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MOLECULAR CONFIGURATIONS: THE FRAGMENTATION OF A ROTATIONAL BAND AT HIGH EXCITATION ENERGIES IN ^{24}Mg AND THE ROTATION-VIBRATION MODEL

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One of the interesting aspects of heavy-ion nuclear physics in its early days was the experimental discovery of resonances in heavy-ion reactions[1)]. The interest of this discovery was in the fact that one did not expect isolated, narrow resonances to be present at energies of excitation of 20-30 MeV. These resonances were found more than 15 years ago but we are still not quite sure what their physical nature is.

In this contribution I shall present the experimental results obtained for the $^{12}C+^{12}C$ system, including some new resonances reported at this Conference[2,3)]. These resonances, together with earlier results, now give a unified picture of the resonances in this system. Later on, I shall report on a new model which, we believe, gives a comprehensive physical picture of the phenomenon.

The presently available experimental results on the resonances in the $^{12}C+^{12}C$ system are shown in Fig. 1. Two features of this picture draw our attention:

(i) all the measured J^{π} values lie in a domain centred around a fairly straight line in the

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[+] Talk presented by N.Cindro

E_{exc} vs J(J+1) plane;

(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 new rotational band at high energies of excitation in ^{24}Mg. On the other hand, the grouping of resonances of the same J^π into clusters is suggestive of fragmenting of wide shape-resonances (∿MeV) into narrower ones (∿100 keV).

In order to account for these data, we present a simple model based on the molecular picture$^{2)}$. We start with the assumption that the J(J+1) dependence of the "gross" structure of resonances implies some sort of underlying rotor-like configuration. The particular location of the resonances in the E_{exc} vs J plane

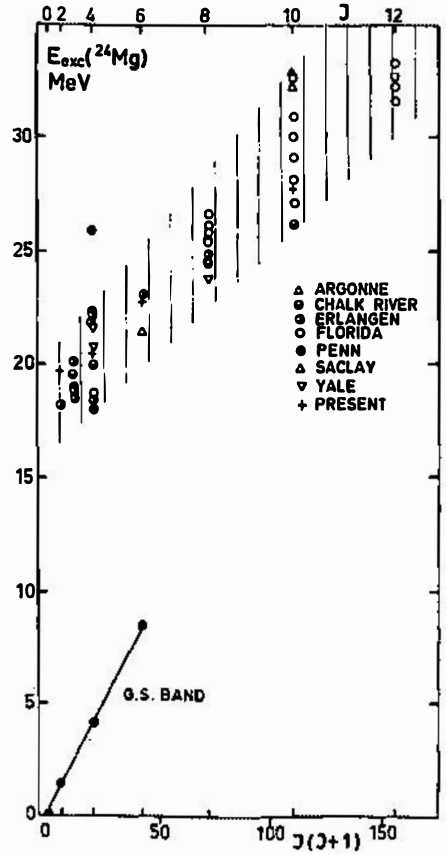

Fig.1. Experimentally observed resonances in $^{12}C+^{12}C$ plotted in an $E_{exc}(^{24}Mg)$ vs J(J+1) diagram. The data are: ARGONNE: H.T. Fortune et al., Phys.Lett. 63B (1976) 403 and Phys.Rev. C14 (1976) 1271; CHALK RIVER: E. Almquist et al., Phys.Rev. 130 (1963) 1140; ERLANGEN: W. Galster et al., Phys. Rev. C15 (1977) 950 and ref. 8, FLORIDA: N.R. Fletcher et al., Phys. Rev. C13 (1976) 1173; PENN: M. Mazarikis et al., Phys.Rev. C7 (1973) 1280, SACLAY: Z. Basrak et al., Phys.Lett. 65B (1976) 119; YALE: K.A. Erb et al., Phys. Rev.Lett. 37 (1976) 670; PRESENT: refs. 2 and 3.

(the resonances lie within the predicted "molecular" channels[4,5]) favours the idea that this rotor is supplied by a "molecular" configuration. To complete the picture, we still have to propose a mechanism that splits the wide resonances and, hence, we propose the following model:

We take two colliding ^{12}C nuclei to provide a molecular type rotor; on the other hand, the shock between the two nuclei leads to surface vibrations of the system, similar to the β and γ vibrations known in deformed nuclei. The coupling of these vibrations to the rotational motion splits the wide rotational resonances into narrower ones.

Here are the arguments in favour of this model:

- the average $E_{exc}(^{24}Mg)$ vs $J(J+1)$ slope obtained from experiment (Fig. 1) yields a moment of inertia for the rotating system equal to

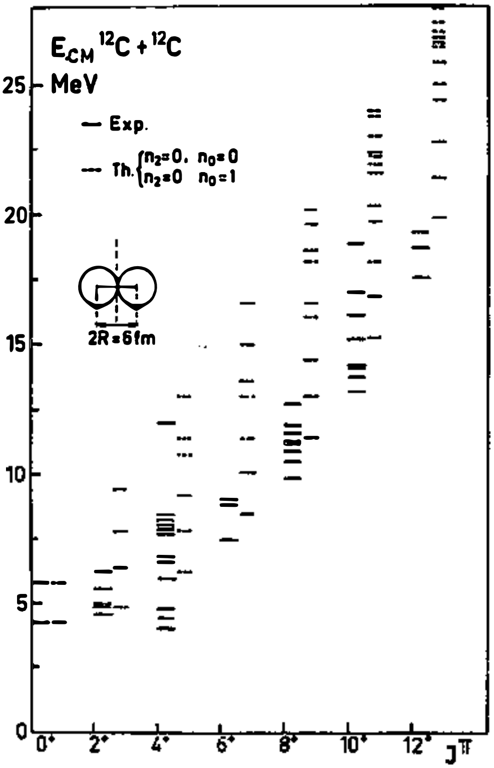

Fig.2. Comparison of experimentally observed (full lines) and calculated (dotted lines) resonance spectra. Theory: eq. (1), with $n_0=0$, $n_2=0$ and $n_0=1$, $n_2=0$ for the lowest 0^+ resonances.

$$\underset{\sim}{\vartheta}_{exp} = 2.2\ 10^{-42}\ \mathrm{MeV\ s^2}\ ,$$

which is essentially equal to that of two ^{12}C nuclei rotating around a median axis at a distance $2R = 2\times 1.3\times(12)^{1/3} = 6$ fm (see Fig. 2);

- this moment of inertia is twice as large as that obtained from the g.s. band, indicating significant structural changes in the two corresponding configurations;
- using the simple classical expression

$$E_{rot} = E(J) - E(0) = \frac{\vartheta\omega^2}{2}$$

and the obtained value of $\underset{\sim}{\vartheta}$, it is possible to calculate the rotation frequency of, say, the 8^+ "gross" resonance. Estimating the median energy of the $J^\pi=8^+$ resonances to 11.5 MeV and that of the bandhead to 5 MeV (see Fig. 1), one obtains

$$\omega = 2.4\times 10^{+21}\ \mathrm{s^{-1}}\ .$$

Assuming the total width of this "gross" resonance to be ∿3 MeV (corresponding to a life-time of $\sim 4\times 10^{-22}$s), one obtains that the system performs about 1/5 of a full rotation before the two ^{12}C nuclei either coalesce or split into the $^{12}C+^{12}C$ channel. (For comparison, the rearrangement time of the nuclear shells was estimated to about 5×10^{-22} s [6]).

We shall now consider the surface vibration. In the first-order rotation-vibration model, the energy spectrum of a rotating and vibrating system is given by[7]:

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

Several of the parameters entering this expression can be evaluated from experiment or guessed from nuclear systematics. First, the value of $\frac{1}{2}\varepsilon = \frac{1}{2}\cdot\frac{\hbar^2}{\underset{\sim}{\vartheta}}$ can be obtained from the slope of E_{exc} vs $J(J+1)$ diagram. The data in Fig. 1 yield a value of $\frac{1}{2}\varepsilon \approx 0.1$ MeV. The values of the surface vibration energies E_γ and E_β are expected from the nuclear systematics to be of the order of a MeV, while the corresponding quantum numbers n_2 and

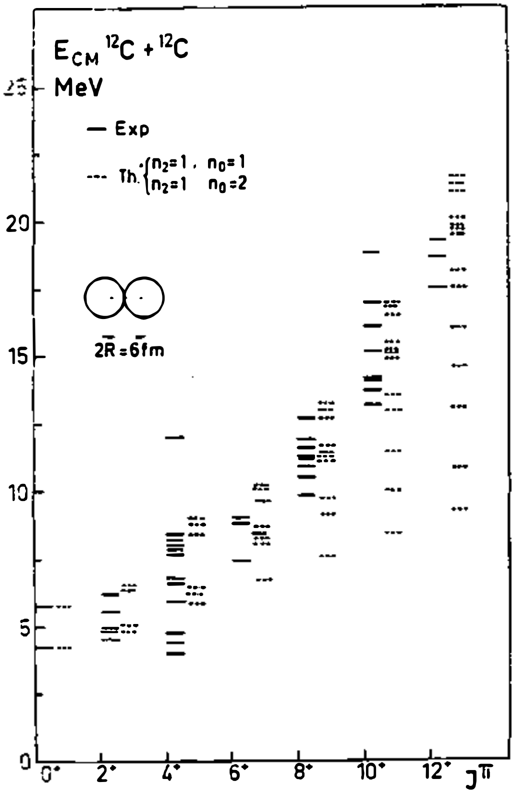

Fig.3. Same as Fig. 2, with $n_o= 1$, $n_2= 1$ and $n_2= 1$, $n_o= 2$ for the lowest 0^+ resonances.

n_o have to be guessed. In this respect, the energies of the 0^+ resonances are of great importance, since, according to eq. (1)

$$E(0^+) = (2n_2+1)E_\gamma + (n_o+ 1/2)E_\beta \quad . \quad (2)$$

Two 0^+ resonances have so far been reported in the $^{12}C+^{12}C$ system: One at 4.25 MeV [8] and the other at 5.80 MeV [3]. The problem now is to identify these resonances with members of the rotation-vibration bands given by eq. (1). The lowest 0^+ resonances given by this expression are the ground state ($n_o= n_2= 0$) and the so-called β-vibrational ($n_o= 1$, $n_2= 0$) bandheads. For reasons that we shall discuss later on, we associate the 4.25 MeV and the 5.80 MeV resonances to these two bandheads, respectively. With these assignments eq. (2) yields $E_\gamma = 3.40$ MeV and $E_\beta = 1.65$ MeV.

The calculated spectra of the two bands are shown in Fig. 2 (dashed lines) and compared with the experimentally observed resonances (full lines). In view of the simplicity of the model and of the fact that once the values of n_2 and n_o have been fixed, no free parameters are left in the calculation, the obtained agreement may be considered fairly satisfactory.

The use of expression (1) to calculate the spectrum of resonances in the $^{12}C+^{12}C$ system requires some comments. In the first place, this expression was developed to account for the coupling of collective rotational and vibrational motions. In our case, however, the rotational motion is provided by an essentially rigid rotor similar to a diatomic molecule; thus the use of the simple expression (1) could be questioned. The second comment is of a more practical nature and concerns the choice of n_2 and n_0. In the preceding paragraph we tacitly assumed that the two observed 0^+ resonances are, respectively, the lowest and the next-to-lowest ones. The fact is that the choice of $n_2 = n_0 = 1$ for the lower and $n_2 = 1$, $n_0 = 2$ for the higher 0^+ resonance with, correspondingly $E_\gamma = 0.64$ MeV and $E_\beta = 1.55$ MeV, gives considerably better agreement with experiment (Fig. 3). This choice, however, implies the existence of still lower energy 0^+ resonances (the lowest 0^+ would be around 1.5 MeV, c.m.). Although it is unlikely that such low-energy resonances, even if present, could ever be determined experimentally, it is of utmost importance to explore the region below 4 MeV. For the time being, however, the choice of n_2 and n_0 shown in Fig. 2 appears to be quite reasonable.

In spite of the above difficulties, we may conclude that the proposed model gives a comprehensive physical picture of the resonance phenomenon, implies reasonable and mutually consistent values of physical parameters (moment of inertia, surface vibration energies, etc.) and yields qualitative agreement with experimental data. Two improvements of the model impose themselves: (i) inclusion of the vibration-rotation coupling term and (ii) increase of the moment of inertia with excitation energy. It is, in fact, clear that this latter modification will lower the calculated energy spectrum, thus improving the correspondence with experiment.

There are no obvious reasons why the above model should not be applicable to other nuclear systems such as $^{12}C+^{16}O$, etc. It would be of great interest to estimate the location of the molecular channel for these systems and see whether the above model yields resonances in the same zone of the E_{exc} vs. J plane. The number of resonances observed so far in systems other than $^{12}C+^{12}C$ is, however, insufficient to allow a better than qualitative comparison with experiment.

References

1) E. Almquist, D.A. Bromley and J.A. Kuehner, Phys. Rev. Lett. 4 (1960) 515.
2) N. Cindro, F. Coçu, J. Uzureau, Z. Basrak, M. Cates, J.M. Fieni, E. Holub, Y. Patin and S. Plattard, "Nuclear Molecular Phenomena", ed. by N. Cindro, North Holland, Amsterdam, 1977, in press;
F. Coçu, N. Cindro, J. Uzureau, Z. Basrak, M. Cates, J.M. Fieni, E. Holub, Y. Patin and S. Plattard, Fizika 9 (Suppl. 2) (1977) 26.
3) F. Coçu, J. Uzureau, S. Plattard, J.M. Fieni, A. Michudon, C.A. Keyworth, M. Cates and N. Cindro, J. Phys. Lettres, 1977, in press.
4) H.J. Fink, W. Scheid and W. Greiner, Nucl. Phys. A188 (1972) 259.
5) A. Arima, G. Scharff-Goldhaber and K.W. McVoy, Phys. Lett. 40B (1972) 7.
6) W. Scheid, R. Ligensa and W. Greiner, Phys. Rev. Lett. 21 (1968) 1479.
7) See e.g. J. Eisenberg and W. Greiner, Nuclear Theory, North Holland, Amsterdam (1975) p. 147.
8) W. Galster, W. Treu, D. Dück, H. Fröhlich and H. Voit, Phys. Lett. 67B (1977) 262.

DISCUSSION

K. Dietrich: I think this is all very beautiful. I have the following question: It seemed that you considered the vibration of the compound "molecule" ^{24}Mg as if it were a spheroid. Should you not consider instead of this the vibrations of the dumb-bell formed by the two ^{12}C nuclei?

N. Cindro: You are quite right. In fact we did take a shape consisting of two close-by spheres (see Fig. 2, e.g.) and then applied the expression (1) deduced for a prolate spheroid. We should thus develop an expression analogous to (1), but for a dumb-bell shape. It is certainly possible to do it. Expression (1) is a crude approximation.

B.G.Giraud: In the molecular picture you advocate, since it is a transient state, there is no need for the two clusters to be eigenstates of ^{12}C. One might as well take the two traditional pancakes and different orientations between each other and look at how many states and with which moments of inertia one obtains.

N. Cindro: I think that the answer is similar as for the preceding question. The model is a very first approximation: we are happy that it works in a qualitative way. What you say is that mixing several possible configurations one would obtain a richer and more meaninful comparison. I quite agree with it except that we did not know how to do it.

M. Rosina: You have shown numerous levels. Where they obtained in the same experiment? If not, is there a danger that some experimental levels are duplicated because different experiments may give them at sligtly different energies?

N. Cindro: The experimental levels were not obtained in the same experiment. Hence a certain overlap can not be excluded. I have taken this into account when plotting the experimental levels on the figures. Only levels differing by more than 100 KeV (c.m.) were plotted separately. I would trust the energy determination to that amount (≈ 200 KeV LAB.).

M. Kamimura: You stressed that the rotation-vibration coupling plays important role in the fragmentation of the molecular resonances. But the rearrangement reactions $^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$ and $\rightarrow ^{16}O + ^{8}Be$ via molecular resonances are often observed. So I would like to ask what do you think about the role of the coupling between the $^{12}C + ^{12}C$ channel and the $^{20}Ne + \alpha$ and $^{15}O + ^{8}Be$ channels in explaining the fragmentation of molecular resonances of the $^{12}C + ^{12}C$ system.

N. Cindro: That is a very important point that you raised. Although we often use the $^{20}Ne + \alpha$ and $^{16}O + ^{8}Be$ exit channels to investigate the resonances it is not obvious that the coupling to these channels is the strongest (i.e. stronger than to the $^{12}C + ^{12}C$ channel). Experimentally, we measure in the above reactions the products $\Gamma_C \Gamma_\alpha$ and $\Gamma_C \Gamma_{Be}$. These products are often large but this does not mean that Γ_α and Γ_{Be} are large. In our model we assume that the coupling to the $^{12}C + ^{12}C$ channel is the strongest, which would imply a large value of Γ_C. This point is to be investigated; in this respect your work and the work of Suzuki presented at this conference may be a useful lead.