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$E0$ decays of 0^+ states in ^{146}Gd: Search for two-phonon octupole excitations

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Conversion-electron measurements following the ^{144}Sm(α,2n) and ^{144}Sm(^{3}He,n) reactions reveal high-energy $E0$ transitions at 3020, 3485, and 3639 keV. The lowest of these deexcites the known two-neutron pairing vibrational state in ^{146}Gd. It is not clear whether either of the others can be associated with the 0^+ member of the $3^- \times 3^-$ two-phonon octupole multiplet.

Despite many attempts to identify two-phonon octupole excitations in nuclei such as doubly magic ^{208}Pb, it has been only recently that states of this type have been established[1,2] in the nuclei ^{147}Gd and ^{148}Gd by the observation of cascades of two $E3$ transitions. Because these states in ^{147}Gd and ^{148}Gd involve the stretched coupling of one or two neutrons to the two-phonon octupole excitation ($\nu f_{7/2} \times 3^- \times 3^-$ in ^{147}Gd or $\nu^2 \times 3^- \times 3^-$ in ^{148}Gd), their descriptions are not as straightforward as would be the case in a doubly closed-shell nucleus. Kleinheinz *et al.*[3] have shown that the gap in the proton single-particle spectrum at $Z=64$, combined with the well-known $N=82$ shell closure, gives ^{146}Gd many of the properties of a doubly magic nucleus. This fact, coupled with the observation of the 3^- octupole phonon at an energy considerably below the quadrupole phonon state, explains why two-phonon octupole excitations have been discovered in this region and suggests that the ^{146}Gd "core" is an excellent nucleus in which to search for the long sought two-phonon octupole multiplet of states.

In ^{146}Gd, a two-phonon octupole quartet of states with spins and parities of 0^+, 2^+, 4^+, and 6^+ should lie at about twice the energy of the 3^- phonon (i.e., in the 3.2-MeV region). We have recently reported[4] the results of our detailed study of ^{146}Gd in which we tried to suppress the population of yrast states in order to study the nonyrast levels in this nucleus. No clearcut identification of the members of the two-phonon quartet emerged from that work. Moreover, it became obvious that the degree of level population (see Figs. 7 and 8 of Ref. 4), coupled with the low sensitivity for the detection of high-energy γ rays, would not lead to the observation of the decays of these states, except for possibly the higher-spin 4^+ and 6^+ members. In addition, the existence of alternative decays from the states of the two-phonon multiplet would make their identification difficult.

The 0^+ member of the multiplet might, on the other hand, offer advantages that are not possible for the higher-spin multiplet members. Relevant competing transitions deexciting a 0^+ state in the 3.2 MeV excitation region of ^{146}Gd are an $E2$ transition to the 1972-keV 2_1^+ state and an $E0$ transition to the ground state. By taking the $B(E2)$ as one Weisskopf unit, a transition rate of $P(E2)=2.0\times 10^{11}$ s^{-1} for the $E2(0^+ \rightarrow 2_1^+)$ transition is obtained. Letting the $E0$ transition correspond to the single-particle unit proposed by Bohr and Mottelson,[5] one obtains $\rho_{\text{s.p.}}=0.7A^{-1/3}=0.13$ for the monopole strength parameter in ^{146}Gd. By using the electronic factor Ω_K from Ref. 6, an $E0$ transition rate via internal K conversion of

$$P_K(E0)=\Omega_K \rho_{\text{s.p.}}^2=3.5\times 10^9 \text{ s}^{-1}$$

is obtained. Internal conversion and internal pair production probabilities are roughly equal for transitions of this energy in gadolinium.[7] Consequently, an order-of-magnitude estimate for the K conversion of the $E0$ branch is 2% of the total deexcitation of the 0^+ state. This estimate suggests that the detection of the internal conversion decay offers a sensitive method for the identification of 3-MeV 0^+ states in ^{146}Gd.

Internal conversion-electron measurements were conducted at Los Alamos National Laboratory (LANL) with the Lawrence Livermore National Laboratory (LLNL) superconducting solenoidal spectrometer[8] and at the Jyväskylä Physics Department (JYFL) with a Siegbahn-Slätis-type magnetic lens and a Ge(HP) detector. The JYFL arrangement is particularly well suited for the detection of high-energy electrons, while the LLNL spectrometer offered somewhat better energy resolution.

In the measurements at LANL, we utilized the ^{144}Sm(α,2n) reaction to excite levels in ^{146}Gd. The α-

particle energy was 25.5 MeV, slightly lower than that used previously,[4] but an energy that should provide near optimal population of the nonyrast states. The target was a thin (700 μg/cm^2) metallic foil enriched to 96% in ^{144}Sm. Gamma-ray spectra were recorded simultaneously with a Ge(HP) detector having 10% relative efficiency. In the conversion-electron spectrum shown in Fig. 1, three peaks can be associated with $E0$ transitions. The $K-L$ energy differences, Q values, and estimated cross sections indicate that all the observed K lines originate from ground-state transitions in ^{146}Gd. In the cases of the 3485- and 3639-keV transitions, it was possible to determine the K/L ratios to be 10 ± 5 and 7.2 ± 0.6, respectively, in good agreement with the value of 7.3 anticipated[6] for $E0$ transitions. The measured L/M ratio of 2.6 ± 0.5 for the 3639-keV transition is also in accord with theoretical expectations.[7]

Only the 2986-keV transition has a corresponding γ ray and is thus not of $E0$ multipolarity. Because of uncertainties in the electron efficiency calibration at these high electron energies, it was not possible to determine the multipolarity of this transition. However, if we make the conservative assumption that the 2986-keV transition is $E1$, upper limits on the relative γ-ray intensities of the higher-lying transitions permit us to establish them to be of $M3$ or higher multipolarity. Since high multipolarity transitions of these energies seem unlikely, we conclude that these are indeed $E0$ transitions.

An additional $E0$ transition at 2165 keV, observed in these and earlier measurements,[9] was at the lower limit of the transmission window used in taking the spectrum of Fig. 1. Because high-energy γ-ray and conversion-electron sources were not available for the energy regime investigated here, energies were necessarily obtained by extrapolation from known, lower-energy lines. This procedure led to a disagreement of only 0.5 keV for the 2986-keV transition, as determined from the γ-ray and electron spectra separately. Therefore, we assign an uncertainty of ±1 keV to the energy of the 2986-keV transition and an uncertainty of ±2 keV to the higher-energy conversion electron lines.

The ^{144}Sm(^{3}He,n) reaction, at energies near the Coulomb barrier, was used at JYFL for population of low-spin states in ^{146}Gd. Only one $E0$ line, the intense peak from the 3638-keV transition, which could be definitely associated with ^{146}Gd was observed in these spectra.[10]

In addition to the ground state, 0^+ excitations at 2165 and 3016 keV had been identified[9,11] in ^{146}Gd before this work was begun. These states have been attributed to the proton- and neutron-pairing vibrations, respectively.

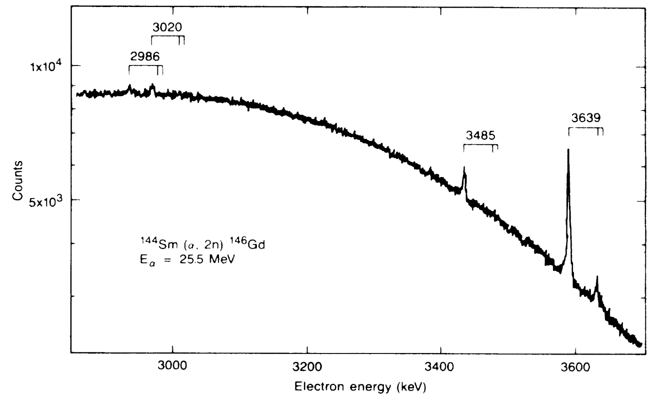

FIG. 1. In-beam conversion electron spectrum from the bombardment of a 700-μg/cm^2 enriched ^{144}Sm target with 25.5-MeV α particles. Transition energies are indicated for each K, L, and M electron multiplet.

We established two higher-energy 0^+ excitations, at 3485 and 3639 keV, by observing their $E0$ decays to the ground state. Either of these higher-energy states could be the expected 0^+ member of the two-phonon octupole multiplet, although the anharmonicities seem inexplicably large. Moreover, there are also other 0^+ excitations from two-proton states—e.g., $g_{7/2}^{-2}$ and $s_{1/2}^2$—anticipated[4] in this energy region, and it seems impossible to characterize these states further from the available data. Any attempt to observe γ-decay branches from these states seems destined to failure because the reaction cross sections are small, and it is only the high sensitivity for detecting $E0$ internal-conversion electrons that permitted us to observe these weakly populated states. For example, even a large γ-ray branch ($>99\%$) to the 1972-keV 2^+ state ($E2$ multipolarity) or to the 1579-keV 3^- state ($E3$) would not be observed because of the much lower sensitivity of γ-ray detection.

In summary, we have identified three $E0$ transitions—at 3020, 3485, and 3639 keV—in addition to the known $E0$ transition of 2165 keV. Either of the two higher-energy transitions could be from the 0^+ state associated with the two-phonon octupole excitation, but other interpretations are also possible.

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[1] P. Kleinheinz, J. Styczen, M. Piiparinen, J. Blomqvist, and M. Kortelahti, Phys. Rev. Lett. **48**, 1457 (1982).

[2] S. Lunardi, P. Kleinheinz, M. Piiparinen, M. Ogawa, M. Lach, and J. Blomqvist, Phys. Rev. Lett. **53**, 1531 (1984).

[3] P. Kleinheinz, R. Broda, P. J. Daly, S. Lunardi, M. Ogawa, and J. Blomqvist, Z. Phys. A **290**, 279 (1979).

[4] S. W. Yates, R. Julin, P. Kleinheinz, B. Rubio, L. G. Mann, E. A. Henry, W. Stöffl, D. J. Decman, and J. Blomqvist, Z. Phys. A **234**, 417 (1986).

[5] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, 1975), Vol. 2, p. 553.

[6] D. A. Bell, C. E. Aveledo, M. G. Davidson, and J. P. Davidson, Can. J. Phys. **48**, 2542 (1970).

[7] J. Kantele, in *Heavy Ions and Nuclear Research,* Mikolajki,

Poland, 1981, edited by B. Sikora and Z. Wilhelmi (Harwood Academic, New York, 1984), p. 391.
[8]W. Stöffl and E. A. Henry, Nucl. Instrum. Methods **227**, 77 (1984).
[9]R. Julin, J. Kantele, M. Luontama, A. Passoja, P. Kleinheinz, and J. Blomqvist, Phys. Lett. **94B**, 123 (1980).
[10]R. Julin, M. Luontama, A. Passoja, W. Trzaska, J. Kantele, P. Kleinheinz, and J. Blomqvist, JYFL Annual Report 1983–84, Jyväskylä, Finland, 1984, p. 75.
[11]E. R. Flynn, J. van der Plicht, J. B. Wilhelmy, L. G. Mann, G. L. Struble, and R. G. Lanier, Phys. Rev. C **28**, 97 (1983).