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Coexistence of Single-Particle, Collective-Quadrupole, and $\alpha + {}^{14}C$ Molecular-Dipole Degrees of Freedom in ^{18}O

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All natural-parity states of ^{18}O have been studied with high accuracy with the $^{14}C(^7Li, t\gamma)^{18}O$ coincidence and $^{14}C(\alpha,\gamma)^{18}O$ radiative-capture reactions. The four-particle, two-hole 0_2^+, 1^-, 2_3^+, and 3_3^- states deexcite with consecutive enhanced $E1$ and $E2$ crossover transitions having $B(E1) \simeq 10^{-2}$ Weisskopf units (W.u.) and $B(E2) \simeq 20$ W.u. These data suggest the existence of an $\alpha + {}^{14}C$ dipole band in ^{18}O similar to those discussed recently by Iachello and Jackson.

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The $A = 18$ system is an attractive one for study of nuclear structure[1] in that it gives access to both charge symmetry and charge independence of the nucleon-nucleon interaction, as well as interplay of the single-particle and deformed collective-quadrupole degrees of freedom.[2-4] Indeed, the coexistence of core-excitation deformed states [e.g., the four-particle, two-hole (4p-2h) 0_2^+ state at 3.63 in ^{18}O] and simple two-particle shell-model states is now well established in ^{18}O.

Recently, it has been suggested[5] that certain nuclei may display an altogether new collective degree of freedom. When the nucleus can be described as a dinuclear molecular system, as this suggestion implies, the relevant degree of freedom is the separation vector of the nuclear centers and the pertinent variables are the length of this vector and two of the three Euler angles which define its spatial orientation. The dinuclear molecular system can be described by a classical geometrical description[6] as well as a group-theoretical algebraic picture.[5] In this latter case the molecular spectra are considered to be generated by one S boson and three P_μ ($-1 \leq \mu \leq 1$) bosons, the generators of U(4).

Two quite distinct physical situations are possible. In the first, the participant nuclei do not themselves deform and only the length of the separation vector undergoes oscillation while the entire system can rotate about its center of mass. Such motion would be expected to lead to a conventional vibration-rotation spectra involving rotational bands having spin sequences $0^+, 1^-, 2^+, 3^-, 4^+$, etc.; additionally it would be expected that enhanced collective $E1$ intraband transitions would be observed in non-self-conjugate systems.[7]

In the second physical situation the participant nuclei interpenetrate as the separation vector oscillates. Such motion can give rise to a spectrum having equidistant multiplets of dipole vibrational character and again enhanced collective $E1$ transitions (between states of different multiplets) are predicted in non-self-conjugate systems.[7]

Recently this enhancement of the radiative widths of transitions linking molecular states has been examined in a model-independent fashion[6] and sum rules have been derived for $E1$, $E2$, and $E3$ transitions. These sum rules together with the usual Wigner limits of reduced widths for particle decay of the presumed molecular states provide an effective signature for such structure as well as a measure of the degree of collective enhancement. They also provide a scale [10^{-2} Weisskopf units (W.u.)] for the $B(E1)$ enhancement.

The best candidate nuclear systems for exhibition of the suggested molecular states would ap-

pear to be ^{8}Be ($\alpha+\alpha$), ^{20}Ne ($\alpha+^{16}$O), and ^{18}O ($\alpha+^{14}$C). In all cases, very stiff, strongly bound component nuclei are involved. The last system is preferable for experimental study since negative-parity states are allowed, and $E1$ transitions are isospin allowed.[7] We have undertaken a careful examination of all low-lying states in ^{18}O to search for this newly suggested[5] collective-dipole degree of freedom.

We have studied the reaction ^{14}C(^{7}Li, $t\gamma$)^{18}O using 15-MeV (Ref. 7) Li beams from the Yale MP tandem accelerator and an enriched (96%) ^{14}C target[8] of 40 μg/cm^2 areal density. Deexciting branches were identified by requiring a fast (full width at half maximum = 5 ns) coincidence between triton groups, detected by an annular counter at 10° ± 2°, and photons detected in a Ge(Li) detector placed at 55° ± 25°. Four million coincidence events, involving ten excited residual states, were collected. States above the $\alpha+^{14}$C threshold (6.228 MeV) were studied via the resonant radiative-capture reaction ^{14}C(α,γ)^{18}O, using a singly charged helium beam of intensity up to 40 μA obtained from the Brookhaven 3.5-MV Van de Graaff accelerator. Enriched (96%) ^{14}C targets[8] of 2–5 μg/cm^2 areal density were used with an oxygen-free 0.02-in.-thick Ta backing. These studies yielded new accurate data on weak deexcitation branches for sixteen ^{18}O states below an excitation energy of 8.3 MeV. All enhanced $E2$ and $E1$ transitions [$B(E1) \geq 10^{-3}$ W.u.] obtained from these data are shown in Fig. 1.

It is well known that the 0_2^+ (3.63 MeV) and 2_3^+ (5.26 MeV) states are primarily of collective cluster parentage and it is normally assumed that the 0_2^+, 2_3^+, and 4_2^+ (7.12 MeV) states are members of a collective $K^\pi = 0^+$ (quandrupole) rotational band similar to the ground-state band of ^{20}Ne and the band based on the 4p-4h 0^+ state at 6.05 MeV in ^{16}O. Indeed we find a corresponding enhanced $E2$ transition $B(E2{:}2_3^+ \rightarrow 0_2^+) = 27$ W.u. in ^{18}O. We find no γ line corresponding to the $4_2^+ \rightarrow 2_3^+$ transition, but establish an upper limit on its intensity: branching ratio $R_b < 0.6\%$, thus $B(E2{:}4_2^+ \rightarrow 2_3^+) < 11$ W.u. For collective states, it is reasonable to assume that the isoscalar $E2$ dominates over the isovector $E2$, which is also allowed for $T=1$ nuclei. Thus, we conclude that the 0_2^+, 2_3^+, and 4_2^+ states do not constitute a *pure* quadrupole rotational band; these states may have only a small parentage based on the assumed deformed $K^\pi = 0^+$ quadrupole collective band, as is the case for the 4_1^+ (3.55 MeV) state which has $B(E2{:}4_1^+ \rightarrow 2_3^+\uparrow) = 14$ W.u. Further, the suggestion that the collective 1^- (4.45 MeV), 3^- (5.10 MeV), and 5^- (8.13 MeV) states are members of a collective $K^\pi = 0^-$ band appears inconsistent with the following enhanced

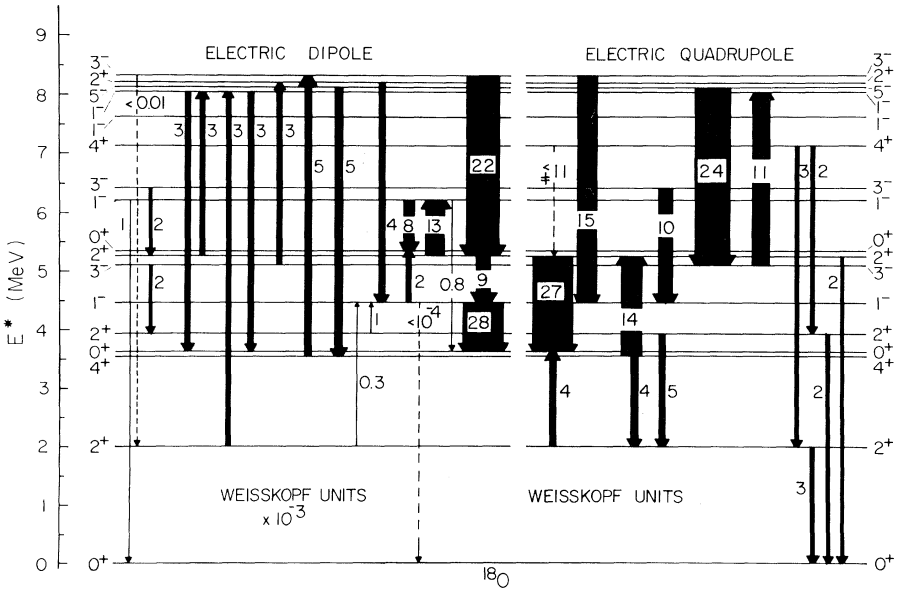

FIG. 1. Enhanced $E2$ and $E1$ transitions in ^{18}O. Correlated enhancement of selective $E1$ and $E2$ transitions is evident. The $B(E1{:}1^- \rightarrow 0_2^+) = 2.8\times10^{-2}$ W.u. is one of the most enhanced $E1$ transitions yet observed in an even-even nucleus.

(~13 W.u.) $E2$ transitions: $3_3^- \to 1^-$, $3_2^- \to 1^-$, and $1_4^- \to 3^-$. Our data thus suggest that the collective states of ^{18}O may be of a more complicated nature than was previously assumed, and furthur suggest that the strength of the assumed quadrupole bands ($K^\pi = 0^+$ and 0^-) having spin sequences $0^+, 2^+, 4^+$ and $1^-, 3^-, 5^- \ldots$ is spread over many states.

On the other hand, as shown in Fig. 1, we find that the *well-known cluster states* 0_2^+, 1^-, 2_3^+, 3_3^- (8.29 MeV) deexcite with three consecutive enhanced $E1$ transitions [$B(E1) \sim 10^{-2}$ W.u.]; we also observe two enhanced $E2$ crossover transitions [$B(E2) \sim 20$ W.u.]. The enhanced $E1$ transitions are very selective: The $1^- \to$ g.s. decay was not observed ($R_b < 0.1\%$) nor did we observe the $3_3^- \to 2_2^+$ (3.92 MeV) or the $3_3^- \to 2_1^+$ (1.98 MeV) transitions ($R_b < 0.5\%$). The upper limits that we establish for reduced matrix elements are $B(E1{:}1^- \to \text{g.s.}) < 10^{-7}$ W.u. and $B(E1{:}3^- \to 2_1^+) < 10^{-5}$ W.u., as shown in Fig. 1. Such small $E1$ matrix elements (of $10^{-4} - 10^{-5}$ W.u.) are usually observed in even-even nuclei. Were we to use energy arguments alone, these $E1$ transitions would have been the major deexcitation modes for the 3_3^- and 1^- states, in contrast to these observations. While the deexcitation of the 1^- and 3_3^- cluster states is very selective, the 1_3^-, 3_2^-, and 2_4^+ (noncluster) states, for example, show all allowed $E1$, $M1$, and $E2$ deexcitation transitions with no apparent selectivity whatsoever. Furthermore, both the 3_3^- and 2_3^+ cluster states deexcite via enhanced $E1$ and $E2$ transitions to the 4_1^+ state, as does the collective 5^- state, discussed above. This enhancement of *both* $E1$ and $E2$ transitions and the selectivity appear in general for states of well-established *clustering* nature, as shown in Fig. 1. The amazing selectivity for $E1$ transitions between cluster states is in contrast to our usual understanding of $E1$ transitions[9] as arising from small accidental mixture of the giant dipole resonance, for example.

The 3_3^- state has a large alpha-particle decay width, which exhausts 20% of the Wigner sum rule for cluster decay width ($\theta_\alpha^2 = 20\%$) — the largest known reduced α width in ^{18}O and, apart from α widths in ^8Be, one of the largest known in light nuclei. The $B(E1{:}1^- \to 0_2^+) = 13\%$ of the molecular $E1$ decay-width sum rule.[6] The $B(E2{:}2_3^+ \to 0_2^+) = 23\%$ of the molecular $E2$ decay-width sum rule.[6] Indeed, the three different sum rules yield consistent fractions for the different decay widths. Furthermore, if we renormalize the Weisskopf estimate for $E1$ transitions by replacing the radius $R = 1.2 \times A^{1/3}$ fm with the assumed permanent separation of an $\alpha + {}^{14}C$ molecular center of charge from the center of mass,[7] we obtain *molecular* W.u. (M.W.u.)[6] for $E1$ with 1 M.W.u. $= 1.79 \times 10^{-3}$ W.u. Thus an $E1$ transition having $B(E1) > 2 \times 10^{-3}$ W.u. should be considered enhanced on the molecular scale, as well as on that of $B(E1)$ in even-even nuclei; e.g., $B(E1{:}1^- \to 0_2^+) = 15.6$ M.W.u.

The energies of the 0_2^+, 1^-, 2_3^+, and 3_3^- (and 4_3^+) states are plotted versus $J(J+1)$ in Fig. 2. The classical moment of inertia of the proposed rotational band extracted from these energies corresponds to that of two touching spheres of radii $R = 1.1 \times A^{1/3}$ fm, where here $A_1 = 4$ and A_2

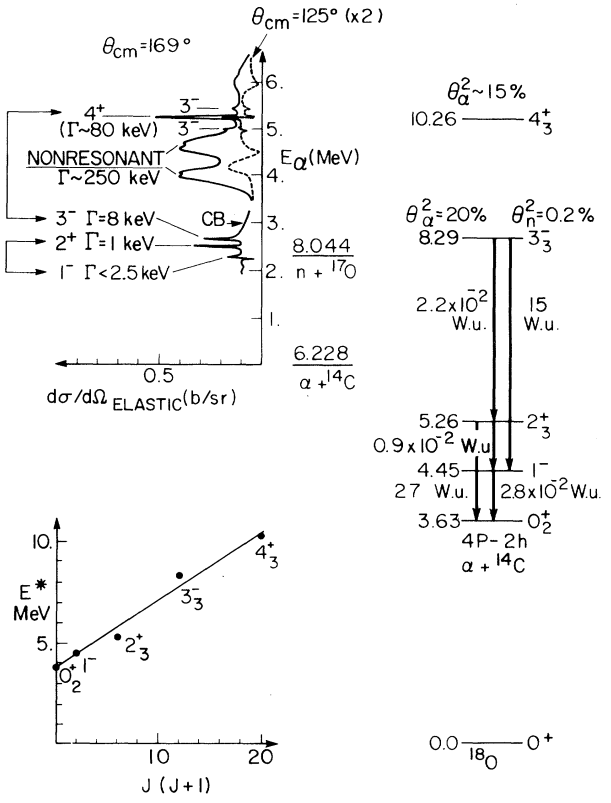

FIG. 2. Proposed "$\alpha + {}^{14}C$ dipole molecular band." We plot the location of 0_2^+, 1^-, 2_3^+, 3_3^- (and 4_3^+) vs $J(J+1)$. The backward-angle $\alpha + {}^{14}C$ elastic scattering (Ref. 1) is shown at two typical angles, and shows structure typical of molecular interaction, as observed, for example, in heavy-ion scattering on a larger energy scale. Large-width (~250 keV), *regular*, nonresonant oscillations have superimposed on them intermediate-width (8–80 keV) molecular resonances having large alpha-particle reduced width. Very narrow (~1 keV) complex compound states having no consistent structure and thus nonselective decay modes are also observed.

= 14. (In this calculation the intrinsic moment of inertia was set to zero, $I_0 = 0$, assuming spherical nuclear participants.) Corresponding to this configuration we can extract a classical $B(E1)$,[6] and again we find that $B(E1{:}1^- \rightarrow 0_2^+) = 17\%$ of this classical $E1$ matrix elements estimate.

All these data suggest that these states have a large parentage based on a molecular $\alpha + {}^{14}C$ structure, as shown in Fig. 2, and that they may indeed constitute the suggested dipole molecular band.

We note, however, that the $B(E1{:}2_3^+ \rightarrow 1^-)$ is considerably smaller than that for the $3_3^- \rightarrow 2_3^+$ and $1^- \rightarrow 0_2^+$ transitions. A careful examination of Fig. 2 shows two additional enhanced $E1$ transitions from 2^+ to 1^- states: $B(E1{:}2_3^+ \rightarrow 1_2^-) = 1.3 \times 10^{-2}$ W.u., and $B(E1{:}2_4^+ \rightarrow 1^-) = 4 \times 10^{-3}$ W.u. We also observe for the 1_2^- state that $B(E1{:}1_2^- \rightarrow 0_3^+) = 8 \times 10^{-3}$ W.u. The 1_2^- state deexcites to the 2_3^+ and we observe no transitions to the 2_2^+ states. The 1_2^- state also exhibits selective enhanced decay modes to the collective 0_2^+, 1^-, and 2_3^+ states. Finally we find $B(E1{:}1^- \rightarrow 0_3^+) = 2 \times 10^{-3}$ W.u., and $B(E1{:}3_2^- \rightarrow 2_3^+) = 2 \times 10^{-3}$ W.u. All these enhanced $E1$ transitions may suggest that the 0_2^+ (4p-2h state) and 0_3^+ (primarily an $s_{1/2}{}^2$ state), 1^- and 1_2^-, 2_3^+ and 2_4^+, and 3_3^- and 3_2^- states are significantly mixed, and that each pair (of cluster state and two-neutron shell-model state) shares the dipole enhancement characteristic of the underlying $\alpha + {}^{14}C$ molecular band, i.e., that the molecular strength mixes systematically with the shell-model strength. The corresponding enhanced $B(E2{:}3_2^- \rightarrow 1^-) = 10$ W.u., and enhanced $M1 + E2$ $1_2^- \rightarrow 1^-$ (not shown in Fig. 1) may arise from that mixing of these shell-model states with those of the $\alpha + {}^{14}C$ molecular band. The interpretation of the decay modes of the 0_3^+ and 1_2^- is further complicated, since the U(4) model[5] predicts yet another collective vibrational 0^+ state with a $0^+, 1^-, \ldots$ band at higher energies. These molecular states can also mix with the higher-lying $s_{1/2}{}^2$ 0^+ and one-particle, one-hole 1^- states.

Our data thus suggest that a full description of ^{18}O must recognize the coexistence of the single-particle, the deformed prolate-shape quadrupole, and the molecular-dipole degrees of freedom.

We are currently continuing our investigation of the apparent molecular aspects of the $\alpha + {}^{14}C$ interaction within the bound states of ^{18}O and the scattering states as studied directly. We have also extended our search for dipole alpha-particle cluster bands to very heavy nuclei where they were first predicted[10] and we have found compelling evidence for very similar phenomena involving coexistence of quadrupole and dipole molecular bands in ^{218}Ra.[11] These studies will be reported in a separate communication.

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