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$^{15}N(p, \gamma_2\gamma)^{16}O$ and the Deformed Giant Resonance in ^{16}O†

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(Received 24 November 1970)

The cascade γ-ray decay of states at 19.9 and 20.4 MeV in ^{16}O has been observed using the reaction $^{15}N(p,\gamma_2\gamma)^{16}O$. These states appear to have the properties expected of giant dipole states based on the $J^\pi = 3^-$ state at 6.13 MeV. Together with earlier work, the result implies that giant dipole states based on the $J^\pi = 0^+$ state at 6.05 MeV are displaced significantly from the energies expected from a simple weak-coupling model.

In a recently published paper[1] Barnett and Tanner reported on the (unresolved) $\gamma_1+\gamma_2$ decay from states in the giant resonance region of ^{16}O reached by proton capture on ^{15}N. They found that there were very strong resonances present in the $\gamma_1+\gamma_2$ yield and that these did not branch to the ground state. The strongest transition, from the resonance at 20.4 MeV, and that from the 19.9-MeV resonance are of special interest as they have the properties expected[1] of known[2] giant-resonance states built by simple p-h (particle-hole) excitations out of either the deformed 0_2^+ state at 6.05 MeV or the more nearly spherical (but strongly collective) 3_1^- state at 6.13 MeV. The experiment of Ref. 1 measured the direct cascade γ ray and could not distinguish between these possibilities; in the present study we undertook to determine whether the basis state was the 3_1^- alternative by a direct γ_2-γ coincidence study. Since the 0_2^+ state decays entirely by pair emission it will not influence the γ-γ yield.

The coincidence γ rays were observed from a gas target containing 97% $^{15}N_2$ at a pressure of 3000 mm Hg and enclosed by a 1-μm nickel foil. The approximate target thickness was 1.7 mg/cm^2 (about 65 keV at $E_p = 8.8$ MeV). The proton beam (<0.3 nA) of the University of Minnesota's MP tandem was focused on the target and was stopped on gold. Two NaI crystals, 7.6 cm diam ×7.6 cm and 10 cm diam×13 cm, were placed 7 cm on opposite sides of the target and were well shielded by lead from nontarget background. A single-channel gating window was set around the 6.13-MeV region of the spectrum from the 10-cm-diam×13-cm crystal (see insert of Fig. 1), and both singles and coincidence spectra from the other crystal were recorded. Crossover timing discriminators gave a coincidence resolving time of $2\tau = 50$ nsec and simultaneous accumulation of the random spectrum showed that the real-to-random ratio was better than 10:1 (with singles deadtimes of up to 5%).

Figure 1 shows the spectra for the decay of the 20.4-MeV state ($E_p = 8.83$ MeV at the target center), accumulated for a total charge of 11.2 μC. A direct comparison of the 14.3-MeV peak in both spectra (as indicated) leads to the required $\gamma_2/(\gamma_1+\gamma_2)$ branching ratio independently of the efficiency of the 7.6-cm-diam×7.6-cm crystal, the gas-target thickness, and the accuracy of the beam-current integration. A coincidence background spectrum, measured above the resonance at $E_p = 9.2$ MeV, is shown in Fig. 1. There is no indication of a 14.3-MeV γ ray in this spectrum. The decay of the 19.9-MeV resonance ($E_p = 8.30$ MeV) is shown in Fig. 2. Corrections to the coincidence peak counts for background were estimated to be $(25\pm10)\%$ for the 14.3-MeV γ ray and $(25\pm25)\%$ for the 13.8-MeV γ ray.

The fraction of the 6.13-MeV spectrum appearing at the single-channel analyzer window (insert of Fig. 1) was measured to be 0.43 ± 0.02 by using the reaction $^{16}O(p,p_2\gamma_{6.13})^{16}O$ at $E_p = 6.9$ MeV with O_2 gas in the target. A pure spectrum of 6.13-MeV γ rays above 4 MeV was obtained. The ef-

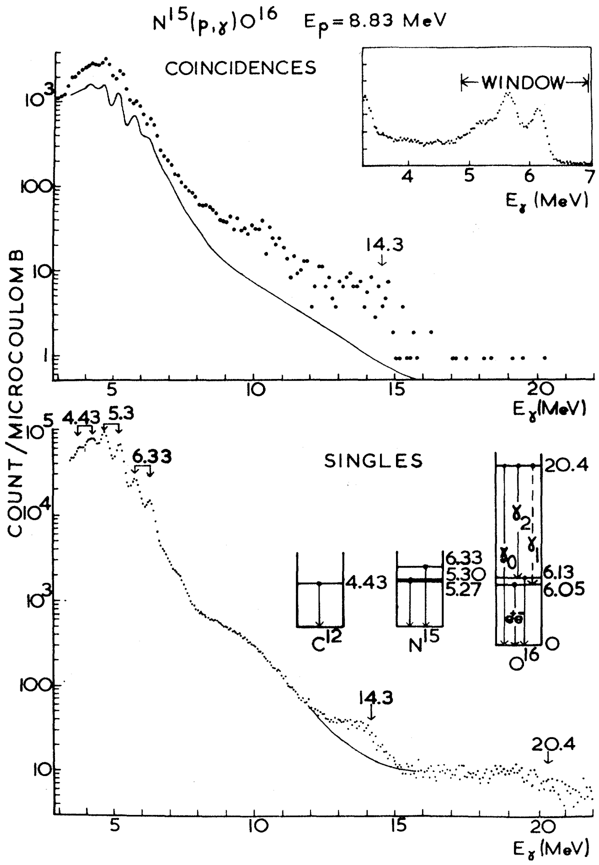

FIG. 1. Singles and coincidence spectra in the 7.6-cm-diam × 7.6-cm NaI crystal. The smooth lines are the measured off-resonance background in the coincidence spectrum, and the assumed pile-up background under the 14.3-MeV peak in the singles spectrum. The total counts in the 14.3-MeV peak are 160 ± 13 and 3025 ± 50, respectively, after a 11.2-μC beam. The insert shows the pure 6.13-MeV γ ray in the 10-cm-diam × 13-cm crystal obtained from the reaction $^{16}O(p,p_2\gamma_{6.13})^{16}O$, and the single-channel analyzer window used to gate the singles spectrum. Other prominent γ rays arise from the reactions $^{15}N(p,p'\gamma)^{15}N$ and $^{15}N(p,\alpha\gamma)^{12}C$.

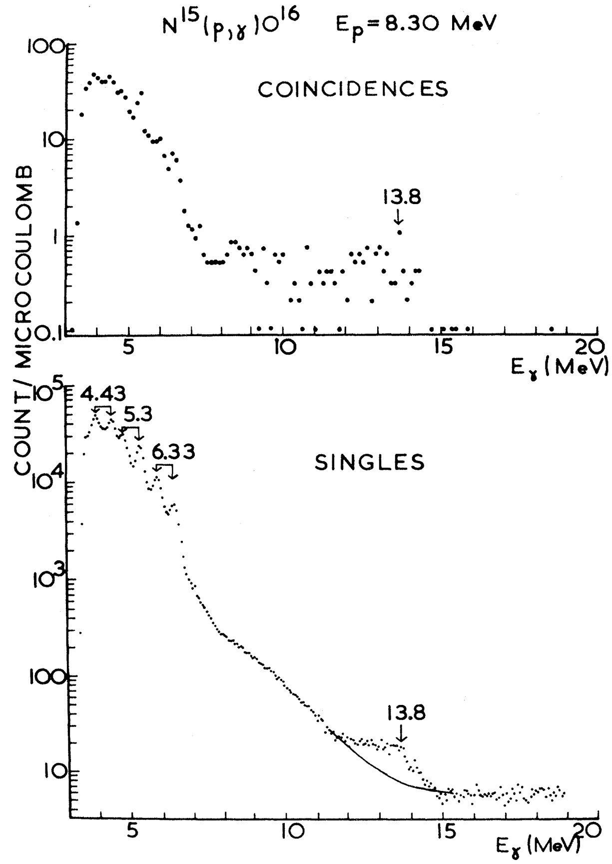

FIG. 2. Spectra obtained at the 19.9-MeV resonance. The 13.8-MeV coincidence yield is 97 ± 10 counts and the singles yield is 2663 ± 400 counts (total charge 9.2 μC).

ficiency of the 10-cm-diam × 13-cm crystal for these γ rays in our geometry was computed to be 0.046 ± 0.002; absorption of the γ rays in the gas-cell walls, etc., was negligible. The product of the efficiency, the fraction of 6.13 γ rays detected, and the relative $\gamma_2/(\gamma_1+\gamma_2)$ branching ratio then equals the ratio of the coincidence to the singles yields. Table I gives the comparison for the 19.9- and 20.4-MeV states and it is clear that in both cases a γ_2 branch of 100 % is indicated by the data. The dominant error for each case comes from the uncertainty of the background corrections. Nevertheless the results show that both states decay significantly through the 3_1^- state, and we note that this fact alone es-

Table I. Comparison of expected and observed coincidence counting rates. Column 3 gives the coincidence rate which would be expected if the 20.4- and 19.9-MeV states decay entirely through the γ-emitting 6.13-MeV state.

State (MeV)	Singles γ-ray count/μC	(Singles count/μC) × (10-cm-diam × 13-cm crystal efficiency)	Observed coincidence count/μC
20.4	570 ± 70	11.3 ± 1.4	10.7 ± 1.3
19.9	300 ± 40	5.9 ± 0.8	7.5 ± 2.5

tablishes that the γ_2 branch is essentially 100% (unless the 19.9- and 20.4-MeV states are multiplets). The singles and coincidence rates were also calculated in absolute terms using the data of Ref. 1 (the geometry, the efficiencies, and the accumulated charge); the results were smaller by less than a factor of 2 (assuming a 100% γ_2 branch) which is quite satisfactory agreement.

Our results thus confirm the suggestion[1] that the 19.9- and 20.4-MeV states are closely connected in structure with the 3_1^- state and not the 0_2^+ state, consequently supporting the weak-coupling model proposed by Barnett and Tanner. In this picture the two states arise from the coupling of the 12.44-MeV, $T=0$ and 13.09-MeV, $T=1$ dipole states to the collective 3_1^- core and so their wave functions are mainly $(3^-0\times1^-0)$ and $(3^-0\times1^-1)$. The spin values of the states could be $J^\pi=2^+, 3^+, 4^+$ (although the experimentally observed decays are also consistent with $M1$ radiation[1] so the possibilities $J^\pi=2^-, 3^-, 4^-$ cannot be eliminated).

The second aspect of the results of Ref. 1, which has perhaps considerable relevance for the problem of the structure of the 0_2^+ state, is the observation that the branching ratios $(\gamma_1+\gamma_2)/\gamma_0$ of known giant dipole states are very small, in fact below the detection limit of a few percent. It then follows that γ_1/γ_0 is also below this limit over the whole range, $E_x=16$-24 MeV, a result which seems to imply that the mixing of the ideal deformed 0_2^+ state and the ideal spherical 0_1^+ ground state is rather small. This conclusion, which is contrary to a number of theoretical predictions, is also suggested by the $E1$ decays of the 7.12-MeV, 1^-, $T=0$ state.[3,4] While for any individual inhibited transition arguments can always be made[3] for the destructive interference of higher configuration admixtures, the γ_1/γ_0 result extends over 8 MeV and appears to be more general.

A particularly interesting feature is that, since the present result establishes the decay through the 3_1^- state of the 19.9- and 20.4-MeV levels, then the first $J^\pi=1^-$ members of the deformed giant resonance (based on the 0_2^+ 6.05-MeV state) do not occur at the energies expected from weak coupling of (12.44+6.05) MeV and (13.09+6.05) MeV, respectively. In the spectrum of $^{15}N(p, \gamma_1+\gamma_2)^{16}O$ (Fig. 2 of Ref. 1), the only remaining candidate for this component of the deformed giant resonance is at 22.7 MeV. However, this has only about $\frac{1}{2}$ of the expected strength, and whether its decay is γ_1 or γ_2 is unknown. If this is not a deformed giant resonance, then the latter is displaced upwards from its expected position by at least 5 MeV (to 24 MeV or higher). Such a displacement in energy was predicted by Kluge and Manakos[5] by considering the breaking of the orbital symmetry of the 0_2^+ state. It can also be understood on the model of Brown and Green[6] for the 0_2^+ state, since in their model the unusually low energy of the 4p-4h excitation arises from the depression of the $K=(\frac{1}{2})^+$ Nilsson orbit based on the $1d_{5/2}$ state at high prolate deformations. However, the formation of a deformed giant dipole by the promotion of further p-h pairs necessarily involves the much higher $K=(\frac{3}{2})^+$ or $K=(\frac{1}{2})^+$ orbits based on the $1d_{5/2}$ and $2s_{1/2}$ states, respectively. Thus the mechanism which provides a dramatic reduction in energy below $4\hbar\omega$ for the 4p-4h state is not present for a 5p-5h state. The present result therefore lends some support to Brown and Green's model. The absence of the deformed dipole states corresponding to the 12.44- and 13.09-MeV spherical dipole states is also suggested by the wave functions of Zuker, Buck, and McGrory,[7] since the spherical dipole states both belong to the configuration $p_{1/2}^{-1}2s_{1/2}$, while the 6.05-MeV state is mainly $p_{1/2}^{-4}$. Thus no excitations are possible involving the removal of $1p_{1/2}$ nucleons from the 6.05-MeV state. However, it is not clear to what extent this prediction is affected by the truncated basis of the wave functions.[8] In fact, the energy of the lowest 1^-, $T=1$, 5p-5h state can be estimated using the French scheme[8,9] which suggests an excitation of 22 to 26 MeV rather than 19 MeV.

Apart from its significance for the structure of the 6.05-MeV state, the present result is also relevant to the dipole decays of the 9.59-MeV, 1^-, $T=0$ state. The latter is believed to be strongly deformed, and would be expected to derive its dipole width from admixtures of deformed 1^-, $T=1$ states. (For example, the predominantly spherical 1^-, $T=0$ state at 7.12 MeV obtains much of its $E1$ width[10] from the spherical 1^-, $T=1$ state at 13.09 MeV.) However, if such states are displaced upwards, the 9.59-MeV state may have only spherical $T=1$ impurities. This would provide a simple explanation of its weak ground-state decay and of its even weaker decay to the deformed 6.05-MeV, 0_2^+ state.

We would like to thank A. P. Zuker, B. Buck, G. Kluge, and P. Manakos for helpful communications. One of us (J.L.) wishes to acknowledge the hospitality of the Williams Laboratory during a visit.

†Work supported by the U. S. Atomic Energy Commission.

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Pairing-Plus-Quadrupole Model Calculation of Band-Mixing Anomalies in ^{152}Sm†

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(Received 30 November 1970)

The pairing-plus-quadrupole model is improved and extended to $I=6$ states. This microscopic theory gives the parameters of the first-order band-mixing theory of Bohr and Mottelson, as well as most of the higher order corrections revealed by the recent measurements of $E2$ matrix elements. The increase in the intra-ground-band transitions as well as the depression of the ground-band levels compared with their rotational-model values are reproduced.

Recent investigations[1-6] of band-mixing anomalies in ^{152}Sm indicate that (i) although the first-order perturbation theory[7] is satisfactory for transitions from the γ-vibrational band to the ground-state (g) rotational band, it is unsatisfactory for transitions involving the β-vibrational band de-excitation, and (ii) the cross γ-β band transitions, forbidden in the model[7] of rotational states built on harmonic vibrations in β and γ, are large,[6] i.e., the corresponding matrix elements are comparable with the allowed γ-g band transitions.

We report here the results of the anharmonic, dynamic theory based on the microscopic, pairing-plus-quadrupole (PPQ) model.[8-10] Although the anomalously low[1,2] value of the $2_\beta \to 4$ transition-matrix element is not reproduced, the present calculation for ^{152}Sm reproduces (i) the correct trends in the deviations from the first-order band-mixing theory, (ii) the large γ-β band mixing, (iii) the increase in the intra-g-band transition matrix elements as well as the depression of the g-band levels compared with their rotational-model values, and (iv) the absolute values of the low-order matrix elements for β-g and γ-g band transitions, which determine the parameters of the phenomenological theory of Bohr and Mottelson.[7]

The method of calculation is essentially the same as that employed previously[9] for the transitional region of W, Os, and Pt nuclei, except for the following two modifications:

(i) An improved method of including the core contribution to the mass parameters has been employed. Recall that the generalized Bohr Hamiltonian for collective quadrupole motion is written as[8]

$$H_{\text{coll}} = V(\beta,\gamma) + \tfrac{1}{2}\sum_{k=1}^{3} \mathcal{J}_k(\beta,\gamma)\omega_k^{\,2} + \tfrac{1}{2}B_{\beta\beta}(\beta,\gamma)\dot{\beta}^2 + B_{\beta\gamma}(\beta,\gamma)\beta\dot{\beta}\dot{\gamma} + \tfrac{1}{2}B_{\gamma\gamma}(\beta,\gamma)\beta^2\dot{\gamma}^2, \qquad (1)$$

where β,γ define the shape of the nuclear quadrupole in the intrinsic system, ω_k are its rotational frequencies, V is the potential energy of deformation, $\mathcal{J}_k$ are the moments of inertia, and $B_{\beta\beta}$, $B_{\beta\gamma}$, and $B_{\gamma\gamma}$ are the inertial functions for β,γ coupled vibrations.

In a practical, microscopic calculation of the inertial functions, only a few shells near the Fermi surface (FS) are employed. The contribution due to the remaining shells below and above the FS is called a "core contribution." In the method[10] based on the unified model,[11] the core is represented by a harmonic oscillator which is coupled to the external nucleons by a quadrupole force. This model leads to the rule that the core