Correlated Spin Orientations in $^{12}C + ^{12}C$ Molecular Resonances

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The correlation between the spin orientations of the two $^{12}C(2^+)$ nuclei in mutual inelastic $^{12}C + ^{12}C$ scattering has been deduced from the directional correlations of the particle-coincident γ rays measured with a crystal-ball detector. Resonances in the cross section are found to be nearly uniquely associated with the mutually aligned component. The strong resonance structure as well as the characteristic behavior of the angular distributions of this reaction component are suggestive of the formation of a rotating dinuclear complex in the sticking configuration.

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New experimental approaches to reveal the nature of resonant $^{12}C + ^{12}C$ scattering, by means of γ-ray–particle coincidence measurements, have added still more puzzling results to this long-standing question[1] of heavy-ion physics. The search[2] for collective γ-ray transitions between states of an assumed molecular band of this system was unsuccessful insofar as the transition strengths were found to be at least an order of magnitude smaller than expected in a collective rotor picture.[3] In another series of experiments,[4-6] the $^{12}C(2^+)$ spin alignment along the scattering normal in single inelastic scattering was found to be only modestly correlated with the resonant structure, as a function of bombarding energy, and to be rather small on average, in contrast to the expectation of an aligned coupling between the orbital angular momentum and the intrinsic spin. The measured values could not be reproduced satisfactorily by either direct-reaction or molecular-model calculations.[7] Classically, an aligned coupling would result from the condition of orbit matching, according to which the intrinsic excitation energy would balance the loss in rotational energy of relative motion at the reaction distance if the potential energy did not change.

A clear and encouraging result, however, was obtained in a measurement of the spin alignment in the case of mutual inelastic scattering, $^{12}C^{12}C \rightarrow {}^{12}C(2^+) + {}^{12}C(2^+)$. The pronounced peaks in the cross section[8] were found to be associated with a strong enhancement of the spin alignment above its rather small average value.[5] This indicated that the resonant configuration is characteristically different from that of the nonresonant background.

In this Letter we report on an experiment performed with the Darmstadt-Heidelberg crystal-ball detector[9] from which we obtain qualitatively new information on the spin orientations in the mutually excited channel. By virtue of the eventwise recording of the directions of both γ rays from the $^{12}C(2^+)$ nuclei we have determined the *orientation correlations* between the two nuclear spins. This allows us to decompose the cross section into the contributions $\sigma_{|m_1||m_2|}$ from the various m-substate combinations. As a function of energy and angle these individual cross sections show dramatic differences. It is clearly suggested by these data that the respective orientation of the deformed ^{12}C nuclei plays a decisive role in their resonance behavior.

Natural-carbon targets of 50-μg/cm^2 thickness were bombarded with ^{12}C beams at nine energies between $E_{lab} = 38.6$ and 69.4 MeV from the Heidelberg MP tandem Van de Graaff accelerator. Heavy ions were detected with two position-sensitive silicon detectors mounted in planar geometry inside a scattering chamber surrounded by the crystal ball. By observation of kinematic coincidences between the two detectors, the various scattering and reaction channels were identified. In coincidence with each mutually inelastic scattering event, the two 4.44-MeV γ rays from the $^{12}C(2^+)$ decay to the 0^+ ground state were recorded with almost 100% efficiency by use of 159 NaI crystals of the full array of 162.

The quantization axis is chosen to be along the direction normal to the scattering plane. After integration over the azimuthal angle, the directional pattern is given by a matrix $W(\vartheta_1,\vartheta_2)\Delta\vartheta_1\Delta\vartheta_2$ of the probability per particle event for the emission of one γ ray into the polar angle ϑ_1 and the other γ ray into the polar angle ϑ_2. This is expanded in terms of the intensity distributions $W_{|m|}(\vartheta)$ for pure-$|m|$ quadrupole radiation, found in textbooks,

$$W(\vartheta_1,\vartheta_2)=\sum_{|m_1|}\sum_{|m_2|}P_{|m_1||m_2|}W_{|m_1|}(\vartheta_1)W_{|m_2|}(\vartheta_2).$$

Interference terms, which are present in the complete angular correlation,[10] cancel by the azimuthal integration. By fitting the data with the above expression, we obtain the joint probabilities $P_{|m_1||m_2|}$ of the $|m_1| \times |m_2|$ substate combinations of both $^{12}C(2^+)$ nuclei. The rather small effects of the transformation into the laboratory system have been taken into account. As a result of reflection symmetry about the scattering plane, only combinations of both even m or both odd m are allowed.[11] Multiplication of the joint probabilities with the particle-inclusive differential cross section $\sigma(\theta)=d\sigma(\theta)/d\Omega$ yields the cross sections for the different substate combinations $\sigma_{22}(\theta)$, $\sigma_{20}(\theta)$, $\sigma_{11}(\theta)$, and $\sigma_{00}(\theta)$. Here, σ_{20} is the sum of the yields with $|m_1|=2$, $|m_2|=0$ and with $|m_1|=0$, $|m_2|=2$ which are equal in symmetric systems.

The cross sections $\overline{\sigma}_{|m_1||m_2|}$, obtained after integration over the range of scattering angles $45° < \theta_{c.m.} < 90°$, are shown in Fig. 1 together with the summed cross section in this angular range (upper panel, large dots), which follows the resonance behavior of the total mutually inelastic cross section of Ref. 8 (upper panel, small dots).

These results reveal with striking clarity that the pronounced resonance structures of $\sigma(E)$ above 23 MeV arise essentially only from the doubly spin-aligned component σ_{22}. Dramatic structure, with peak-to-valley ratios of one order of magnitude, is observed for this component. The other m-substate combinations have characteristically different excitation functions. Weak structure is observed for σ_{20} which is, however, correlated with that of σ_{22}. The partially aligned component σ_{11} does not participate in the resonant behavior. The nonaligned component σ_{00} is most weakly excited at all energies.

The smallness of σ_{00} reflects the mismatch of zero total spin projection by about $4\hbar$ at $Q=-8.88$ MeV. For the same reason, contributions with $m_1=-m_2$ to σ_{22}, which are not distinguishable from $m_1=m_2$ by means of the off-plane correlation patterns, are expected to be small.

The widths of the $^{12}C+^{12}C$ resonances, seen in the inclusive cross section as well as in the alignment,[5] are

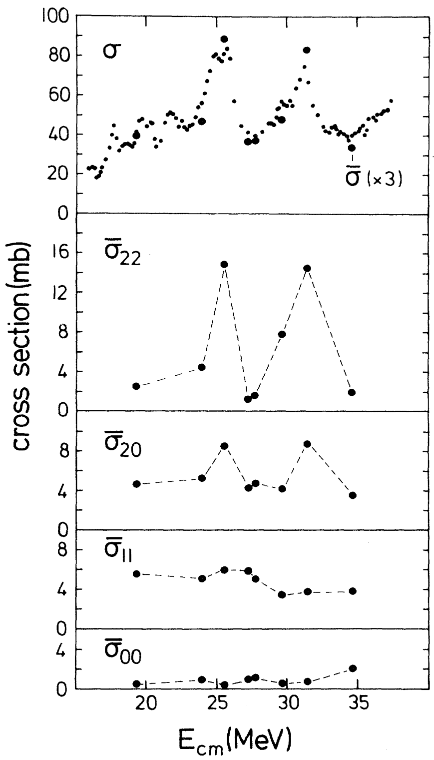

FIG. 1. Decomposition of the cross section for mutually inelastic $^{12}C+^{12}C$ scattering into the contributions from different m-substate combinations. The particle-inclusive cross section $\overline{\sigma}$ (scaled up by a factor of 3 in the upper panel, large dots) and the contributions $\overline{\sigma}_{|,m_1||m_2|}$ (the sum of which yields $\overline{\sigma}$) are integrated over the angular range $45° < \theta_{c.m.} < 90°$. The total integrated cross section σ (small dots, upper panel) is taken from Ref. 8. The dashed lines are drawn to guide the eye and do not exclude any finer structure (Ref. 12). The target thickness corresponds to an avarage over $E_{c.m.}=100$–170 keV.

smaller than those expected for pure shape resonances and larger than those expected for compound-nucleus decay.[1,8] The width of the resonances of σ_{22} is confined by these observations to the same range. A study of the individual $\sigma_{|m_1||m_2|}$ excitation functions in narrower steps would be of interest.

A second characteristic of the resonance mechanism is displayed by the angular distributions $\sigma_{22}(\theta)$ shown in Fig. 2. Their structure changes from strongly oscillating at cross section minima (cf. Fig. 1) to rather smooth and approximately following a $1/\sin\theta$ shape at the cross section maxima at $E_{c.m.}=25.6$ MeV and 31.5 MeV. Such a behavior is expected for a sequence of single–partial-wave resonances in a well-matched reaction. In the case of angular momentum transfer $L=4$, $M(=m_1+m_2)=\pm 4$, the partial-wave decomposition of the differential cross section is in good approximation given by[13]

$$\sigma_{M=\pm 4}(\theta) \sim (1/\sin\theta)\left|\sum_{l_f}(2l_f+1)\Big\{A_{l_f,l_f-4}\exp\{\mp i[(l_f+\tfrac{1}{2})\theta-\pi/4]\} + A_{l_f,l_f+4}\exp\{\pm i[(l_f+\tfrac{1}{2})\theta-\pi/4]\}\Big\}\right|^2,$$

with complex amplitudes A_{l_f,l_i} containing the radial integrals and angle-independent phases. Rapid oscillations of $\sigma(\theta)$ are due to the interference of the terms with positive and negative exponents in this equation which, semiclassically, are interpreted as arising from opposite sides of the interaction region (see, e.g., Bond[14]). The radial integral $|A_{l_f,l_f+4}|$ is large on resonance if $l_i = l_f + 4$ fulfills the classical matching condition, while the term with $l_i = l_f - 4$, mismatched by $8\hbar$, will be comparatively small and cause only weak interferences. Off resonance, the two terms may be more similar in magnitude such that the interferences become clearly visible.

These concepts apply also to a distribution of partial waves around a dominant l value where, however, additional low-frequency modulations of $\sigma(\theta)$ arise from the presence of neighboring partial waves. Off resonance, this type of interference is indicated by the deviation from $1/\sin\theta$ of the gross shape (see Fig. 2). On resonance, in contrast, the dominance of a single partial wave becomes apparent by the observed $1/\sin\theta$ behavior. This change of pattern is enhanced in symmetric systems where only even partial waves contribute. It is quite conceivable that the l sequence proposed in Ref. 8 accounts for the patterns shown in Fig. 2. These angular distributions, subdivided into the different respective spin orientations, will be much better suited than the m-summed $\sigma(\theta)$ for a quantitative theoretical analysis.

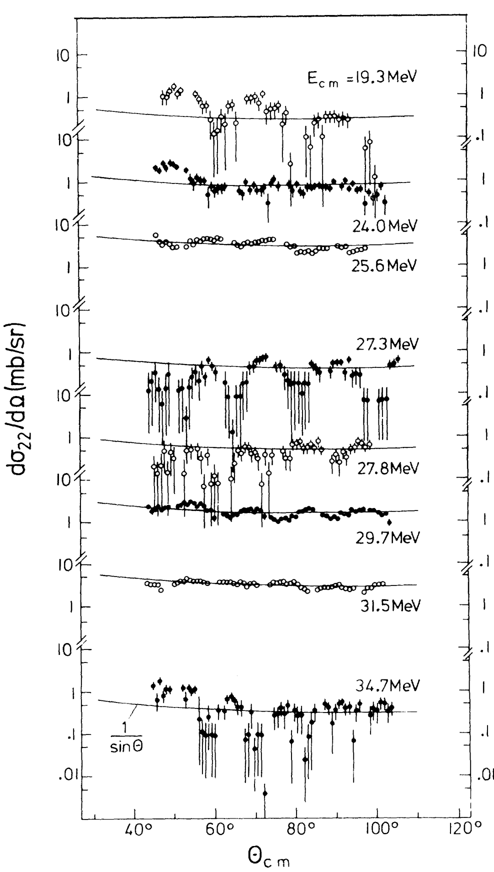

FIG. 2. Differential cross section for the doubly spin-aligned reaction component. The $1/\sin\theta$ curves, shown for comparison, have been adjusted arbitrarily to the data around 90°.

The identification of σ_{22} as the primary constituent of the prominent resonances is suggestive of an interpretation in terms of a specific intermediate resonance configuration. The combination of $m_1 = m_2 = +2$ or -2 fulfills the classical sticking condition which demands parallel intrinsic spins pointing into the direction of l_i, with magnitudes $I_1 = I_2 \approx 2\hbar$ in the case of $^{12}C + {}^{12}C$ at $l_i = (14\text{–}16)\hbar$. It has been pointed out[15] that this condition is relevant for the formation of a molecular complex. In the proposed geometry[15,16] the two pancake-like ^{12}C nuclei touch edge to edge so that the separation line is vertical to the two parallel axes of intrinsic rotation. As borne out by two-center–shell-model[16] and Hartree-Fock[17] calculations, this configuration is more strongly bound at the touching distance than the axially symmetric face-to-face configuration. Moreover, the nonaxially symmetric edge-to-edge configuration has a large structural overlap with the triaxial shape isomers of ^{24}Mg, predicted by Nilsson-Strutinsky model calculations.[18] This similarity in structure makes it particularly suited at the intermediate stage in a doorway coupling scheme.[19]

The observed confinement of the resonance behavior in the mutually inelastic channel to that configuration which fulfills the classical sticking condition lends strong support to these concepts. The regularities of the angular distributions $\sigma_{22}(\theta)$ indicate that this geometry results in a well-defined orbit matching and hence in a stringent angular momentum selectivity.

By the same arguments, one may also understand the small average spin alignment in both inelastic channels and the complicated energy dependence in the single inelastic channel.[5] On the basis of the present experiment, it is suggested that those results are due to the various respective orientations of the oblate ^{12}C nuclei in the entrance and exit channels. The associated differences of the potential energies will modify the matching conditions.

To summarize, using a 4π γ detector, we have deduced the resonance behavior of the various correlated spin orientations in mutually inelastic $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ scattering. The prominent role of the doubly aligned component is in accordance with the concept of an intermediate rotating dinuclear complex in the sticking geometry. Because of the deformed shape of ^{12}C, the sticking condition, which is a well-known classical characteristic of deep-inelastic collisions in heavier systems,[20] becomes relevant for the quantum mechanical phenomenon of $^{12}\mathrm{C}+{}^{12}\mathrm{C}$ resonances.

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