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F. Cocu, J. Uzureau, S. Plattard, J.M. Fieni, A. Michaudon, G.A. Keyworth,  
M. Cates, N. Cindro

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## ON THE EXISTENCE OF A SECOND $J^\pi = 0^+$ RESONANCE AT HIGH EXCITATION ENERGY IN $^{24}\text{Mg}$ AND A POSSIBLE MECHANISM FOR THE OCCURRENCE OF RESONANCES IN THE ( $^{12}\text{C} + ^{12}\text{C}$ ) SYSTEM

F. COÇU, J. UZUREAU, S. PLATTARD, J. M. FIENI, A. MICHAUDON, G. A. KEYWORDH (\*),  
 M. CATES (\*) and N. CINDRO (\*\*)

Service de Physique Nucléaire, Centre d'Etudes de Bruyères-le-Châtel,  
 B.P. n° 561, 92542 Montrouge Cedex, France

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**Résumé.** — L'existence d'une seconde résonance  $J^\pi = 0^+$  à haute énergie d'excitation dans  $^{24}\text{Mg}$  ( $E_x = 19,70$  MeV) est mise en évidence au cours d'une étude de la réaction  $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$  effectuée à  $E_{c.m.} = 5,80 \pm 0,05$  MeV. Ce résultat ainsi que les résultats antérieurs nous amènent à établir une comparaison avec les résonances observées dans le second puits de la barrière de fission de certains actinides.

**Abstract.** — Evidence for the existence of a second  $J^\pi = 0^+$  resonance at high excitation energy in  $^{24}\text{Mg}$  ( $E_x = 19.70$  MeV) is shown from a study of the  $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$  reaction at  $E_{c.m.} = 5.80 \pm 0.05$  MeV. Using this result and those obtained previously, a comparison is made with the resonances observed in the second well of the fission barrier of some actinides.

The excitation function of the  $^{12}\text{C} + ^{12}\text{C}$  reaction exhibits pronounced resonances demonstrated by correlations observed among the different exit channels [1]. Extensive study of this reaction has taken place in recent years and has shown that more data are necessary for a better understanding of the nature of these resonances [2, 3]. The resonances observed so far appear to be grouped in excitation energy in clusters of the same  $J^\pi$ , the mean energy of the clusters approximately following a  $J(J + 1)$  law [4, 5]. This clustering suggested the existence of a fragmented rotational band in  $^{24}\text{Mg}$  at high excitation energies. In the set of available data, however, only two  $J^\pi = 6^+$  [5, 6] and one  $0^+$  resonance [7] were observed. Since the latter plays a particularly important role in the understanding of the nature of these resonances, we focused our attention on results for the  $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$  reaction obtained between  $E_{c.m.} = 5.5$  and 6 MeV, where additional  $0^+$  resonances, if present, were expected. As a matter of fact, of the two previously reported resonances at 5.92 ( $J^\pi = 4^+$ ) and 5.64 MeV ( $J^\pi = 2^+$ ) [7] the latter had a width twice as large as that of other sub-Coulomb resonances, which suggested the exis-

tence of another unresolved resonance in this energy region. In this letter we present evidence for the existence of a second  $0^+$  resonance at 5.8 MeV and propose a unified picture of the resonances in  $^{12}\text{C} + ^{12}\text{C}$  on the basis of the rotation-vibration coupling.

In the present experiment the  $\text{C}^{3+}$  ions were provided by the Super EN tandem of CE Bruyères-le-Châtel. The alpha particles emitted in the  $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$  reaction were analysed with a split-pole magnetic spectrometer and detected in a wire counter located along the spectrometer focal plane. The self-supported carbon target was 5  $\mu\text{g}/\text{cm}^2$  thick.

In the first part of the experiment, the excitation functions of the  $^{12}\text{C}(^{12}\text{C}, \alpha)$  reaction leading to the ground and several excited states of  $^{20}\text{Ne}$  were measured at  $\theta_{\text{lab}} = 23.5^\circ$  and  $42^\circ$ . These angles were chosen to correspond to the first minimum of the squared Legendre polynomials of order 4 and 2, respectively. Under these conditions, the ground state excitation function measured at  $\theta_{\text{lab}} = 23.5^\circ$  (or  $42^\circ$ ) should present a reduced contribution from the  $J^\pi = 4^+$  (or  $2^+$ ) resonances known to be present in this energy region in contrast to the  $J^\pi = 0^+$  resonances that have an isotropic contribution. The  $J^\pi = 0^+$  resonances should therefore stick out more sharply in the ground state excitation function at these two angles; however, they should display pronounced minima in the excitation function of the

(\*) Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545, USA.

(\*\*) Rudjer Boskovic Institute, 41000 Zagreb, Croatia, Yugoslavia.

$\alpha$  particles leading to the  $J^\pi = 2^-$  state at 4.97 MeV in  $^{20}\text{Ne}(\alpha_3)$  since, in this case, even values of their angular momentum  $L$  are forbidden.

The data in figures 1 and 2 show a definite anti-correlation between  $\alpha_0$  and  $\alpha_3$  around 5.8 MeV for two mutually distant angles ( $\theta_{c.m.} \simeq 30^\circ$  and  $55^\circ$  respectively) showing that the resonant phenomenon cannot be attributed totally to statistical fluctuations. Since, in addition, data from reference [7] show a deep minimum at  $E_{c.m.} = 5.8$  MeV for the angle-integrated cross-section of the reaction  $^{12}\text{C}(^{12}\text{C}, \alpha_3)^{20}\text{Ne}$ , a strong conjecture existed that a  $J^\pi = 0^+$  resonance is present around this energy.

In order to prove this conjecture seven angular distributions of the  $^{12}\text{C}(^{12}\text{C}, \alpha_0)^{20}\text{Ne}$  reaction were measured in steps of 50 keV between 5.65 and 5.95 MeV

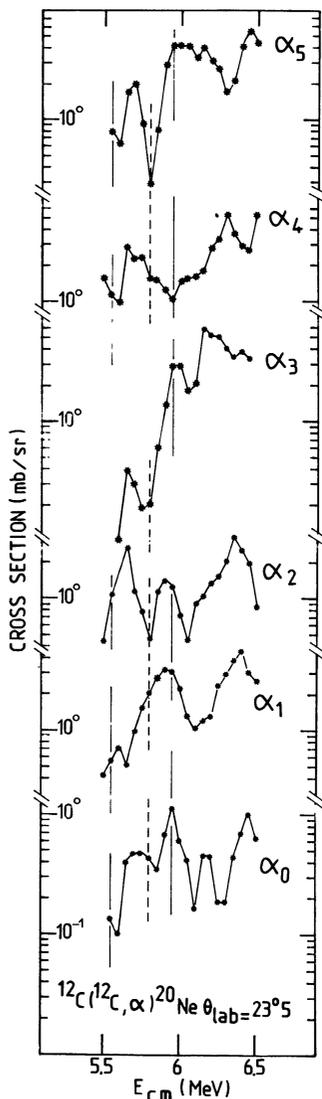


FIG. 1. — Excitation functions at  $\theta_{lab} = 23.5^\circ$  of the  $^{12}\text{C}(^{12}\text{C}, \alpha)$  reactions leading to the ground and the 1.63, 4.25, 4.97, 5.62 and 5.78 MeV excited states of  $^{20}\text{Ne}$  ( $\alpha_0$  to  $\alpha_5$ ) respectively. The dashed vertical lines indicate the position of the observed resonant structure. The full lines mark the resonances already observed at 5.65 and 5.90 MeV.

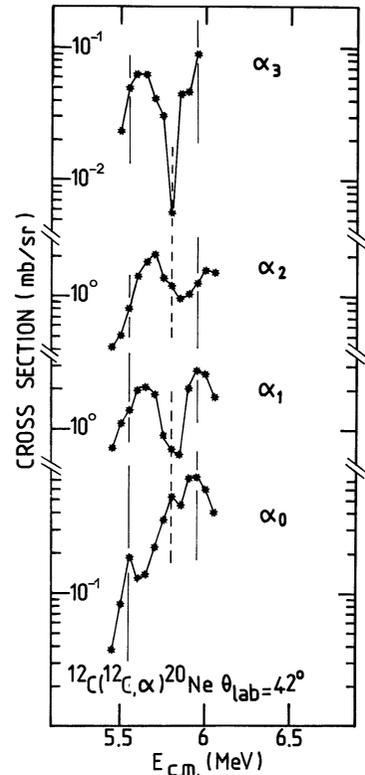


FIG. 2. — Same as figure 1 at  $\theta_{lab} = 42^\circ$  for  $\alpha_0$  to  $\alpha_3$ .

and subjected to a  $\chi^2$  analysis in terms of the development [8] :

$$\sigma(\theta)_{res,J} = \sum_{l=0}^{l_{max}=2J} a_l P_l(\cos \theta); l \text{ even}. \quad (1)$$

Figure 3 shows the angular distribution at 5.75 MeV and a fit obtained with 5 even Legendre polynomials ( $l_{max} = 8$ ). Figure 4 gives the values of  $\chi^2$  vs.  $l_{max}$  for the angular distributions at 5.65, 5.75 and 5.90 MeV. The drops in  $\chi^2$  for  $l_{max} = 4$  and 8 confirm the previous

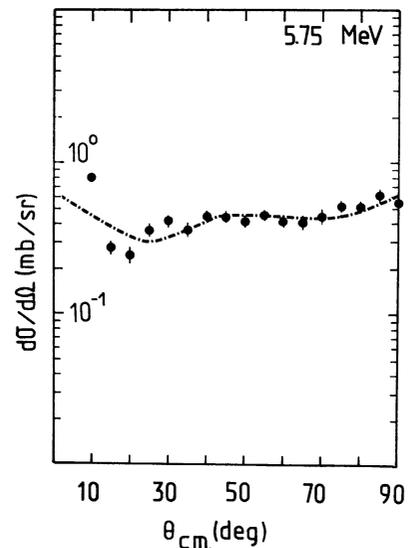


FIG. 3. — The angular distribution at 5.75 MeV (dots) and a fit with 5 even Legendre polynomials ( $l_{max} = 8$ , dot-dashed line).

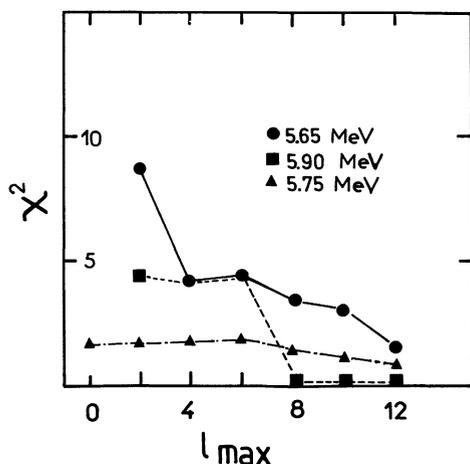


FIG. 4. — The values of  $\chi^2$  vs  $l_{\max}$  for the angular distributions at 5.65, 5.75 and 5.90 MeV.

assignments of  $J^\pi = 2^+$  and  $4^+$  to the resonances at 5.65 and 5.90 MeV respectively [7]. On the contrary, for the angular distribution at 5.75 MeV a value of  $\chi^2 = 1.6$  is obtained with only *one* polynomial ( $P_0$ ). The coefficients  $a_i$  in the expression (1) for this angular distribution are given in table I. The stability of  $a_0$  upon inclusion of higher-order polynomials and the stability of  $\chi^2$  are strong arguments for the presence of a  $J^\pi = 0^+$  resonance around 5.8 MeV c.m. As the behaviour of the angular distributions around 5.8 MeV varies rather smoothly, the experimental width of this resonance appears to be rather large, and we cannot determine its energy better than  $5.80 \pm 0.05$  MeV. According to Bloch [9] a resonance with a large experimental width indicates interference with the adjacent levels, which is a characteristic of s-wave resonances.

TABLE I

Best fit Legendre polynomial coefficients in mb/sr and  $\chi^2$  values for the angular distribution at 5.75 MeV for different values of  $l_{\max}$

$l_{\max}$	$a_0$	$a_2$	$a_4$	$a_6$	$a_8$	$\chi^2$
0	0.53					1.6
2	0.51	- 0.123				1.7
4	0.51	- 0.150	0.062			1.8
6	0.51	- 0.150	0.056	0.019		1.9
8	0.51	- 0.135	0.075	- 0.043	0.25	1.4

These angular distributions for the  $^{12}\text{C}(^{12}\text{C}, \alpha_0)^{20}\text{Ne}$  reaction can also be described by a partial wave expansion

$$\sigma(\theta) = \left| \sum_{l=0}^L B_l P_l(\cos \theta) \right|^2 \quad (2)$$

where  $B_l$  are complex quantities related to the contribution of different (integrated) partial cross-section by

$$\sigma_l = \frac{4\pi}{2l+1} |B_l|^2. \quad (3)$$

Table II lists the partial cross-sections  $\sigma_l$  derived from the code GENERE [10] for the measured angular distributions. These data show that :

(i) the contribution of  $\sigma_0$  is large in the whole region around 5.8 MeV ;

(ii) the contributions of  $\sigma_2$  and  $\sigma_4$  are the largest at  $E_{\text{c.m.}} = 5.65$  and 5.90 MeV respectively, which confirms the spin values of  $2^+$  and  $4^+$  already assigned to these resonances.

TABLE II

The partial cross-section  $\sigma_l$  for the measured angular distributions (<sup>a</sup>)

$E_{\text{CM}}$	5.65	5.70	5.75	5.80	5.85	5.90	5.95
$\sigma_0$ mb	1.69	2.29	3.26	3.87	5.56	5.20	4.23
$\sigma_2$ mb	1.57	1.35	1.33	1.45	0.21	0.24	0.35
$\sigma_4$ mb	0.22	0.30	0.43	0.58	0.97	2.18	2.18

(<sup>a</sup>) The above cross-sections were obtained using the code GENERE [10].

The apparent discrepancy in the energy of the resonance obtained from the  $\chi^2$  analysis using equation (1) (5.75 MeV) and that obtained from the partial cross-section analysis using equation (2) (5.85 MeV) can be easily explained by the influence of the  $4^+$  resonance at 5.9 MeV. The effect of this resonance should be felt on the shape of the angular distributions, hence on the  $\chi^2$  analysis using expression (1), while the contribution of the  $\sigma_0$  partial cross-section should be independent of the presence of another resonance. In fact, as already stressed, the contribution of  $\sigma_0$  remains large throughout the whole region from 5.75 to 5.95 MeV.

Thus our experiment gives convincing evidence for the existence of a wide  $J^\pi = 0^+$  resonance in the ( $^{12}\text{C} + ^{12}\text{C}$ ) system at  $E_{\text{c.m.}} = 5.80 \pm 0.05$  MeV, corresponding to an excitation energy in  $^{24}\text{Mg}$  of 19.7 MeV. Earlier, a  $0^+$  resonance was observed at  $E_{\text{c.m.}} = 4.25$  MeV, corresponding to  $E_{\text{exc}}$  in  $^{24}\text{Mg}$  of 18.2 MeV [7].

The existence of a second  $0^+$  resonance has considerable impact on our understanding of the nature of the resonances in the ( $^{12}\text{C} + ^{12}\text{C}$ ) system. As a matter of fact, this new piece of information is expected to clarify the properties of the potential between these two interacting heavy ions. A crude picture would

consist of the assumption that the interaction between the two  $^{12}\text{C}$  nuclei is either adiabatic or described by the sudden approximation. But, in the present case, the choice between these two extreme approximations is delicate since the collision time is comparable to the rearrangement time ( $\approx 5 \times 10^{-22}$  s). One way to get around this difficulty is to consider that the heavy ion potential comes from a combination of adiabatic and sudden contributions, the latter being the weaker but relatively more important at short distances [11]. However, it is very likely that a realistic description of quasi-molecular states should require a full dynamical treatment of the ( $^{12}\text{C} + ^{12}\text{C}$ ) system.

The description of the observed sequence of resonances is often made in terms of molecular states in the potential of two loosely bound  $^{12}\text{C}$  nuclei. The general trend of the resonance energies varying linearly with  $J(J+1)$  strongly suggests the pattern of a rotational band. The value  $\hbar^2/2\mathcal{I} \approx 100$  keV derived from a fit to these data yields a moment of inertia  $\mathcal{I}$  of the composite ( $^{12}\text{C} + ^{12}\text{C}$ ) system consistent with two  $^{12}\text{C}$  nuclei touching and therefore with a quasi-molecular well.

It has been pointed out that this kind of heavy ion potential well shows great similarity to the second (or third ?) well in the actinide fission barrier which is responsible for the existence of fission isomers, though the adiabatic approximation is sufficient to obtain a fission potential with a double-humped shape [3, 12]. The presence of strongly deformed vibrational, rotational and compound nucleus states in this second well can provide a unified explanation of many interesting properties of the fission cross-sections such as gross structure, intermediate structure and fine structure [13]. The similarity between the ( $^{12}\text{C} + ^{12}\text{C}$ ) potential and the second fission wells, despite different deformations, suggests an interpretation of the sequence of resonances in the ( $^{12}\text{C} + ^{12}\text{C}$ ) system inspired by the explanation of the fission results. For example, a gross structure appears sometimes in the fission cross-sections, composed of big and widely spaced peaks called *vibrational resonances* because they are caused by vibrational states in the second well. Fine structure components can also be detected in these big peaks, composed of sharp and closely spaced spikes due to the rotational band associated with the corresponding vibrational state and having a small value of  $\hbar^2/2\mathcal{I}$ . For quasi-molecular states of the ( $^{12}\text{C} + ^{12}\text{C}$ ) system, the rotational levels are more widely spaced because the parameter  $\hbar^2/2\mathcal{I}$  then takes a much higher value (100 keV instead of a few keV).

These levels cover a fairly wide energy range, not

only because of their large spacings but also because high angular momentum values can be brought in by the incident ion, in contrast to low energy neutron induced fission where only low spin levels can be excited. If, in addition, the vibrational states of the ( $^{12}\text{C} + ^{12}\text{C}$ ) system are not too wide, we may face a situation similar to that of fission but with reversed effects of rotations and vibrations. For quasi-molecular states, the main pattern of the sequence of resonances would be given by a large number of widely spaced rotational states (as observed) but the bunching of levels having the same spin would be caused by more closely spaced vibrational states coupled to the rotations. In this representation, it is essential to find the first states of the rotational bands, hence the importance of detecting low-spin resonances, especially those having  $J=0$ . The discovery of a second  $J^\pi = 0^+$  resonance is therefore of crucial value for the verification of this mechanism. It is in fact possible to identify two series of known resonances corresponding to the two detected  $J^\pi = 0^+$  resonances, both series having an energy which varies linearly as a function of  $J(J+1)$ , with the same slope  $\hbar^2/2\mathcal{I}$  but separated by 1.5 MeV, the energy difference between the two  $J^\pi = 0^+$  resonances. These two series of resonances are therefore consistent with two rotational bands weakly coupled to two  $K=0$  vibrations having an energy difference of 1.5 MeV. The detailed nature of these two  $J^\pi = 0^+$  states cannot be determined from the available experimental results. In addition to the possible contribution of the ground state in the ( $^{12}\text{C} + ^{12}\text{C}$ ) potential well for one of them, it is more likely that the two  $J^\pi = 0^+$  resonances may correspond to excitations of  $\beta$ -phonons, groups of two  $\gamma$ -phonons coupled to  $K=0$  or combinations of both. Despite the interest of finding a second  $J^\pi = 0^+$  resonance, more low-spin resonances (especially  $J^\pi = 0^+$ ) are still necessary to explain completely the spectrum of resonances in the ( $^{12}\text{C} + ^{12}\text{C}$ ) system. But, if the heavy ion potential well is too deep, the cross-sections may be too small to detect these new resonances in experiments of this type. A more complete discussion of our experimental results will be presented in a forthcoming paper.

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