Effect of the critical angular momentum on the high spin selectivity of heavy-ion compound reactions

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(Received 12 June 1978)

A drastic limitation of the high-spin selectivity of heavy-ion compound reactions is shown to be introduced by the angular momentum cutoff J_{max} in the composite system. However, for final spins near J_{max} a strong shape dependence of the angular distributions (being peaked at 90̊) arises as result of a strong decrease of the alignment of the final nucleus and can be used for high spin spectroscopy.

[NUCLEAR REACTIONS: Statistical model calculations–critical angular momentum effects.]

The selective population of discrete states of high spin from the continuum at high excitation energies via particle spectroscopy in heavy-ion compound reactions has proved to be a powerful method for high-spin spectroscopy in light nuclei.[1-4] In this communication it will be shown, that *in addition* to the decrease of the high-spin selectivity (HSS) at high excitation energy due to the increasing continuum,[1] *a further* limitation with respect to high spins *independent* on excitation energy arises from an effect of the critical angular momentum J_{max} for compound nucleus formation on the cross sections. On the other hand, J_{max} introduces a strong dependence of the shape of the angular distributions on I for states with $I \approx J_{max}$, an effect related to a change in alignment of the final nucleus. Though the effect of J_{max} properly has been taken into account in earlier work on high-spin states in light nuclei, where states at medium excitation energies (<18 MeV) in the final nuclei were investigated,[1-4] the effect of the critical angular momentum on the HSS of heavy-ion compound reactions has not yet been discussed. In the present paper this effect will be described using the reaction $^{10}B(^{16}O,d)^{24}Mg$ as a typical example.

The angle integrated cross section for a compound reaction $A(a,b)B$ is given[1,2] by

$$\sigma(E_B,I_B)=\sum_{J=0}^{J_{max}}\sigma_{form}(J)G(E_B,I_B,J)/g(J)$$

$$=\sum_{J=0}^{J_{max}}\sigma_J(E_B,I_B)\,,$$

where σ_{form} is the compound nucleus formation cross section and $G(E_B,I_B,J)$ and $g(J)$ describe the partial and total decay widths of a compound nucleus state with spin J. The value of J_{max} limiting the summation over the partial cross sections σ_J represents the maximum angular momentum at which the compound nucleus can be formed via this entrance channel. Recent fusion experiments[5,6] show that in light nuclei this limitation is mostly due to dynamical processes in the entrance channel[7-9] rather than to the yrast line in the compound nucleus or the lowering of the fission barrier of the compound nucleus at high angular momentum.[10]

The compound nuclear formation cross section

$$\sigma_{form}(J)=\pi\lambda\!\!\!^{-2}\,\frac{2J+1}{(2I_A+1)(2I_a+1)}\sum_L T_L(E_{CN})\,,$$

without this cutoff, will be peaked at an L value of the order of the grazing angular momentum in the entrance channel. Due to the comparably small grazing angular momentum in the exit channel, high-spin states in the final nucleus will be mainly fed from the high spins in the compound nucleus. Consequently the contributions $\sigma_J(E_B,I_B)$ to the final state will be a function peaked at the higher angular momentum J, the higher the spin of the final state, and only a few partial cross sections σ_J are essentially contributing [Fig. 1(a)]. Consequently a truncation of high-spin components in the compound nucleus will decrease preferentially the cross sections for final states of high spin. Figure 1(b) shows the angle integrated cross section as a function of the angular momentum cutoff J_{max} in the compound nucleus for the reaction $^{10}B(^{16}O,d)$. The lower the cutoff value J_{max} is compared to the grazing angular momentum L_{graz}, the stronger is the attenuation of cross sections for states of high spin and the higher the spin the more drastic is the lowering. For exit channels involving heavier particles, as a consequence of the larger orbital angular momentum carried away, the effect of the cutoff by J_{max} on the cross sections will be more pronounced and appear also for final states of lower spin. This is the explana-

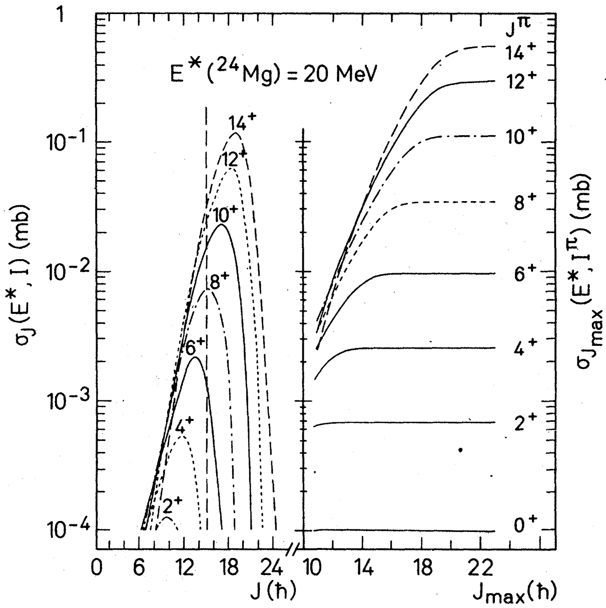

FIG. 1. (a) Partial cross sections $\sigma(J)$ for the excitation of states of different spin at $E=20$ MeV in ^{24}Mg by the reaction ^{10}B(^{16}O,d) at $E_{1ab}=60$ MeV [calculated with the program STATIS (Ref. 15)]. The dashed vertical line corresponds to the experimental critical angular momentum (Refs. 6 and 12) for this case. Details on the parameters used in the calculations are given in Ref. 12. (b) Angle integrated cross sections for the states shown in (a) as a function of the critical momentum. For the experimental value $J_{max}=15$ the cross sections for high-spin states ($\gtrsim 10$) are seen to be strongly affected.

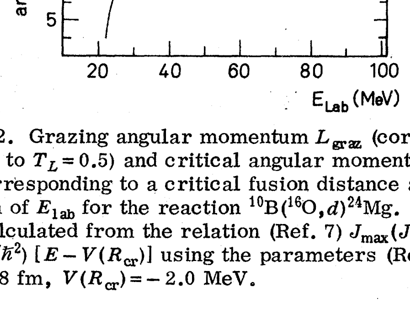

FIG. 2. Grazing angular momentum L_{graz} (corresponding to $T_L=0.5$) and critical angular momentum J_{max} corresponding to a critical fusion distance as a function of E_{1ab} for the reaction ^{10}B(^{16}O,d)^{24}Mg. J_{max} has been calculated from the relation (Ref. 7) $J_{max}(J_{max}+1) = (2\theta cr/\hbar^2)\,[E-V(R_{cr})]$ using the parameters (Ref. 6) $r_{cr}=1.08$ fm, $V(R_{cr})=-2.0$ MeV.

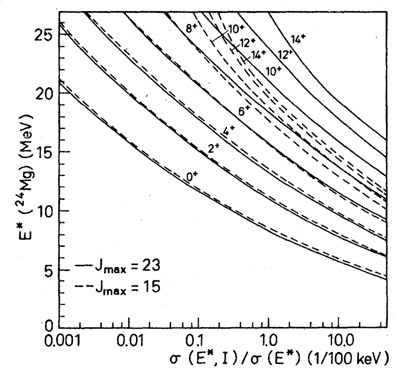

FIG. 3. Effect of the critical angular momentum cutoff on the selectivity. The reaction ^{10}B(^{16}O,d) at $E_{1ab}=60$ MeV has been chosen for illustration. The solid curves correspond to *no* cutoff in the compound nucleus formation ($J_{max}=23$), the dashed lines correspond to $J_{max}=15$, obtained experimentally (Refs. 6 and 12).

tion for the difference in sensitivity of the deuteron and ^{6}Li channels to the cutoff by J_{max} discussed in Ref. 11 for the reaction ^{16}O$+^{14}$N for final states of low spin.

As shown in Fig. 2, the grazing angular momentum in the entrance channel increases more rapidly with increasing bombarding energy than the critical angular momentum limiting the compound nucleus formation and this leads to a shift of the angular momentum cutoff for complete fusion or compound nucleus formation from L_{graz} to J_{max}. This can be understood as a consequence of the critical distance of approach in the fusion process. The reason is that the curvatures of the parabolas in Fig. 2 are determined by the moment of inertia of the composite system at the grazing and critical fusion distances, respectively. The curve for J_{max} can be calculated within the framework of models basing on a critical fusion distance.[7-9]

The influence of J_{max} on the cross section affects the *high-spin selectivity* of the reaction [defined[1,4] as the ratio between the cross section $\sigma(E_B, I_B)$ and the integral cross section $\sigma(E)=\sum_{I_B}\sigma(E_B, I_B) \times \rho(E_B, I_B)dE$ per excitation energy interval dE corresponding to the experimental energy resolution] as shown in Fig. 3. It can be seen that in our example of the reaction ^{10}B(^{16}O,d)^{24}Mg at $E_{lab}=60$ MeV for the experimental value of $J_{max}=15$ (from Refs. 6 and 12) states of spin $I \gtrsim 10$, though still expected to stand out in the spectrum, can hardly be expected any more to be distinguishable in spin from their *total* cross sections, in contrast to a hypothetical case with *no* spin cutoff.

On the other hand the truncation of high spins in the compound nucleus gives rise to a strong spin dependence of the shape of the angular distributions for the high-spin final states (Fig. 4). The reason

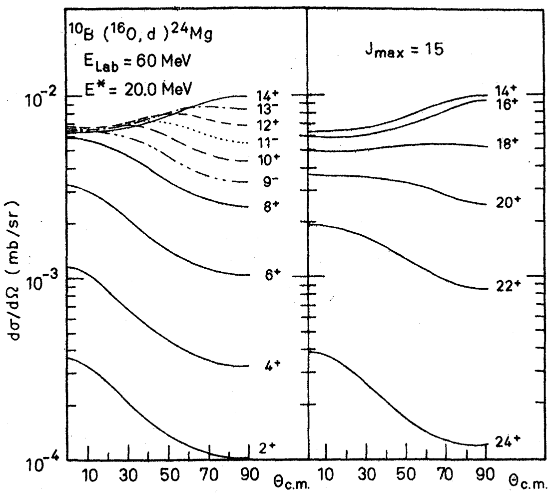

FIG. 4. Differential cross sections (for $J_{max}=15$) calculated with the program STATIS for the states shown in Fig. 1 excited in the reaction $^{10}B(^{16}O,d)^{24}Mg$. The critical angular momentum introduces a drastic loss of selectivity at forward angles, the spin dependence of the cross sections remains, however, up to relatively high spins at angles around $\theta_{c.m.}=90°$.

is that the strong alignment of the *final* nucleus for spins much lower than J_{max}, which is mainly due to the small grazing angular momentum in the exit channel and which is responsible for the classical "flywheel" limit $d\sigma(\theta)/d\Omega \sim 1/\sin\theta$, is lost for final spins near the cutoff value. For final spins near J_{max} the angular momenta of the outgoing particles—in contrast to the upper case—can be nearly perpendicular to the maximum angular momentum in the compound nucleus (giving the main contribution to the cross section). An angular momentum of the emitted particles perpendicular to the spin of the compound nucleus, however, yields in a classical limit an angular distribution

$$d\sigma(\theta)/d\Omega \sim \ln[(1+\sin\theta)(1-\sin\theta)^{-1}]^{1/2}\sin^{-1}\theta$$

and thus a maximum at 90°. This simple explanation would predict similar shapes of angular distributions for states with spins I, for which $|I-J_{max}|$ is equal and this is indeed reproduced by the statistical model calculations (Fig. 4). This shape dependence, for states with $I\approx J_{max}$, compensates for the loss of selectivity in the total cross sections because the ratios of differential cross sections at 0 and 90° become strongly dependent on the spin. This fact has been used in the search for the $I=10$ yrast states in ^{24}Mg (Ref. 12) and ^{22}Ne.[16]

To find the most selective reaction for highly excited states with high spins in a given final nucleus the following points have to be considered. *In addition* to the prescription given in Ref. 1, the bombarding energy has to be chosen high enough to provide a critical angular momentum lying much higher than the spin values of the final states of interest. On the other hand, of course, the bombarding energy must be low enough to assure that the reaction mechanism is still mainly compound, if statistical model calculations shall be used for spin assignments as described in Ref. 2. This upper limit in $E_{c.m.}$ lies around 40 MeV for compound systems with $A\approx 25-30$.[3,13] To obtain the maximum selectivity possible for a given reaction one further has to measure the differential cross sections around $\theta_{c.m.}=90°$ where also for high spins—in contrast to the drastic loss of selectivity at forward angles—a spin dependence of the cross sections remains (Fig. 4).

As the steep yrast lines in light nuclei ($A\lesssim 30$) favor particle decay compared to the γ channel from the yrast line down to relatively low excitation energy, or in other words, since the α pinch-off effect[14] arises at low excitation energy,[15] also with the upper limit discussed in this paper, high-spin selective (HI, particle) compound reactions are still a means by far superior to γ spectroscopy for spectroscopy of high-spin states in the mass region (see also Refs. 17 and 18).

One of the authors (A. S. deT) was supported in part by the Fundacao de Amparo a Pesquisa do Estado de Sao Paulo, Brasil and Alexander von Humboldt-Stiftung.

*On leave of absence from Instituto de Fisica da Universidade de Sao Paulo, Brasil, during 1977–1978.

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