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Evidence for a Rotational Band in ^{24}Mg and Its Fragmentation: A Rotation-Vibration Coupling?

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Three resonances in $^{12}C + ^{12}C$ with $E_{c.m.}(J^\pi)$ of 8.85(6^+), 11.2(8^+), and 13.75(10^+) are reported. Together with earlier data, these resonances fit in a rotational band in ^{24}Mg. A model based on the rotation-vibration coupling is proposed to account for these data.

Several recent experiments[1-4] have provided new information on spins and parities of resonances in ^{24}Mg at high energies of exitation. In the present experiment, we investigate the reaction $^{12}C(^{12}C,\alpha)^{20}Ne$ in the range $6.85 \leq E_{c.m.} \leq 15$ MeV and report three resonances at $E_{c.m.} = 8.85$, 11.2, and 13.75 MeV to which we assign definite J^π values. Combining these results with the data from previously reported measurements[3] and the results of other authors,[1,2,4-9] we attempt a unified picture of the resonances in ^{24}Mg.

The present experiment was performed using the Model FN tandem accelerator of the Centre d'Etudes Nucléaires Bruyères le Châtel. α particles from the reaction $^{12}C(^{12}C,\alpha)^{20}Ne$ were momentum analyzed in a split-pole magnetic spectrograph and detected in position-sensitive detectors. The excitation functions of four α groups leading to, respectively, the ground state and the 1.63-, 4.25-, and 4.97-MeV states in ^{20}Ne were measured at 10° and 20° using a 30-μg/cm^2 carbon target. In addition, the ground-state excitation function was measured at 7.5° lab using a 50-μg/cm^2 target. From the correlated maxima in the excitation functions of transitions leading to natural-parity states in ^{20}Ne and the relative smallness of the 2^- excitation function at very forward angles, energies around $E_{c.m.} = 8.85$, 11.2, and 13.75 MeV were selected as likely candidates for resonances, and ground-state α angular distributions were measured on and off these energies. For a narrow, noninterfering resonance of spin $J = L$, the angular distribution follows the form

$$\sigma(\theta) = A_L{}^2 P_L |\cos\theta|^2 \quad (1)$$

or else (equivalently)

$$\sigma(\theta) = \sum_{l=0}^{l_{max}=2L} a_l p_l(\cos\theta) \quad (l \text{ even}). \quad (2)$$

The comparison of the angular distributions at $E_{c.m.} = 11.2$ and 13.75 MeV with the $P_8{}^2(\cos\theta)$ and $P_{10}{}^2(\cos\theta)$ shapes, respectively, is shown in Fig. 1; the agreement is quite satisfactory.

The measured angular distributions were subsequently submitted to a $\chi^2(l_{max})$ analysis using expression (2). The values of χ^2 plotted vs the maximal degree of polynomials used are shown

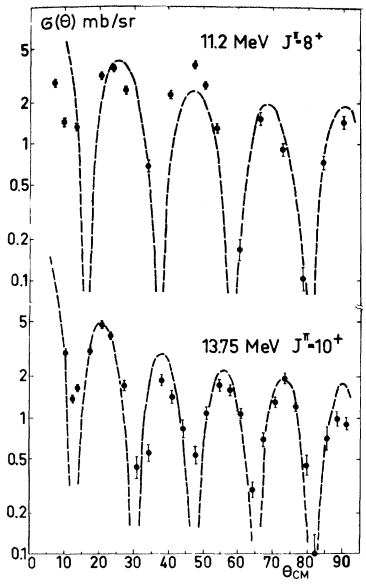

FIG. 1. The 11.2- and 13.75-MeV angular distributions compared with the $P_8{}^2(\cos\theta)$ and $P_{10}{}^2(\cos\theta)$ shapes, respectively.

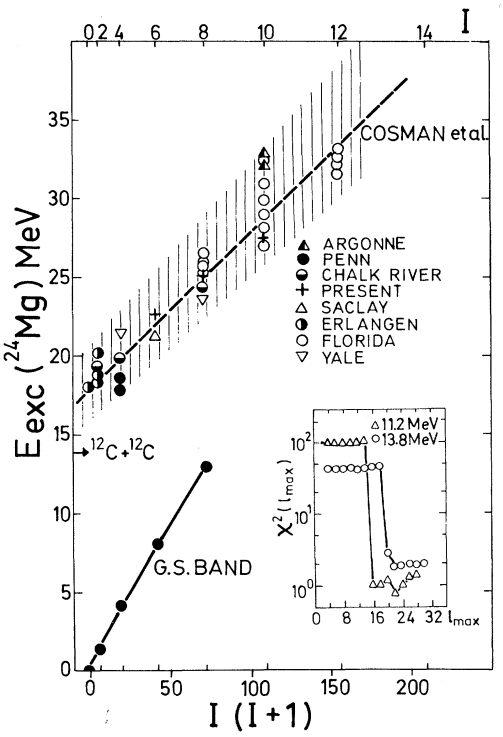

FIG. 2. Resonances in $^{12}C + ^{12}C$ plotted as $E_{exc}(^{24}Mg)$ vs measured spin. Data: ARGONNE, Ref. 2; PENN, Ref. 6; CHALK RIVER, Refs. 4 and 9; PRESENT, this work; SACLAY, Ref. 3; ERLANGEN, Ref. 8; FLORIDA, Ref. 7 (only selected resonances of given J^π plotted); YALE, Ref. 1. Inset: Plot of χ^2 vs l_{max} for the angular distributions at 11.2 and 13.75 MeV.

in the inset of Fig. 2 for the 11.2- and 13.75-MeV angular distributions; the values of $\chi^2(l_{max})$ drop sharply for $l_{max}=16$ and $l_{max}=20$, respectively, and remain stable afterwards. These findings confirm the $J^\pi=8^+$ and 10^+ assignments to these resonances. An equally sharp decrease in $\chi^2(l_{max})$ is observed for the 8.85-MeV resonance at $l_{max}=12$, giving $J^\pi=6^+$ (not shown in the figure).

Angular distributions off the resonance energies showed none of the features described above. Thus, it appears that no explanation in terms of grazing angular momentum [$\sim(8-12)\hbar$ in this energy region for a collision radius of 5 fm] could account for the above-described resonant behavior. Crucial to the resonance interpretation, however, is the elimination of the possibility of statistical fluctuations and other nonresonant phenomena. In this respect we observed that for all the reported resonances the extrema in the excitation functions were correlated for all transitions leading to natural-parity states. We also looked for evidence for the above resonances in other reaction channels. A resonance at 8.85 MeV was reported by Basrak *et al.*[3] in $^{12}C(^{12}C,p)$, while a resonance around 11.4 MeV was reported by Cosman *et al.*[8] in $^{12}C(^{12}C,p)$ and by Fletcher *et al.*[7] in $^{12}C(^{12}C,{}^8Be)$; finally, a resonance in $^{12}C(^{12}C,{}^8Be)$ at 13.85 MeV was reported in Ref. 7. After cross checking the energies of the resonances and taking into account their experimental width, we concluded that the uncertainty in our reported energies is ± 0.075 MeV. Thus an indubitable identification with the above resonances could be done only for the 8.85-MeV one.

In view of the pure $P_L{}^2(\cos\theta)$ shapes for the ground-state angular distributions, the drop in χ^2 at $2L=12$, 16, and 20, the correlated maxima in the transitions to natural-parity states in ^{20}Ne, the minima in the forward-angle transitions to the 2^- state, as well as the presence of some of these resonances in other reaction channels, we conclude that pure $J^\pi=6^+$, 8^+, and 10^+ resonances exist in ^{24}Mg at 22.8 ± 0.1, 25.1 ± 0.1, and 27.7 ± 0.1 MeV, respectively. The experimental width Γ_{expt} of the first resonance is estimated at ~ 0.2 MeV, while those of the two latter resonances are estimated at ~ 0.3 MeV.

Figure 2 shows the present results together with the results of some earlier measurements plotted vs $I(I+1)$. Two features of this plot strike the eye: (i) All the measured values lie on a fairly straight line, and (ii) resonances of the same J^π appear to be grouped within a few MeV.

A conclusion stemming from (i) is the presence of a collective rotational band at high energies of excitation in ^{24}Mg. Such a band has already been proposed by Cosman *et al.*[8] Starting from the 4^+ and 6^+ resonances at 19.9 and 21.4 MeV, respectively, these authors have determined a slope for the proposed rotational band and found that several other resonances (23.3, 28.2, 33.2, and 39 MeV) fall on the same straight line (see Fig. 2). Thus, they have assigned J^π values of 8^+, 10^+, 12^+, and 14^+ to these resonances, respectively. We have proceeded in a different way, i.e., we have plotted E_{exc} vs the *measured* values of $I(I+1)$. Although our results show that the J^π assignments of Ref. 8 are essentially correct, it is clear from Fig. 2 that a whole domain (rather than a line) in the E_{exc} vs $I(I+1)$ plane should be taken into account.

The grouping of resonances of the same J^π into clusters is suggestive of fragmenting of wide shape resonances (a few MeV) into narrower ones (a few hundred keV). This phenomenon, pointed out by Feshbach,[10] has already been ob-

served in Ref. 7; the present results, however, suggest a considerably larger amount of mixing in of resonances differing by 2 units of spin. It is also obvious that other resonances of $J^\pi = 6^+$ should be expected around $E_{c.m.} \approx 8$ MeV.

The existence of narrow resonances at high excitation energies implies a particular intrinsic structure. A vibration coupled to a rotational band, for example, would provide such a structure, exhibiting both the grouping and smaller admixtures of resonances of close J^π values. The existence of rotational bands at high energies of excitation was predicted a few years ago by Fink *et al.*[11] and by Arima *et al.*[12] Both of these predictions yielded bands in "molecular" channels which agreed with the experimentally observed resonance domain in ^{24}Mg. The calculated widths of the resonances were, however, substantially larger than the observed widths of a few hundred keV; on the other hand, these widths would agree with the spreading of the envelopes of resonances of the same J^π (a few MeV).

Taking the above models at their face value, we can describe the observed "molecular" band in terms of two rotating ^{12}C nuclei, where the splitting of the wide (rotational) resonances would be due to surface vibrations of the rotating ^{12}C-^{12}C system. Thus the physical picture would be the following: First, the two colliding ^{12}C nuclei provide a rotor consisting of a ^{12}C-^{12}C "molecule." It is impressive that the average slope of E vs $I(I+1)$ in Fig. 2 gives an experimental moment of inertia for the rotating system essentially equal to that of two carbon nuclei rotating around a median axis at a distance $R = 1.3 \times 12^{1/3} = 3$ fm. This value of the moment of inertia is about twice as large as that deduced from the ground-state band in ^{24}Mg. Pushing this picture still further, we obtain the value of 2.6×10^{21} s^{-1} for the frequency of rotation corresponding to, e.g., the 8^+ resonance at 11.2 MeV. Furthermore, considering the envelope of all the known 8^+ resonances (~ 3 MeV) as the width of the 8^+ "molecular" resonance, we obtain a lifetime of $\sim 4 \times 10^{-22}$ s. Thus in the above simple picture, the two ^{12}C nuclei would perform a fraction ($\sim \frac{1}{10}$) of a full rotation before either coalescing or splitting into the ^{12}C + ^{12}C exit channel.

The shock between the two ^{12}C nuclei may lead to surface vibrations in the system, similar to β and γ vibrations. These vibrations will split a wide rotational resonance into several narrower resonances. We can apply the first-order rotation-vibration model,[13] where the energy spectrum is given by

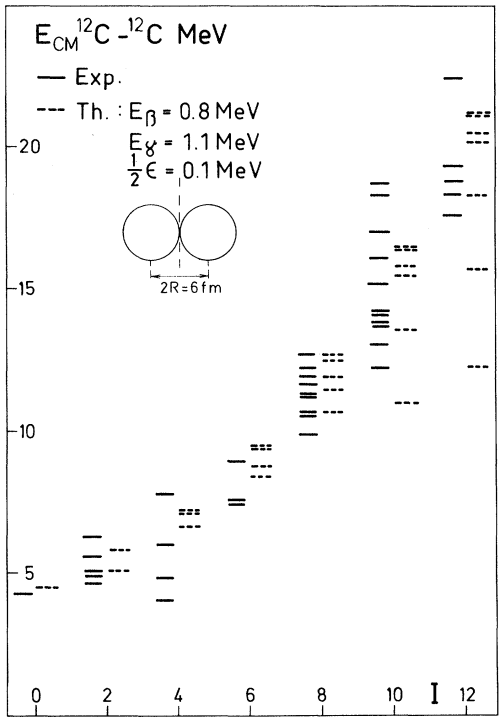

FIG. 3. Comparison of the experimental and calculated resonance spectra (rotation-vibration model, no coupling).

$$E_{IKn_2n_0} = |I(I+1) - K^2|\tfrac{1}{2}\epsilon + (\tfrac{1}{2}|K| + 1 + 2n_2)E_\gamma + (n_0 + \tfrac{1}{2})E_\beta, \qquad (3)$$

with $n_0 = n_2 = 1$. The parameter $\frac{1}{2}\epsilon = \hbar^2/2\mathcal{I}$ is determined from the average slope in Fig. 2. We take $E_\beta = 0.8$ MeV (an arbitrary but reasonable value); then, fixing the bandhead near the experimental value of $E_{c.m.} = 4.2$ MeV, we obtain $E_\gamma = 1.1$ MeV. Thus the ratio E_γ/E_β appears as the only free parameter in the calculation. Figure 3 shows that the calculated and experimental spectra are in fair qualitative agreement. It is hoped that inclusion of the rotation-vibration coupling would improve the above picture, giving, in particular, the width of the resonances.

A more sophisticated approach, but leading to similar conclusions, has been suggested by Leander and Larssen.[14] Their results show that a shell develops for $N = Z = 12$ with increasing deformation, thus favoring the formation of ^{12}C clusters. The collective rotation of these may be associated with the observed rotational band.

An additional piece of information on the nature

of these resonances is given by the $^{12}C+^{12}C$ and α_0 widths, Γ_C and Γ_{α_0}. From $\sigma_{tot}=8\pi\lambda^2(2L+1)\Gamma_C \times\Gamma_{\alpha_0}/\Gamma^2=8.9\pm2.3$ mb for all the 11.2-MeV 8^+ resonance, one obtains $\Gamma_C\Gamma_{\alpha_0}/\Gamma^2=0.015\pm0.004$, which is comparable with the value of 0.0068 obtained in Ref. 2 for the 19.0-MeV 10^+ resonance. Furthermore, taking $\Gamma\sim\Gamma_{\alpha_0}+\Gamma_C$, one obtains that $\Gamma_{\alpha_0}\sim\Gamma_C$ within the experimental error. From the relative penetrabilities of ^{12}C and α particles, for the reduced widths we conclude $\gamma_C^2>\gamma_{\alpha_0}^2$, thus strengthening the "molecular" picture of the resonances.

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Three-Photon Excitation of Xenon and Carbon Monoxide

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With intense light of a pulsed tunable dye laser, the $^3P_1$ resonance state of xenon and the P, Q, and R branches of the (2-0) band of CO in the fourth positive system ($A^1\Pi\leftarrow X^1\Sigma^+$) are excited by simultaneous absorption of three visible laser photons. The excitation is monitored by detecting the fluorescent decay in the vacuum ultraviolet.

We report the excitation of Xe and CO by simultaneous absorption of three visible photons. In this first observation of the excitation of an atomic and a molecular gas by three-photon absorption[1] the $^3P_1$ resonance state of xenon and the P, Q, and R branches of the (2-0) band of CO in the fourth positive system ($A^1\Pi\leftarrow X^1\Sigma^+$) are excited with intense tunable-dye-laser radiation of about 4400 Å. The three-photon excitation is monitored by detecting the fluorescent decay of the excited states in the vacuum ultraviolet.

There is considerable interest in three-photon excitation of atomic and molecular states. For instance, as demonstrated in the present experiments, this method permits high-resolution laser spectroscopy in the spectral region of the vacuum ultraviolet in a simple experimental arrangement. In this spectral region nonlinear laser spectroscopy has been performed so far by two-photon excitation of atoms[2] and molecules[3] with intense ultraviolet light of frequency-doubled dye lasers. Since two-photon excitation is restricted to the excitation of levels of the same parity as the ground state and three-photon absorption excites states of opposite parity, the two methods complement each other for nonlinear spectroscopy. As discussed below, both methods can provide a Doppler-free recording of the observed transitions in an almost identical, simple scheme of excitation.

The intense tunable-laser radiation, required for the present experiments, is generated with a pulsed-dye-laser oscillator amplifier system.[4] For the recording of the three-photon exitation of xenon (Fig. 1) the blue laser light, exceeding 80-kW pulse peak power, was focused by a lens of 500-mm focal length into a small gas cell (a 50-cm-long section of 20-mm-diam glass tubing with parallel quartz windows) to a beam waist of about 50 μm. The fluorescence at $\lambda=1470$ Å is observed through a MgF_2 side window and monitored by a solar-blind photomultiplier (EMR 541 G). The signal is amplified and accumulated by a gated integrator before being recorded by an x-y recorder. Because of the high transition probability[5] ($A=2.2\times10^8$ sec^{-1}) of the observed resonance transition, the fluorescence is resonantly trapped and reduced due to the quenching