ^{211}At from the reaction ^{209}Bi(α,2n) indicates angular momentum saturation at 44–48 MeV of incident alpha energy. The average angular momentum in the evaporation residue ^{211}At is estimated to be $18\hbar$.

The determination of the limiting value of angular momentum of the compound nucleus leading to the evaporation residue is of great interest in studies of fusion reactions.[1] While the majority of such studies are based on heavy ion induced fusion reactions, a limited number of investigations have been made with (α,xn) reactions in the rare-earth rotational region.[2,3] The angular momentum of the evaporation residue is estimated from a measurement of the γ-ray multiplicity M_γ in these reactions. For rotational nuclei each yrast transition corresponds to an average spin change $\Delta I \sim 1.8\hbar$, taking into account small $M1$ admixtures in the intraband $E2$ cascades. Therefore M_γ and the maximum spin of the evaporation residue are simply related.[1] However, for nuclei near ^{208}Pb the presence of isomeric states leads to unrealistically low values of spin[2] of the evaporation residue from the γ-ray multiplicity measurements. As the fission barrier drops below the neutron threshold at spin values of $25-30\hbar$ for the nuclei above ^{208}Pb,[1] it is of considerable interest to study the spin-saturation effect in fusion reactions in this region. In the present work, the reaction ^{209}Bi(α,2n) has been used to study the angular momentum saturation in the evaporation residue ^{211}At. At $E_\alpha = 34$ MeV, the above reaction strongly populates[4] a high spin state, $\frac{39}{2}^-$, near the expected value of the saturation spin. The two evaporation neutrons, together with a few statistical γ rays, can take away only about $3\hbar$ of angular momentum from the compound nucleus ^{213}At. The absence of any side branching[4] in ^{211}At (see Fig. 1) therefore ensures that the yield of the $\frac{39}{2}^-$ isomer in terms of the input angular momentum can demonstrate the angular momentum saturation near the expected spin values.

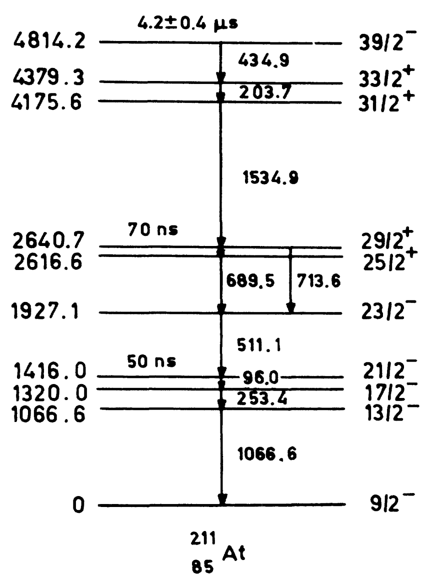

FIG. 1. The decay scheme of the isomeric states in ^{211}At excited in the ^{209}Bi(α,2n) reaction.

The alpha beam from the Variable Energy Cyclotron of Bhabha Atomic Research Center, Calcutta, was optimized[5] by tuning of the cyclotron central region parameters and by using an unbevelled slit in front of the ion source. The time spread of the beam was 4.5 ns and the energy spread was about 70 keV. Extremely pure rolled Bi (70 mg/cm^2), having a rectangular dimension of 8 mm$\times$15 mm, was used as the target in the experiment. The alpha beam spot was less than 2 mm in diameter as viewed at the target position. The γ ray detector was a 120 cm^3 gamma-X Ge detector, whose on-line resolution was measured to be 1.8 and 2.3 keV at 254 and 1500 keV, respectively. The detector was calibrated using the known[6] γ ray energies and intensities of the residual activities ^{209}At and ^{210}At produced in the ^{209}Bi (α,xn) reaction. The decay of the isomeric states in ^{211}At is studied

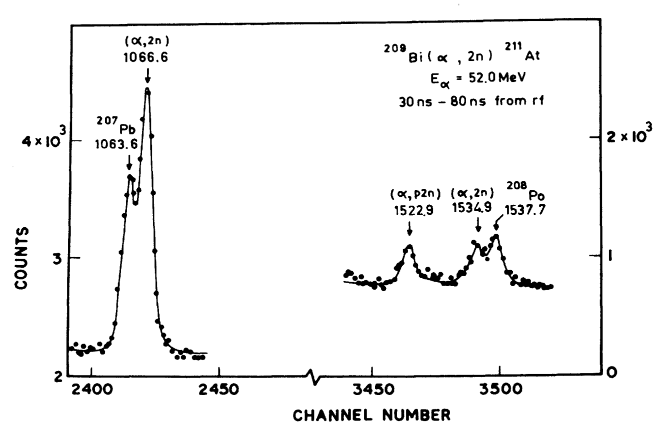

FIG. 2. γ-ray spectrum in the ^{209}Bi(α,2nγ)^{211}At reaction at $E_\alpha = 52.0$ MeV, showing the 1066.6 and 1534.9 keV γ rays used for the estimation of isomer yields.

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TABLE I. Isomer yield (%) in the $^{209}Bi(\alpha,2n)\,^{211}At$ reaction.

Isomeric state	Alpha Energy (MeV) 34.0	44.0	48.0	52.0
$\frac{39}{2}^-$	5.9±0.4	8.8±0.3	10.1±0.3	10.1±0.3
$\frac{29}{2}^+$ a	71±7	70±7	62±7	59±7
$\frac{21}{2}^-$ a	23±2	21±2	28±3	31±3
$\frac{29}{2}^+ + \frac{21}{2}^-$	94±3	91±3	90±3	90±3

[a]Population by feeding from the upper isomer is subtracted.

by recording the delayed γ-ray spectra during the time interval 30–80 ns in between two rf bursts separated by about 140 ns. Figure 2 shows a typical delayed spectrum at $E_\alpha = 52.0$ MeV showing 1066.6 and 1534.9 keV γ rays corresponding to the decay of the isomeric states in ^{211}At as indicated in Fig. 1. Since the yield of the 1534.9 keV gamma ray may change with incident alpha energy due to the presence of an isomeric state at higher excitation above the $\frac{39}{2}^-$ isomer, the possibility of such a state was carefully examined. The intensities of all the γ rays observed in the delayed spectra are fully accounted for in terms of the known[6] decay schemes of the isomeric transitions in ^{211}At, ^{210}At, and ^{209}At formed by the (α,2n), (α,3n), and (α,4n) reactions, respectively, on ^{209}Bi. Also from shell model considerations, the existence of a higher isomeric state in ^{211}At is not possible.

The relative populations of the three isomeric states, $\frac{39}{2}^-$, $\frac{29}{2}^+$, and $\frac{21}{2}^-$, are estimated from a measurement of the intensities of the γ rays, 1534.9 (689.5 + 713.6), and 1066.6 keV, respectively, in the delayed spectrum (Fig. 1). Appropriate decay and feeding corrections were made to obtain the relative populations of the three isomers formed in the ^{209}Bi (α,2n) reaction. Table I lists the relative yields of the three isomeric states in ^{211}At. As shown in Table I, the yields of the two lower isomeric states are not determined accurately. This is due to the large background from the broad peak at 693 keV from the ^{72}Ge (n,n′) reaction in the Ge detector making the intensity determination of the 689.5 and 713.6 keV γ rays inaccurate. However, the combined yield for the $\frac{29}{2}^+$ and $\frac{21}{2}^-$ states is determined accurately from the 1066.6 keV gamma ray.

Our data reveal several interesting aspects of the $^{209}Bi(\alpha,2n)$ reaction. Table I indicates that the yield of the $\frac{39}{2}^-$ isomeric state saturates between incident alpha energies of 44 and 48 MeV. The excitation function for the $^{209}Bi(\alpha,2n)$ reaction attains peak value at $E_\alpha \sim 30$ MeV. So the saturation occurs at 14 to 18 MeV above this energy. This is in agreement with the previously obtained energy separation (12–18 MeV) measured in the ^{150}Sm (α,xn) reactions.[2] Following Refs. 2 and 7 we calculate the maximum input angular momentum $L^{\max}$ brought in by the alpha particle. Assuming uniform volume absorption of the projectile the average angular momentum of the compound nucleus is $\bar{I}_c = \frac{2}{3}L^{\max}$. To balance this angular momentum of the compound nucleus the following equation holds:[7]

$$\bar{I}_c = l_n^e + l_n^p + I^s + I^y ,$$

where l_n^e and l_n^p are the angular momenta carried by the equilibrium and preequilibrium neutrons, and I^s and I^y are the total angular momenta carried by the statistical and yrast γ rays, respectively, in the evaporation residue ^{211}At. Each equilibrium neutron carries on an average angular momentum of $0.5\hbar$, while the angular momenta carried by the preequilibrium neutrons are given by[7]

$$l_n^p = \tfrac{1}{3} R N_p A_p (2M_n E_n^p)^{1/2} ,$$

where R is the nuclear radius, N_p is the number of preequilibrium neutrons, A_p is their asymmetry coefficient, and E_n^p is the average energy of the preequilibrium neutrons. On the average, 3 to 4 statistical γ rays having energy greater than 600 keV are emitted in the (α,xn) reaction,[7] each with a spin change of $0.3\hbar$.

In Table II we list the values of $\bar{I}_c$, l_n^e, l_n^p, I^s, and I^y for $E = 34$ and 52 MeV. It is evident from the angular momentum balance that the ^{209}Bi (α,2n) reaction at 34 MeV can be visualized as a pure equilibrium process. The slight imbalance in the angular momenta, $I - I_c \sim 1.4\hbar$, can be rectified by assuming a surface localized fusion reaction instead of uniform volume absorption. For $E_\alpha = 52$ MeV, the need to incorporate preequilibrium process is clearly indicated in Table II. For this energy we have given two sets of values for l_n^e and l_n^p corresponding to $N_p = 2$ and 1, respectively, and $A_p = 0.5$. The l_n^p listed in Table II corresponds to $E_n \sim 9$ MeV. Table II indicates that even if we take into ac-

TABLE II. Angular momenta ($\hbar$) balance in the $^{209}Bi(\alpha,2n)\,^{211}At$ reaction.

E_α (MeV)	I_c	l_n^e	l_n^p	I^s	I^y	I^a
34.0	15.5	1	0	0.9	15	16.9
52.0	19.2	0.5	1	1.2	15	17.7
		0	2	1.3	15	18.2

[a]$I = l_n^e + l_n^p + I^s + I^y$.

count the preequilibrium process, the angular momentum balance at $E=52$ MeV requires a cutoff value of $\bar{I}_c \sim 18\hbar$. This value of $\bar{I}_c$ leads to I_c (max) $\sim 27\hbar$ for ^{213}At, in agreement with the theoretical estimates.[1]

To summarize, the present experimental work demonstrates the saturation effect in the angular momentum of the evaporation residue ^{211}At as determined from the isomer yield of the $\frac{39}{2}^-$ state in ^{209}Bi$(\alpha,2n)$ reaction. Detailed angular momentum balance in the reaction indicates the effect of preequilibrium processes and fission, which restricts the average angular momentum of the compound nucleus leading to the evaporation residue to $18\hbar$ at $E_\alpha \sim 52$ MeV.

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