"MOLECULAR" STATES FORMED BY TWO CARBON NUCLEI

Erich Vogt and Hugh McManus
Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
(Received April 14, 1960)

Experiments with heavy ions by Bromley, Kuehner, and Almqvist[1,2] have led them to postulate the existence of "molecular" states of two C^{12} nuclei. We show that the partial widths of the observed resonance structure are in agreement with this suggestion. We discuss the physical origin of this new kind of state and its implications for nuclear structure. The experimental data[1,2] are the cross sections obtained by the bombardment of carbon and oxygen by C^{12} and O^{16} ions over an energy range from a few Mev to 15 Mev (in the center-of-mass system). In $C^{12}+C^{12}$ reactions, sharp resonances with a spacing of about 300 kev appear at the same energy in all reactions near the top of the Coulomb barrier. The elastic scattering above the barrier exhibits similar sharp structure. No such structure is observed in the $O^{16}+O^{16}$ data.

The width and spacing of the observed $C^{12}+C^{12}$ resonance levels cannot be attributed to the compound nucleus Mg^{24}. Even at the energy where the structure is first observed (~6 Mev in the center-of-mass system = 20-Mev excitation in Mg^{24}), the spacing[3] of the compound levels is at least an order of magnitude smaller than 300 kev. On the other hand, area analysis of the prominent reaction resonances at 6 Mev (as well as of the sharp structure at higher energies in the elastic scattering) yields partial widths, $\Gamma_{\lambda C^{12}}$, for formation of compound states by C^{12} of the same order of magnitude as the observed widths (~150 kev). Such a large width (corresponding to a reduced width approximately equal to the sum rule limit) is to be contrasted with the widths of a few kev which are estimated[4] for alpha-particle or proton emission in each channel from the levels of Mg^{24} at 20-Mev excitation. The observed resonances are thus attributed to almost pure single-particle states of two C^{12} nuclei. If these states occur within the normal compound nucleus, it is very hard to understand why they are not mixed into neighboring compound states more strongly. Moreover, the spacing of the C^{12} states is that of a well much larger than the usual Mg^{24} nucleus [see the spacing in the large well of Fig. 1(b), below]. States of the required spacing and width can be obtained if the resonance structure is attributed to "molecular" states in which both C^{12} nuclei retain their identities for appreciable periods, with relative motion over large distances. We suggest a model of such states which is intimately connected with the deformability of C^{12}—the lack of structure in the $O^{16}+O^{16}$ observations is attributed to the rigidity of O^{16}.

When two C^{12} nuclei come into contact, a nuclear attraction arises. Near the point of contact the attraction may occur fairly abruptly, due to a loss of surface energy, and it will be purely real because the C^{12} nuclei have a large Q value (~14 Mev) for nucleon transfer. Only at smaller separations are the two nuclei strongly absorbed into a compound system of Mg^{24}. If the surface vibrations of the two C^{12} nuclei are coupled with the center-of-mass motion resulting from the nuclear attraction of their touching surfaces, there are several normal modes. All but one of these have the high energy[5] ($\hbar\omega \sim 4$-10 Mev) of the surface vibrations of C^{12}. There is one mode, however, with a much lower energy ($\hbar\omega \sim 1$ Mev). In this mode every part of the system simultaneously stretches (or contracts), at constant density, along the axis joining the two C^{12} nuclei. Because of the high energy and small mass involved in the surface vibrations of C^{12}, we can approximate the motion in the low-energy "breathing" or stretching mode by assuming that for each value of separation, r, of the mass centers of the C^{12} nuclei, the nuclear surfaces will deform adiabatically to a minimum energy of the system. If $V_N(r)$ is the nuclear attractive potential of two spherical carbon nuclei, then $V_N[r/(1+\delta)]$ is the nuclear potential of the deformed nuclei, where δ is the fraction by which each C^{12} nucleus is stretched along the axis joining the nuclei. The adiabatic condition is then

$$\frac{d}{d\delta}V_N[r/(1+\delta)] = -\frac{d}{d\delta}V_D, \tag{1}$$

where

$$V_D \equiv C\delta^2 \tag{2}$$

is the distortion energy of the system and C is a constant.[5] In (1) we have neglected the change in Coulomb energy for the quadrupole distortions we are considering.

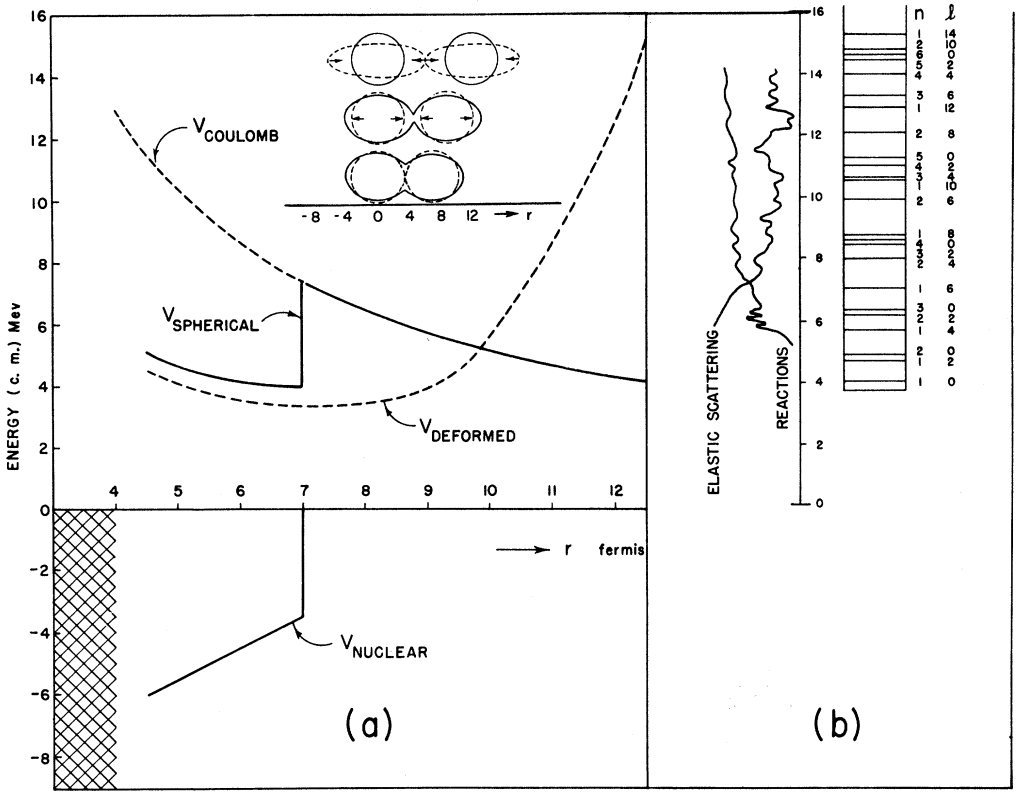

FIG. 1. (a) A qualitative illustration of the potentials connected with the motion of two C^{12} nuclei, as a function of their separation, r. The potential $V_{\text{spherical}} \equiv V_{\text{nuclear}} + V_{\text{Coulomb}}$ is the interaction between two spherical C^{12} nuclei. V_{deformed} is the interaction between the nuclei in the breathing mode. The inset gives the shapes of the nuclei, both in $V_{\text{spherical}}$ and V_{deformed}, for various separations, r, of their centers of mass at a total energy of about 12 Mev. For $r=7$ fermis the spheres are in contact and deform adiabatically by the amount shown. For $r=9$ fermis the deformed mode is still energetically favored and the spherical incoming particles tend to snap together to form a mode in the well; for $r=12$ fermis the spherical mode is energetically favored and the oscillating drops tend to snap apart, passing through a barrier to their favored spherical shape. (b) A qualitative comparison of the levels in V_{deformed} with the structure of the $C^{12}+C^{12}$ data. The level scheme on the right is that for particles of six proton masses in an infinite square well of radius 10.8 fermis and the indicated depth—dimensions comparable to that of V_{deformed} on Fig. 1(a). The surface energy step in V_N has been chosen so that the three prominent peaks seen in all reactions correspond to the $1g$, $2d$, and $3s$ levels in the well. No significance should be attached to this particular identification.

As two carbon nuclei approach each other their rapid surface vibrations, at any r, may bring their surfaces into contact, thus gaining contact or saddle point energy, although for $r>7$ fermis (assumed to be the sum of the radii for two spherical C^{12} nuclei) the energy $V_N[r/(1+\delta)]+V_D$ constitutes a barrier that inhibits the contact if the gain in saddle point energy is sufficiently abrupt. However, once the nuclei touch, the same barrier prevents them from snapping apart. The center-of-mass motion is then given by the potential well:

$$V_{\text{deformed}}(r) = V_N[r/(1+\delta)]+V_D+V_{\text{Coulomb}}(r), \quad (3)$$

where δ is determined for each r by (1). The attractive well V_N may extend to large distances before the repulsive term V_D takes over.

The motion of the two C^{12} nuclei as they stretch in V_{deformed} is very reminiscent of fission.[6]

The present case has an essential simplicity in that the C^{12} nuclei cannot change their identities by nucleon transfer so that the effective potential, V_{deformed}, is intimately related to the structure of C^{12}.

The low frequency of the breathing mode ($\hbar\omega \sim 1$ Mev) implies that the nuclei make only a few vibrations before decay into the absorptive core (observed widths ~150 kev). The decay inward is inhibited by the centrifugal barrier (for states of high angular momentum), and by the rearrangement energy (Pauli principle) encountered when two C^{12} nuclei coalesce into a state of Mg^{24}.

To illustrate the properties of the states in the "molecular" potential V_{deformed}, Fig. 1(a) shows the V_{deformed} which is found for the particular V_N given on that figure and for a V_D ($C = 25$ Mev[5]) based on the structure of C^{12}. This deformability of C^{12} yields a well extending out to about 11 fermis. The saddle point energy which fixes the well depth has been chosen as 4 Mev on the figure. The slope of V_N between the saddle point and the absorptive core [shaded part of Fig. 1(a)] fixes the value of δ to be 0.15 for $r < 8$ fermis. For larger r the two C^{12} nuclei stretch retaining their saddle point energy, as in the breathing mode described above.

The "molecular" states are given in Fig. 1(b) for a square well of dimensions like that of V_{deformed} in Fig. 1(a). The spacing is similar to that observed. The form of spectroscopy implied by Fig. 1(b) should prove useful in studying the structure of any pair of nuclei which are easily deformed and which are stable against nucleon transfer reactions. The properties of the nuclear potential, V_N, and hence of the "molecular" states may be intimately connected with the fluid or superfluid properties of the nucleons in the surface of the coalescing drops.

The rigidity[7] of O^{16} not only narrows the "molecular" potential and increases the absorptive width of the "molecular" states, but it also strongly decreases the formation probability for such states; hence the lack of structure in the $O^{16}+O^{16}$ observations.

From detailed balance applied to the smoothly varying (compound nucleus) part of the $C^{12}+C^{12}$ data, the fission cross section, $Na^{23}(p, C^{12})C^{12}$ or $Ne^{20}(\alpha, C^{12})C^{12}$, for incident particles above 8 Mev should be of the order of 1% of the absorption cross section of the incident particles. The "molecular" resonances would not be expected to show prominently in the fission reactions.

The authors would like to acknowledge many useful discussions with E. Almqvist, D. A. Bromley, and J. Kuehner who initiated our interest in this problem and with L. G. Elliott and T. D. Newton who also contributed many helpful suggestions.

---

[1]D. A. Bromley, J. Kuehner, and E. Almqvist, Phys. Rev. Letters 4, 365 (1960).

[2]E. Almqvist, D. A. Bromley, and J. Kuehner, preceding Letter [Phys. Rev. Letters 4, 515 (1960)].

[3]If the spacing, $D_{J\pi}$, of levels of a given spin and parity is assumed to be $D_{J\pi} \equiv D/(2J+1)$, then at 13-Mev excitation in Mg^{24} the data give $D \sim 1$ Mev. Level density formulas give $D \sim 250$ kev at 20 Mev, yielding spacings for the 0+, 2+, 4+, 6+ levels of 250, 50, 27, 20 kev, respectively. For a nuclear radius of 7 fermis and a center-of-mass energy of 6 Mev the C^{12} penetrabilities for $l = 0$, 2, and 4 are all of the order of unity, so that approximately one compound level should be observed in every 20 kev.

[4]In the reactions involving Mg^{24} compound states at 13 Mev, as well as in nuclear reactions generally, reduced widths for nucleon or alpha emission have an average value of about $(0.05-0.10)D_{J\pi}$, where $D_{J\pi}$ is the level spacing discussed in reference 3. At 20-Mev excitation the reduced widths are therefore several kev on the average. For a typical compound state at that energy about 10 alpha-particle channels and 30 proton channels (and a few neutron channels) have penetrabilities of the order of unity, leading to the total widths (~150 kev) observed in the $C^{12}+C^{12}$ data as well as in $Na^{23}+p$ data at the same energy [H. E. Gove (private communication)]. Similarly, if the smoothly varying background lying underneath the resonance structure of the $C^{12}+C^{12}$ data is taken to be due to "normal" compound nucleus formation one finds $\gamma_{C^{12}}{}^2/D_{J\pi} \approx 0.025$, yielding "normal" widths for formation of compound states by C^{12} of a few kev.

[5]The low-lying levels of C^{12} have appreciable collective character [D. Kurath, Nuclear Phys. 14, 398 (1960)]. If the energy required to produce a prolate distortion of C^{12} is assumed to be $\frac{1}{2}C\delta^2$, where δ is the fractional elongation of the major axis, then the constant C has been calculated by T. D. Newton (private communication), see also Can. J. Phys. (to be published), to be ~25 Mev, in agreement with the quoted value of $\hbar\omega$.

[6]N. Bohr and J. A. Wheeler, Phys. Rev. 56, 426 (1939); D. L. Hill and J. A. Wheeler, Phys. Rev. 89, 1102 (1953); A. Bohr, Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1955 (United Nations, New York, 1956), P/199.

[7]J. J. Griffin, Phys. Rev. 108, 328 (1957).