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Quasimolecular states of ^{24}Mg excited in the ^{16}O+^{12}C interaction

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The study of the $^{16}\mathrm{O} + ^{12}\mathrm{C} \rightarrow ^{12}\mathrm{C} + ^{12}\mathrm{C} + \alpha$ reaction performed at $E(^{16}\mathrm{O})$=113 MeV shows evidence for the excitation of resonant states of ^{24}Mg, eventually decaying in the ^{12}C+^{12}C channel, with a width of about 500 keV. From the angular correlation of the two emitted ^{12}C ions a value $J = 14$ is obtained for the spin of two resonances at 35.1 and 36.3 MeV excitation energy. This allows for an interpretation in terms of quasimolecular states of ^{24}Mg. The data are compared with previous results obtained at 85 MeV incident energy, and the role of the angular momentum transfer in the reaction process is discussed.

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I. INTRODUCTION

In a previous work [1,2], we have reported evidence for the formation of quasimolecular (QM) states in ^{24}Mg through the study of the reaction

$$^{16}\mathrm{O} + ^{12}\mathrm{C} \rightarrow ^{12}\mathrm{C} + ^{12}\mathrm{C} + \alpha, \tag{1}$$

performed at an incident energy of the ^{16}O beam of 85 MeV.

Two sequential processes can contribute to reaction (1). The first one proceeds through the excitation of ^{16}O,

$$^{16}\mathrm{O} + ^{12}\mathrm{C} \rightarrow ^{16}\mathrm{O}^* + ^{12}\mathrm{C}, \tag{2a}$$

$$^{16}\mathrm{O}^* \rightarrow ^{12}\mathrm{C} + \alpha, \tag{2b}$$

while an excited state of ^{24}Mg is formed in the process of interest:

$$^{16}\mathrm{O} + ^{12}\mathrm{C} \rightarrow ^{24}\mathrm{Mg}^* + \alpha, \tag{3a}$$

$$^{24}\mathrm{Mg}^* \rightarrow ^{12}\mathrm{C} + ^{12}\mathrm{C}. \tag{3b}$$

The signature of both these processes was found by studying the relative energy spectra for any two of the three particles in the final state of reaction (1). In fact, resonances in the $^{12}\mathrm{C} + \alpha$ relative energy correspond to states of ^{16}O* [Eq. (2b)], while resonances in the ^{12}C+ ^{12}C relative energy indicate the formation of states of ^{24}Mg* [Eq. (3(b)]. After a suitable analysis carried on to disentangle the two effects, a few peaks were found in the ^{12}C-^{12}C relative energy corresponding to an excitation energy $E_{\mathrm{exc}}(^{24}\mathrm{Mg})$ ranging from 26.3 to 31.6 MeV (see Table I).

To have a confirmation of the QM nature of a resonance, it is necessary to obtain information on its angular momentum J. In fact, for QM states, one expects [3] not only that the angular correlations will be dominated by a unique value of J, but also that the excitation energy and the J value must be approximately connected by the rigid rotator relationship

$$E_{\mathrm{QM}} = E_0 + \alpha J(J+1). \tag{4}$$

Here the bandhead energy E_0 is essentially equal to the binding energy of the two nuclei plus their relative Coulomb energy, and the slope α is given by $\alpha = \hbar^2/2I$ with the momentum of inertia I calculated for two tangent nuclei.

A study of the angular distribution of the ^{12}C ions emitted in the ^{24}Mg rest frame was then performed. It allowed the assignment of the value $J = 12 \pm 2$ to the angular momentum of the levels at $E_{\mathrm{exc}}(^{24}\mathrm{Mg})$=30.7 and 31.6 MeV. The result is in good agreement with the prediction of Eq. (4). In fact, for QM states of ^{24}Mg having a ^{12}C-^{12}C structure, the parameters E_0 and α take approximately the values [3] of 20 and 0.07 MeV, respectively, yielding $E_{\mathrm{QM}} = 31$ MeV for $J = 12$. The angular range covered by the experiment was not large enough to attempt a similar fit for the other peaks.

In the present paper, we report on a new measurement, performed at Laboratorio Nazionale del Sud with an higher ^{16}O incident energy, with the aim of following the process in a different region of the ^{24}Mg QM band. The results have already been partially reported [4,5].

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II. EXPERIMENT

A beam of ^{16}O ions was accelerated to 113 MeV by the SMP tandem accelerator of the Laboratorio Nazionale del Sud, Catania. The target was a self-supporting C foil, 150 μg/cm^2 thick, placed at the center of a standard reaction chamber. Two heavy-ion telescopes were used to determine the energy and the angle of the emitted particles. In a first run (run A), they covered the angles between 23° and 33° on both sides of the beam. Each telescope consisted of a transversal field ionization chamber, used as a ΔE detector, followed by 600-μm thick Si position-sensitive detectors, giving the E information. The time signals from the position-sensitive detectors were sent to a time-to-amplitude converter (TAC), whose output was used as a general trigger for computer acquisition of all the signals in the event-by-event mode. The calibration of the detectors was performed by using an ^{241}Am α source and the scattering of ^{12}C ions from a thin gold target at various incident energies. In a second run (run B), the telescopes were moved to smaller angles, covering the angles between 10° and 20° on both sides of the beam, with the aim of detecting events with smaller ^{12}C-^{12}C relative energy.

III. DATA ANALYSIS

In the off-line analysis, a window was put on the time peak of the TAC spectrum. For all accepted events, the particle energies were determined after corrections for energy losses in the target, in the ionization chamber windows, and in the dead layers of the silicon detectors.

The total energy of the ^{12}C + ^{12}C + α exit channel was calculated from momentum conservation for each ^{12}C-^{12}C coincidence event yielding the Q spectrum reported in Fig. 1 for run A. Note that even if the detecting setup does not allow for mass but only for charge identification of the ions, the possible contribution of C isotopes different from ^{12}C cannot appear under the three narrow peaks of Fig. 1, since the Q value is in this case much more negative (about -20 MeV). To make sure that the measured ^{12}C-^{12}C events were to be attributed to reaction (1), a check on the data was performed according to the procedure of Ref. [6]. No appreciable contamination of the target or of the beam was detected.

For the events lying under each peak in the Q spectrum, the relative kinetic energy E_{ij} of any two of the three particles in the final state was then calculated as

$$E_{ij} = [m_j E_i + m_i E_j - 2(m_i m_j E_i E_j)^{1/2} \cos(\theta_{ij})]/(m_i + m_j), \qquad (5)$$

where m_i (m_j) and E_i (E_j) are the mass and kinetic energy of particle i (j), and θ_{ij} is the angle between their directions in the laboratory system.

Figure 2 is the scatter plot of the two ^{12}C-α relative energies for all events lying under the Q_{gg} peak. The clustering of events along lines parallel to the two axes indicates the observed dominance of a strong ^{12}C-α interaction (i.e., the formation of ^{16}O* states). The presence of the ^{12}C-^{12}C interaction is understood in the faint accumulation along curves symmetrical with respect to 45°, in the right upper part of the plot. Under these conditions the spectrum of the $E_{^{12}\text{C}\text{-}^{12}\text{C}}$ relative energy for all events would not give any clear indication, being largely affected by the contribution of ^{16}O* states. However, Fig. 2 shows also that such contributions disappear at the highest ^{12}C-α relative energies. So taking into account *only* the events above 16 MeV in both ^{12}C-α relative energies, the spectrum of Fig. 3 is obtained. It clearly shows at least two peaks which have to be attributed to the strong ^{12}C-^{12}C interaction and hence to relatively long living ^{24}Mg* states at 35.1 and 36.3 MeV excitation energy [note that $E_{\text{exc}}(^{24}\text{Mg}) = E_{^{12}\text{C}\text{-}^{12}\text{C}} + 13.9$ MeV].

A similar analysis was carried on using the data taken

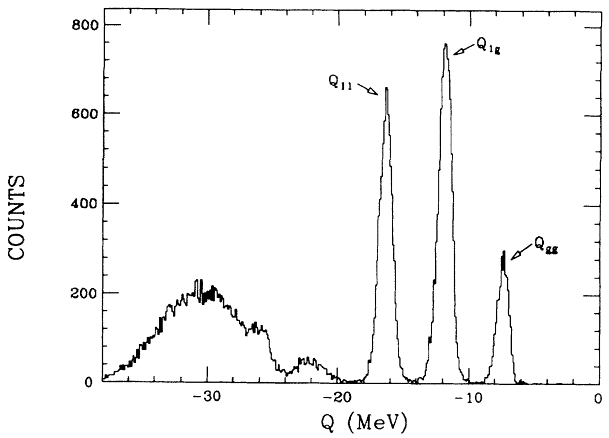

FIG. 1. Q-value distribution for the ^{16}O + ^{12}C $\rightarrow$ ^{12}C + ^{12}C + α reaction, measured at $E(^{16}\text{O})$ = 113 MeV. The detectors covered the angles between 23° and 33° on both sides of the beam. The three peaks marked by Q_{gg}, Q_{1g}, Q_{11}, correspond to final states involving ^{12}C ions left in their ground state or in their first excited level.

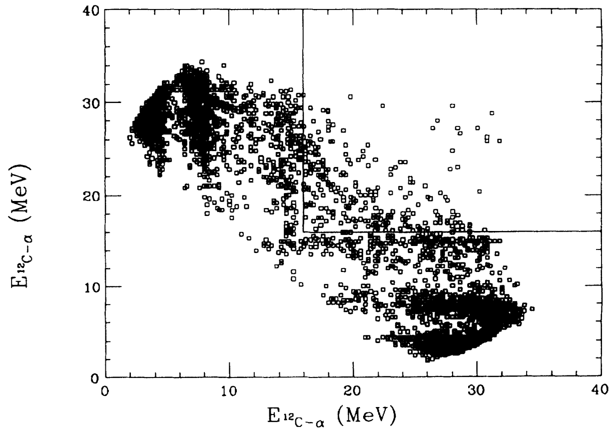

FIG. 2. Scatter plot of the two ^{12}C-α relative energies for all the events under the Q_{gg} peak in Fig. 1. The solid lines show the cuts at 16 MeV for both ^{12}C-α relative energies used to obtain the ^{12}C-^{12}C relative energy spectrum of Fig. 3 (see text).

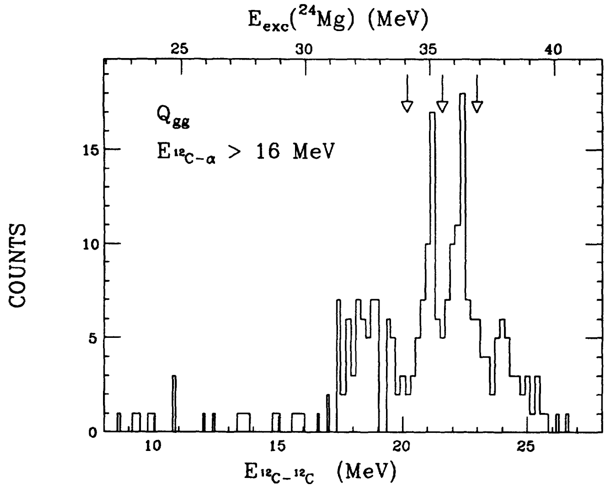

FIG. 3. ^{12}C-^{12}C relative energy spectrum for the coincidences of Fig. 2, corresponding to ^{12}C-α relative energies above 16 MeV. The arrows show the energy cuts used to obtain the angular distribution for each peak.

during run B, i.e., with the telescopes moved to smaller angles with respect to the beam axis. The $E_{^{12}C-^{12}C}$ spectrum showed a low counting and essentially no structure.

A Monte Carlo simulation was performed in order to evaluate the instrumental resolution due to the beam spot size, the target thickness, and the uncertainty of the position-sensitive detector response due to the lack of information on vertical position and to the horizontal position inaccuracy. The calculations gave a full width at half maximum (FWHM)$\approx$ 950 keV for the peaks in the Q-value spectrum. This is in agreement with the experimental result reported in Fig. 1.

The same calculation gave also a FWHM$\approx$ 250 keV for the width of the peaks of the relative energy $E_{^{12}C-^{12}C}$. The large difference in the instrumental widths of the Q value and of the relative energy peaks is to our knowledge a common feature of this kind of experiment. It reflects the different sensitivity to variations in the input values of the kinematical relationships used to determine the two required quantities. However, the measured width of the $E_{^{12}C-^{12}C}$ peaks is of the order of 500 keV (Fig. 3). Therefore, an intrinsic width still of the order of 500 keV can be attributed to these peaks.

IV. DISCUSSION

Let us call θ^* the angle of emission of ^{24}Mg* in the c.m. system, while ψ is the angle of emission of one of the two ^{12}C ions in the ^{24}Mg* c.m. system. Both angles are measured with respect to the beam axis [7].

Since we are dealing only with the events under the Q_{gg} peak, all nuclei involved in reaction (1) have $J^\pi = 0^+$. Therefore, whenever ^{24}Mg* is emitted at an angle $\theta^* = 0°$, the angular distribution $W(\psi_0)$ of ^{12}C has to be given by a squared Legendre polynomial $\mid P_J(\cos\psi_0)\mid^2$, where J is the angular momentum of ^{24}Mg* and the symbol ψ_0 is meant to indicate the values of ψ for $\theta^* = 0°$.

For $\theta^* \neq 0°$, the behavior of $W(\psi)$ is not predictable in a straightforward manner. However, in some cases all the events can be used to deduce the value of J [7]. Figures 4(a) and 4(b) show the events under the two peaks in a θ^*-ψ scatter plot. According to Ref. [7], a value of ψ_0 was assigned to each event after projection onto the θ^* axis along the tilted straight lines which were taken to fit the "ridges" in the plot. Since the two sets of lines have the same slope and the same spacing, one can deduce [7] that both states have the same value of J.

All the events of Figs. 4(a) and 4(b) were then treated together to improve the statistics, with the procedure underlined above. The result is shown in Fig. 5 together with a $\mid P_{14}(\cos\psi_0)\mid^2$ squared Legendre polynomial arbitrarily normalized to the data. In spite of the rather limited angular range, it is clear that the angular distribution is dominated by a single value of the angular momentum.

We can conclude that the levels at 35.1 and 36.3 MeV excitation energy, being preferentially excited in a region of high level density, with a width of about 500 keV and having a $J = 14$ angular momentum, are of QM nature. Table I reports the ^{24}Mg QM levels studied at 113 MeV (present work) and at 85 MeV incident energy [1,2]. They are also reported in Fig. 6 and compared with previously known QM states [8].

Let us remember here that more than a decade ago reaction (1) was largely investigated at c.m. energies of the order of 50 MeV. The energy of the α particles emitted in reaction (3a) was measured by two groups of researchers [9–12]. The spectra showed broad peaks, which were interpreted as corresponding to preferentially excited states in ^{24}Mg. The energy, width, and spacing of these states were such as to suggest an interpretation in terms of excitation of QM resonances. This picture turned out to be in contrast with the findings of other experiments which measured not only α-particle spectra [13,14], but also α-^{12}C and ^{12}C-^{12}C coincidences [15–21].

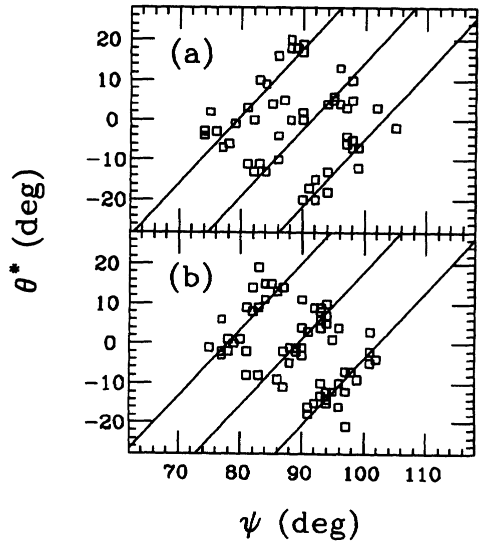

FIG. 4. $\theta^* - \psi$ scatter plot for the events falling under the (a) first and (b) second peaks in Fig. 3. The straight lines used to fit the data have the same slope and the same spacing.

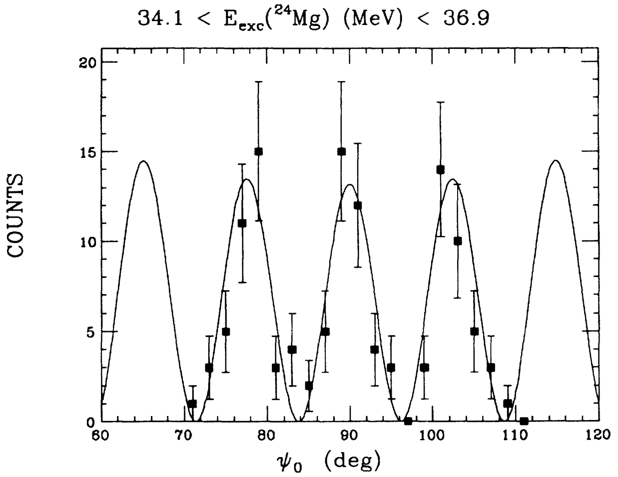

FIG. 5. ^{12}C angular distribution for the $^{24}Mg^*$ states at 35.1 and 36.3 MeV, compared with a $L = 14$ squared Legendre polynomial arbitrarily normalized to the data.

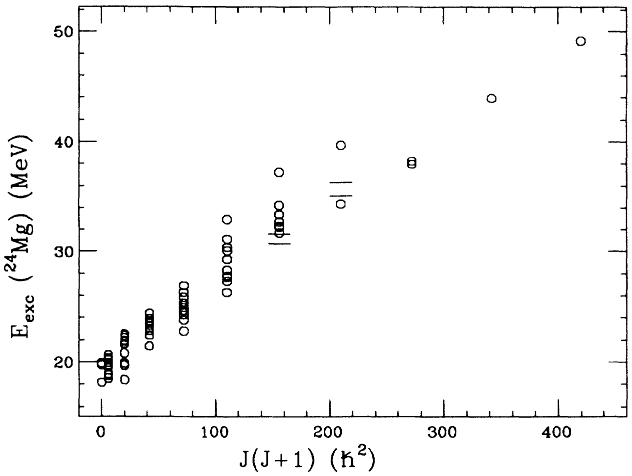

FIG. 6. $E_{exc}(^{24}Mg)$ vs $J(J + 1)$ for all the reported QM states [8] (open circles) and for those obtained (Refs. [1,2] and present work) in the $^{16}O + {}^{12}C$ interaction (dashes).

The interpretation of Refs. [9–12] was questioned, and the most common conclusion was that the peaks did not come from the ^{12}C-^{12}C final state interaction, but rather from the α-^{12}C one or, in other words, from the decay of ^{16}O excited at 10–20 MeV in the interaction with the ^{12}C target. The debate was settled when new α-particle spectra measurements [22,23] showed that the apparent excitation energy of ^{24}Mg changed continuously, when changing the incident energy, thus contradicting the previous interpretation in terms of the excitation of QM states in ^{24}Mg.

Only a few very weak peaks in the α spectra reported in Ref. [22] corresponded to a ^{24}Mg excitation energy not changing with the beam energy, thus indicating that reaction (1) proceeds also through the sequential process (3a). We stress here that the procedure we have used (the study of the ^{12}C-^{12}C relative energy distribution only for events having both ^{12}C-α relative energies greater than 16 MeV) has reduced the dominance [13–21] of the $^{16}O^*$ decays. Therefore, the detection and the study of the $^{24}Mg^*$ states have been made possible. Such a procedure was already used in our previous work [1,2] and in Ref. [15]. It is justified by the evident (Fig. 2) reduction in selective ^{16}O excitation at the highest energies, which in turn can be explained by the corresponding increase in number of states and of open channels. On the other hand, it introduces a cutoff at the highest ^{12}C-^{12}C relative energy (which increases when the ^{16}O-α relative energies decrease) and reduces the range of the θ^* and ψ angles which are useful to get information on the spin J of $^{24}Mg^*$.

TABLE I. Resonances observed as ^{12}C-^{12}C final state interaction in the $^{16}O + {}^{12}C \rightarrow {}^{12}C + {}^{12}C + \alpha$ reaction at $E(^{16}O) = 85$ and 113 MeV.

$E_{exc}(^{24}Mg)$(MeV)	J	$E(^{16}O)$
30.7	12	85
31.6	12	85
35.1	14	113
36.3	14	113

In order to understand the mechanism of the reaction, it is interesting to evaluate the angular momentum transfer to the ^{24}Mg nucleus. Since the reaction proceeds through the transfer of a spinless cluster between spinless nuclei, the simple condition $L_i = L_f + J$ must hold (see the Appendix). Here L_i and L_f are the grazing orbital angular momenta in the entrance and exit channels of reaction (3a), respectively, and J is the spin of the excited state of ^{24}Mg. The matching value of the angular momentum J as a function of E_{exc} can then be calculated by following a method proposed by Brink [24] for the transfer of a single nucleon. In the Appendix we report about a development of the Brink model which takes into account the transfer of a large cluster.

The result of these calculations are shown in Fig. 7 for 85 and 113 MeV as dashed curves. They have been calculated by assuming a ^{12}C transfer from the ^{16}O to the ^{12}C target nucleus to form ^{24}Mg. The curves for the alternative ^8Be transfer from ^{12}C to ^{16}O were found to be very similar and are not reported in Fig. 7. In the figure the hatched areas mark approximately the range of the ^{24}Mg excitation energy which can be reached in the experiment. The two resonances measured at 85 MeV fall in the overlap region between the average behavior of the QM band (solid curve), the hatched area, and the angular momentum matching condition (dashed curve). It is evident from Fig. 7(b) how the increase in incident energy from 85 to 113 MeV and the change in the kinematical conditions (run A) allow one to reach different regions of the QM band. We remark finally that no evidence for resonances was obtained in the measurement of run B, where the condition for angular momentum matching is not fulfilled.

In conclusion, the study of the $^{16}O + {}^{12}C \rightarrow {}^{12}C + {}^{12}C + \alpha$ reaction has shown that QM configurations can be excited in ^{24}Mg through the $^{16}O + {}^{12}C \rightarrow {}^{24}$

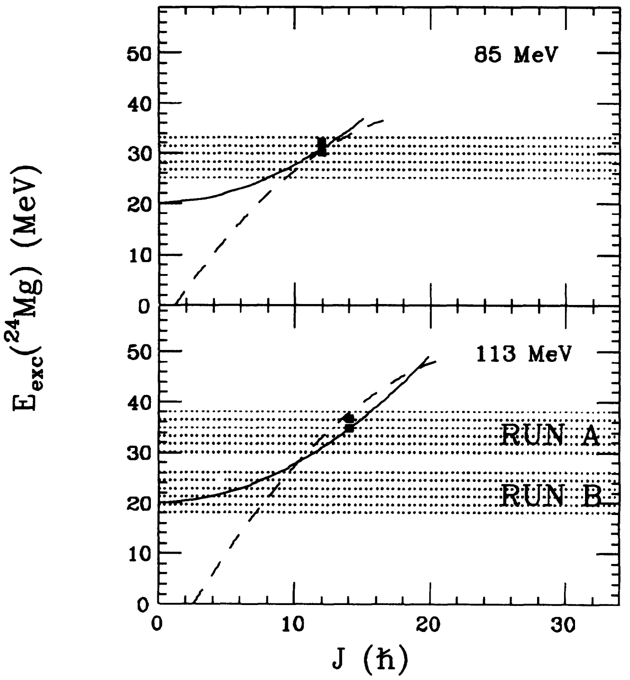

FIG. 7. Relationship $E_{\rm exc}(^{24}\rm Mg)$ vs J. The solid curves give the average trend of the ^{24}Mg QM band, while the dashed line reports the matching value of J as a function of $E_{\rm exc}(^{24}\rm Mg)$, obtained for $E(^{16}\rm O)$= (a) 85 MeV and (b) 113 MeV. The dotted areas indicate the ranges of $E_{\rm exc}(^{24}\rm Mg)$ which have been reached at 85 MeV and in the two runs at 113 MeV (see text).

Mg* + α process, in a large range of incident energy. Moreover, the results summarized in Figs. 7(a) and 7(b) give evidence to the dominant role of the angular momentum transfer in the process. In the present work, the resonances have been studied only through their decay into the ^{12}C + ^{12}C channel. Their nature should also be further investigated by measuring the different branching ratios for the decay into the various channels (^{12}C + ^{12}C, ^{16}O + ^{8}Be, ^{20}Ne + α, etc.). This was not possible with our experimental setup, which could not measure properly light ions.

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APPENDIX

Let us consider a transfer reaction

$$(a+x)+b \rightarrow a+(x+b),$$

in which a cluster x is transferred from the nucleus $(a+x)$ to a nucleus b to form a final nucleus $(x+b)$ with an excitation energy E^*. The angular momentum J of the final nucleus can be determined in a classical model, by modifying the procedure first suggested by Brink [24] for nucleon transfer, in order to take into account the large mass of cluster x. The following simplifying assumptions are made for the involved intrinsic angular momenta: (i) zero spin for clusters a, b, and x, (ii) $l=0$ for the $a-x$ relative motion in nucleus $(a+x)$, and (iii) $l=J$ for the $b-x$ relative motion in nucleus $(x+b)$.

The conservation of angular momentum and the fact that the initial and final orbital angular momentum vectors $\mathbf{L}_i$ and $\mathbf{L}_f$ are perpendicular to the reaction plane give the following matching condition for J:

$$J_{\rm match} = L_i - L_f = p_i d_i - p_f d_f,$$

with $p_k = \sqrt{2\mu_k E_k}$, where p_k, μ_k, E_k and d_k are the relative momentum, the reduced mass, the relative energy, and the distance between the centers of mass of the two interacting nuclei at the collision for the entrance $(k=i)$ and exit $(k=j)$ channels, respectively.

The relative energies E_k have to be deduced from the asymptotic relative energies E_k^∞ by subtracting the Coulomb energy at the interaction distance, so that one gets (energies in MeV and distances in fm)

$$E_i = E_i^\infty - 1.44\,\frac{Z_{a+x}Z_b}{d_i},$$

while

$$E_f = E_f^\infty - 1.44\,\frac{Z_a Z_{b+x}}{d_f},$$

where the Z's are the charges of the nuclei involved in the process and

$$E_f^\infty = E_i^\infty + Q - E^{\rm exc},$$

Q being the energy balance of the reaction. Note that for a particular reaction, L_f and hence $J_{\rm match}$ depend on the excitation energy $E_{\rm exc}$ of the $b+x$ nucleus.

To calculate the distances d_i and d_f, let us consider that at the collision the interacting nuclei can be assimilated to three spheres in a row, with cluster x in between the two clusters a and b. By assuming also that the three clusters have the same charge-to-mass ratio, one obtains

$$d_i = \frac{A_a}{A_b + A_x}\,(r_a + r_x) + r_x + r_b$$

and

$$d_f = \frac{A_b}{A_a + A_x}\,(r_b + r_x) + r_x + r_a,$$

where A_j and r_j are the mass and radius of the clusters $(j = a, b, x)$. For the radii we assumed the usual relationship

$$r_j = r_0 A_j^{1/3}, \quad r_0 = 1.3 \text{ fm}.$$

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