THE 2.57 MeV 19/2$^-$ TWO-PHONON OCTUPOLE STATE IN ^{147}Gd

P. Kleinheinz, J. Styczen[+], M. Piiparinen[++], M. Kortelahti[+++]
Institut für Kernphysik, KFA Jülich, Jülich, F.R. Germany

J. Blomqvist
Research Institute of Physics, Stockholm, Sweden

Abstract

The half life of the $(\nu f_{7/2} \times 3^- \times 3^-)_{19/2^-}$ two-phonon octupole state at 2.572 MeV in ^{147}Gd was measured as $T_{1/2}$ = 0.37(8) ns, which gives a transition strength of 52(15) W.U. for the 1525 keV E3 transition to the 0.997 MeV $(\nu f_{7/2} \times 3^-)_{13/2^+}$ one phonon excitation. The $\nu i_{13/2}$ admixture in the 13/2$^+$ one-phonon state, as well as the dominant $\pi h_{11/2} d_{5/2}^{-1}$ component of the ^{146}Gd 3$^-$ state give rise to large anharmonicities for the two-phonon excitation. An estimate of the energy shifts based on empirical coupling matrix elements gives 2.66 MeV excitation for the 19/2$^-$ two-phonon state, in good agreement with the observed energy of that state.

Since many years attempts have been made to identify two-phonon octupole states in nuclei. Such excitations could in principle be most clearly observed in Coulomb excitation with heavy ions. But even in the simple case of ^{208}Pb, which was studied through Coulomb excitation with ^{208}Pb beam as well as through other experiments, it was so far not possible to identify the two-phonon octupole states expected in the 5.2 MeV region.

In ^{146}Gd the octupole phonon lies 1 MeV lower than in ^{208}Pb, at 1.6 MeV, and in the neighbouring ^{147}Gd nucleus it occurs as low as 1 MeV. This low excitation, and the detailed knowledge of the ^{147}Gd level structure below 3 MeV, makes this nucleus particularly favourable for a study of two-phonon octupole excitations.

Some time ago we have observed$^{1)}$ in ^{147}Gd a 19/2$^-$ level at 2.572 MeV which decays through two stretched E3 transitions to the $\nu f_{7/2}$ ground state (Fig. 1). In ref. 1 we have discussed that this level must have a significant $\nu f_{7/2} \times 3^- \times 3^-$ two-phonon contribution, but at that time the experimental data were insufficient to determine the properties of this state in detail. Since then more quantitative knowledge emerged on octupole-particle coupling phenomena in this region$^{2,3)}$ which will also strongly affect the two-phonon excitations. Furthermore, we have now measured the strength of the 19/2$^-$ → 13/2$^+$ E3 transition.

A measurement of the 19/2$^-$ level half life is difficult since other high-spin isomers, with $T_{1/2}$ = 4 ns and 27 ns, occur closely above in the level scheme (fig. 1), and since only ≈ 13 % of the yrast decay proceeds through the 19/2$^-$ state. Moreover, an 84 keV E1 γ-ray competes with the 1575 keV E3 deexcitation, and therefore the level half life is expected to be well below 1 ns. For these reasons, various coincidence measurements involving detection of γ-rays and conversion electrons only gave an upper limit of < 1 ns for the level half life. A much better population yield for the 19/2$^-$ level is achieved in the (^{3}He,3n) reaction where the direct side feeding to the state is quite large and where the higher-lying isomers are only weakly populated. This makes it possible to determine the half life in a singles timing experiment. In a measurement of the time-delay relative to the beam burst of 1575 K electrons carried out with a 22 MeV ^{3}He beam from the cyclotron at Jyväskylä we obtained the result

$$T_{1/2}\ (19/2^-, 2.57\ \text{MeV}) = 370(80)\ \text{ps}.$$

The conversion electrons were focussed in a magnetic lens spectrometer operated in swept-current mode and energy analyzed in a Si(Li) spectrometer$^{4)}$. This measurement simultaneously provided several prompt standards at neighbouring energies which were essential for evaluation of the final result. (In an independent measurement at slightly higher bombarding energy the ^{146}Gd 3$^-$ state at 1.58 MeV is also populated, and from the delay of the 1579 K electrons we obtained $T_{1/2}$ (3$^-$, 1.58 MeV) = 1.06(6) ns in perfect agreement with the earlier$^{5)}$ result). Taking into account the error in the 1575 to 84 keV intensity ratio the measured half live gives

$$B(E3,\ 1575\ \text{keV}) = 52(15)\ \text{W.U.}$$

This very high transition strength supports the two-phonon character of the 19/2$^-$ level.

The simplest expectation is that the two-phonon state should occur at twice the energy of the one-phonon state, and should decay with a rate twice as large as the one-phonon transition. It is apparent that the experimental findings deviate from this simple predictions for both, energy and transition rate.

Two different phenomena are expected to affect the energy of the two-phonon state in ^{147}Gd. The first is associated with the coupling of the neutron $f_{7/2} \rightarrow i_{13/2}$ excitation to the octupole vibration, while the second reflects the action of the Pauli principle between the particle-hole components of the two phonons.

The 13/2$^+$ level at 1.00 MeV has a considerable admixture of the $i_{13/2}$ single neutron state due to the large coupling matrix element

$$m = \langle i_{13/2} |\ H_{\text{coupl}}\ | f_{7/2} \times 3^-;\ 13/2 \rangle .$$

The situation is basically similar to that observed in the N=127 nucleus ^{209}Pb, where the corresponding single particle orbits are $\nu g_{9/2}$ and $\nu j_{15/2}$ (fig. 2). Whereas however in ^{209}Pb the 1.42 MeV 15/2$^-$ state is of ≈ 70 % single particle character$^{6)}$ with about 30 % admixture of $\nu g_{9/2} \times 3^-$, the situation is reversed in ^{147}Gd, where the octupole lies lower in energy than the $\nu i_{13/2}$ single particle state.

When the difference δ between the single particle excitation energy $\varepsilon_{13/2} - \varepsilon_{7/2}$ and the phonon energy $\hbar\omega_3$

$$\delta = \varepsilon_{13/2} - \varepsilon_{7/2} - \hbar\omega_3$$

[+] On leave from Institute of Nuclear Physics, Cracow, Poland

[++] A.v. Humboldt fellow 1978-80, on leave from Inst. of Physics, University of Jyväskylä, Finland

[+++] Inst. of Physics, Univ. of Jyväskylä, Finland

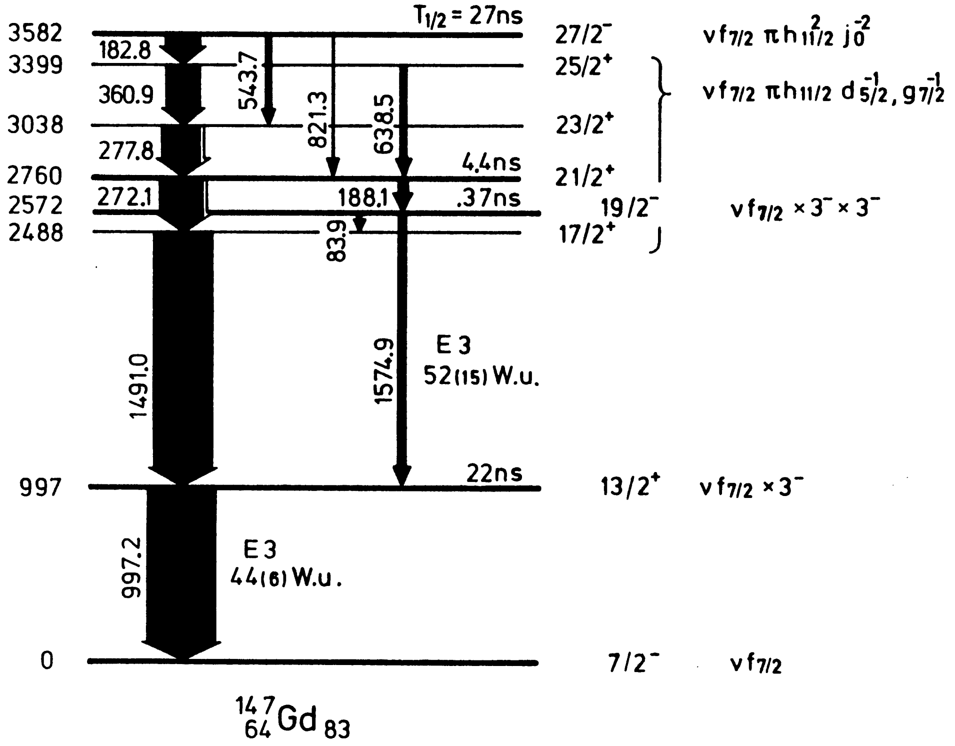

Fig. 1: High-spin levels in the one-neutron nucleus ^{147}Gd observed in the (α,5n) reaction$^{1)}$. The 19/2$^-$ half life is from the present work.

is comparable to the coupling matrix element m, the energy E of the low-lying mixed state is obtained by diagonalizing the 2 x 2 Hamiltonian

$$E_{13/2} = h\omega_3 - \frac{1}{2}\,|\sqrt{\delta^2 + 4m^2} - \delta\,|$$

Similarly, the energy of the lowest 19/2$^-$ state is obtained by diagonalizing the Hamiltonian in the basis of the two states $f_{7/2} \times 3^- \times 3^-$ and $i_{13/2} \times 3^-$

$$E_{19/2} = 2h\omega_3 - \frac{1}{2}\,|\sqrt{\delta^2 + 8m^2} - \delta\,|$$

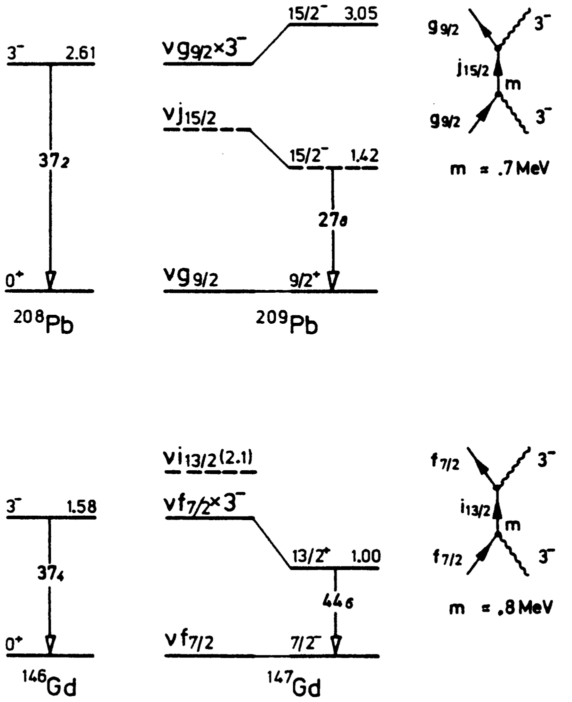

Fig. 2: Coupling of the valence neutron to the core octupole in ^{209}Pb and ^{147}Gd.

In second order perturbation theory the harmonic spectrum is preserved,

$$E_{13/2} = h\omega_3 - m^2/\delta$$

$$E_{19/2} = 2h\omega_3 - 2m^2/\delta = 2E_{13/2}.$$

However, for strong coupling, as in the present situation, this result is modified. $E_{19/2}$ is higher than $2E_{13/2}$ by the amount

$$\delta E_{19/2} = \sqrt{\delta^2 + 4m^2} - \frac{1}{2}|\sqrt{\delta^2 + 8m^2} + \delta|.$$

The unperturbed $\nu i_{13/2}$ energy in ^{147}Gd (and hence δ) is experimentally not well known, but systematics of the N=83 isotones$^{7)}$ and other indirect spectroscopic evidence$^{8,9)}$ suggest a ≈ 2.1 MeV $f_{7/2}$ to $i_{13/2}$ single particle energy separation, which is indicated in fig. 2. Using thus δ = 0.52 MeV, the observed $E_{13/2}$ = 1.00 MeV excitation is reproduced with m = 0.8 MeV. These values give

$$\delta E_{19/2} = + 0.26 \text{ MeV}.$$

The second effect is associated with the microscopic composition of the octupole phonon. There is evidence that the proton $h_{11/2}d^{-1}_{5/2}$ particle hole component occurs with large probability in the 3$^-$ state. This was in particular seen$^{2)}$ clearly in the $\pi h_{11/2} \times 3^-$ particle-phonon multiplet in ^{147}Tb. The experiment identified the 17/2$^+$ and 15/2$^+$ members of this group, which are separated by the large energy of 772 keV. This can be understood as an effect of the Pauli principle where the $h_{11/2}$ proton particle in the phonon interferes with the $h_{11/2}$ valence proton. The associated particle-phonon interaction matrix element M in the exchange process (fig. 3) is obtained from the 772 keV 17/2$^+$ to 15/2$^+$ splitting to be

$$M \approx 1.1 \text{ MeV}$$

taking for the energy denominator Δ the value

$$\Delta = \varepsilon_{11/2} - \varepsilon_{5/2} - h\omega_3 \simeq 1.5 \text{ MeV}.$$

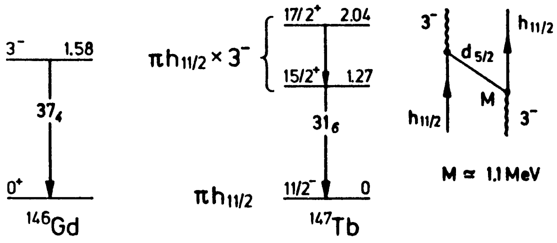

Fig. 3: Coupling of the $h_{11/2}$ valence proton of ^{147}Tb to the core octupole.

The two-phonon exchange process, which is analogous to the exchange coupling in fig. 3, is illustrated in the fourth order diagram of fig. 4. The large $\pi h_{11/2} d_{5/2}^{-1}$ components in the two octupole phonons interact by exchanging the particle (or the hole). The interaction vertices in figs. 3 and 4 are the same, and we can therefore use the empirical values of M and Δ which describe the Pauli effect in the ^{147}Tb case to evaluate the energy shift δE_I corresponding to the diagram in fig. 4. The shift is given by the expression

$$\delta E_I = 98 \; X \left(\frac{11}{2}\,\frac{5}{2}\; 3;\; \frac{5}{2}\,\frac{11}{2}\; 3;\; 3\; 3\; I\right) \times \frac{M^4}{\Delta^3}$$

where I is the coupled angular momentum of the two phonons. For the case I=6 the geometric coefficient is

$$98 \; X = + \frac{44239}{52272} = 0.846$$

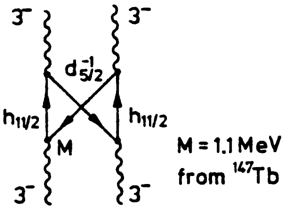

Fig. 4: Phonon-phonon coupling in ^{146}Gd.

and the energy shift

$$\delta E_6 \simeq 0.846 \times \frac{1.1^4}{1.5^3} \text{ MeV} = + 0.41 \text{ MeV}.$$

This shift can also be adopted for the 19/2⁻ state of ^{147}Gd, neglecting the $i_{13/2} \times 3^-$ content in that state. This approximation may be of similar quality as the use of fourth order perturbation theory in describing the $3^- \times 3^-$ coupling.

Adding up the two contributions (fig. 5) the total energy shift δE for the 19/2⁻ state is

$$\delta E = \delta E_{19/2} + \delta E_6 = (0.26 + 0.41) \text{ MeV} = 0.67 \text{ MeV},$$

which compares well with the experimental shift

$$\delta E_{\text{exp}} = (E_{19/2} - E_{13/2}) - (E_{13/2} - E_{7/2})$$
$$= (1575 - 997) \text{ keV} = 0.58 \text{ MeV}.$$

Similar processes as those discussed above causing the energy shifts will also give rise to a reduction relative to the harmonic expectation of the 19/2 to 13/2 E3 strength.

The present data provide the first clear indication of a two-phonon octupole state. It has been shown that the large departure from equal energy spacing corresponding to harmonic vibration can be quantitatively understood in terms of the microscopic composition of the states and can be connected with other observed features of the octupole vibrations in this region.

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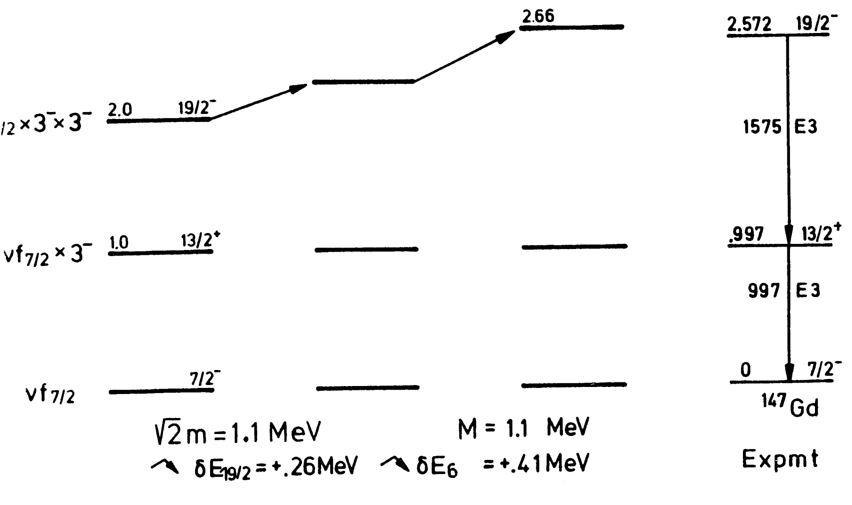

Fig. 5: Calculated energy shifts for the $\nu f_{7/2} \times 3^- \times 3^-$ two-phonon octupole state in ^{147}Gd.