First Identification of Dipole Excitations to a $2^+ \otimes 3^- \otimes$ Particle Multiplet in an Odd-A Nucleus

A. Zilges,(1) R.-D. Herzberg,(1) P. von Brentano,(1) F. Dönau,(2),(5) R. D. Heil,(3) R. V. Jolos,(1),(6) U. Kneissl,(3) J. Margraf,(3) H. H. Pitz,(3) and C. Wesselborg(4)

(1) *Institut für Kernphysik, Universität zu Köln, W-5000 Köln 41, Germany*

(2) *Institut für Theoretische Physik, Universität zu Köln, W-5000 Köln 41, Germany*

(3) *Institut für Strahlenphysik, Universität Stuttgart, W-7000 Stuttgart 80, Germany*

(4) *Institut für Kernphysik, Justus-Liebig-Universität Giessen, W-6300 Giessen, Germany*

(5) *Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf, O-8051 Dresden, Germany*

(6) *Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Russia*

(Received 10 February 1993)

A photon scattering experiment has been performed on the odd-A nucleus ^{143}Nd. Strong dipole excitations have been detected in the energy region around 3.2 MeV. This is near the expected position of the two-phonon ($2^+ \otimes 3^-$) multiplet in the even-even neighboring nucleus ^{142}Nd. The summed dipole strength between 2.8 and 3.6 MeV in ^{143}Nd is in agreement with the sum rule for weak particle coupling to the core nucleus ^{142}Nd. Model calculations in a harmonic approximation are in very good agreement with the experiment and they suggest a two-phonon ($2^+ \otimes 3^-$) particle structure of the excitations in ^{143}Nd.

PACS numbers: 25.20.Dc, 21.10.Re, 21.60.Ev, 27.60.+j

Collective excitations such as quadrupole or octupole vibrations are the characteristic features in the low energy level scheme of spherical nuclei [1]. In the last years much work has been spent to investigate multiphonon excitations, i.e., the coupling of two or more collective states. A very extensively studied example is the coupling of two quadrupole 2^+ vibrations forming a multiplet of states with J^π=0^+, 2^+, and 4^+. This multiplet has been found experimentally and described theoretically in many nuclei [1,2]. The coupling of two octupole 3^- phonons has been observed by Kleinheinz, Piiparinen, and co-workers. They found a single level belonging to a ($3^- \otimes 3^- \otimes$particle) multiplet in ^{147}Gd [3] and a two-to-one-phonon $E3$ transition in ^{148}Gd [4].

Another class of two-phonon states arises by coupling the quadrupole 2^+ vibration to an octupole 3^- excitation [5]. A prominent feature is very strong $E1$ ground-state transitions from the 1^- state of this multiplet [6]. Enhanced $E1$ transitions from octupole states have been described in nonspherical nuclei, too [7–9]. As nuclei in the $N = 82$ region have relatively low lying 3^- states with very strong ($E3$; $3^- \to 0^+$) transitions, many investigations on ($2^+ \otimes 3^-$) states concentrate on different Ba, Ce, Nd, and Sm isotopes. In photon scattering experiments the 1^- member of the $2^+ \otimes 3^-$ multiplet has been found in various $N = 82$ nuclei [10–13]. Experimental effort is under way to detect other members of this multiplet with different experimental techniques, but the information is sparse; see, e.g., [14–16].

In photon scattering experiments on ^{142}Nd an isolated $E1$ ground-state transition from a 1^- state at 3425 keV was detected [12,13]. This energy is close to the sum energy of the 2^+ and 3^- vibrations at 1576 and 2084 keV, respectively. The $E1$ transition strength $B(E1)\downarrow$=$(5.4\pm0.8)\times10^{-3}$ $e^2\,\mathrm{fm}^2$ is 2–3 orders of magnitude larger than the usual E1 strengths in this mass region [17]. This underlines the collective character of this 1^- state [13]. Other evidence for the two-phonon character of this state came from calculations in the *sdf* interacting boson model (IBM), where it is impossible to reproduce the experimental transition rates without a two body ($2^+ \otimes 3^-$) term in the $E1$ operator in the isotonic nucleus ^{144}Sm [18].

In this paper we will study the coupling of an additional particle to the ($2^+ \otimes 3^-$) multiplet, i.e., we will investigate the structure of the excitations in an odd-A neighboring nucleus. In the case of ^{143}Nd the additional neutron occupies the $f_{7/2}$ subshell. Because of the coupling to the odd neutron the five levels of the $2^+ \otimes 3^-$ multiplet in the core nucleus split into 31 levels in ^{143}Nd. It is clear that one needs an experimental method which is selective in strength and spin to detect these fragmented two-phonon particle levels in the energy region around 3 MeV where the level density is already high. Photon scattering fulfills these requirements: (i) From the ground state almost exclusively dipole transitions are induced, (ii) a very high energy resolution can be achieved by detecting the scattered γ rays with Ge detectors, and finally (iii) model independent cross sections and absolute transition strengths can be measured using adequate photon flux calibrators [19].

We performed a photon scattering experiment on ^{143}Nd to search for the ($2^+ \otimes 3^- \otimes$ particle) excitations. The experiments have been carried out at the bremsstrahlung facility of the Stuttgart dynamitron accelerator. The end-point energy was $\simeq$ 4 MeV; thus all strong dipole excitations between 1 and 4 MeV were found. Figure 1 shows the spectrum of ^{143}Nd in the energy region between 2.8 and 3.5 MeV. One can clearly identify a number of strong dipole transitions. The differential cross

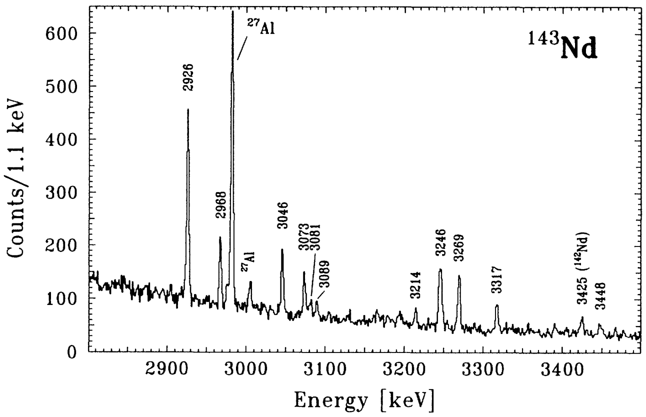

FIG. 1. Spectrum of photons scattered off ^{143}Nd between 2.8 and 3.5 MeV. The intensive line at 2981 keV arises from a transition in the ^{27}Al calibration target.

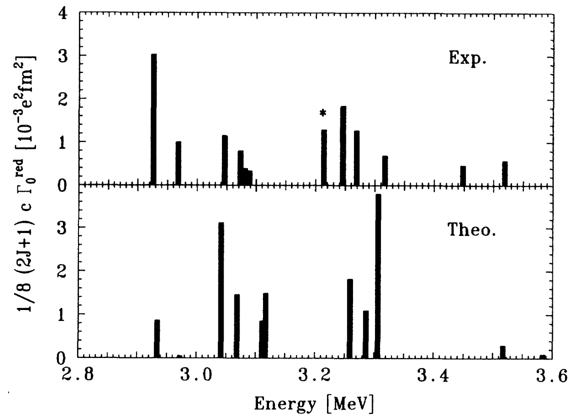

FIG. 2. Experimental (upper part) and theoretical (lower part) strength distribution in ^{143}Nd between 2.8 and 3.6 MeV. If the transition has an $E1$ character one finds [cf. Eq. (3)] $\frac{1}{8}(2J+1)b\Gamma_0^{\rm red} = B(E1;n,J \to J_0)\downarrow$. We note that $\Gamma_0^{\rm red}=\Gamma(n,J \to J_0)E_r^{-3}$ and $b = 0.9553 \times 10^{-3}$ $e^2\,{\rm fm}^2\,{\rm MeV}^3/{\rm meV}$. In the experimental analysis pure dipole character is assumed for all transitions. The theoretical model calculates directly the $B(E1;n,J \to J_0)\downarrow$ values. The level marked with an asterisk shows a strong branching to the $3/2^-$ level at 742 keV and is not expected to be reproduced by our theoretical calculation.

section for bremsstrahlung scattering to a resonance at the energy E_r is

$$\frac{d\sigma}{d\Omega} = \pi^2 \lambda\!\!\!^{-}{}^2 \frac{2J+1}{2J_0+1}\Gamma_0 \frac{\Gamma_f}{\Gamma}\frac{W(\Theta)}{4\pi}\,, \tag{1}$$

where $\lambda\!\!\!^{-} = \hbar c/E_r$, J_0 denotes the ground-state spin, J is the spin of the excited state n, $\Gamma_0 = \Gamma(n,J \to J_0)$ is the ground-state transition width, $\Gamma_f = \Gamma(n,J \to J_f)$ the transition width to the final state (in case of elastic scattering Γ_f=Γ_0, otherwise $\Gamma_f = \Gamma_1$), and $W(\Theta)$ is the angular correlation function.

We have measured the (γ,γ') spectra at three different angles (90°, 127°, and 150°) but due to the rather constant behavior of the angular correlation functions $W(\Theta)$ for the possible spin cascades in the odd nucleus ^{143}Nd we were not able to assign spins to the observed levels. Therefore we extract the ground-state decay width Γ_0 times a factor depending on the spin of the excited state from the measured cross sections:

$$\frac{2J+1}{2J_0+1}\Gamma_0 = \frac{2J+1}{8}\Gamma_0 = \frac{1}{(\pi\hbar c)^2}\left(1+\frac{\Gamma_1}{\Gamma_0}\right)E_r^2 I_s\,, \tag{2}$$

where Γ_1/Γ_0 is the measured branching ratio to the first excited state and I_s is the integrated cross section. The factor 1/8 stems from the ground-state spin in ^{143}Nd, $J_0 = 7/2$. As mentioned before the angular correlation functions are nearly independent of the spin of the excited state and take the value $W(\Theta) \simeq 1.0$.

The ground-state decay width Γ_0 is related to the reduced $B(E1)$ transition probability:

$$B(E1)\downarrow = 0.9553 \times 10^{-3}\Gamma_0/E_r^3\,, \tag{3}$$

where B is in $e^2\,{\rm fm}^2$, Γ_0 in meV, and E in MeV. We assume that only dipole transitions are induced from the ground state. Thus the spin factor has the value $\frac{2J+1}{8} = 0.75$, 1.0, and 1.25 for the spins $J = 5/2$, $7/2$, and $9/2$, respectively, in ^{143}Nd. The measured strength distribution is shown in the upper part of Fig. 2. The assumption of electric dipole character for these transitions is highly favorable from the known dipole excitation in the even-even neighbor nuclei.

To compare the measured strength in ^{143}Nd with the E1 strength in the core nucleus ^{142}Nd we use the sum rule for $B(E1)\downarrow$ valid for weak particle coupling [20],

$$\sum_n B(E1;n,J \to J_0) = B(E1;1^- \to 0^+)\,. \tag{4}$$

If the pure configurations are mixed, so that the strength is distributed among several levels, the total $B(E1)$ strength in the odd-A nucleus for each spin corresponds to the $B(E1)$ value in the core nucleus. This sum rule implies equal summed cross sections in both the even and the odd nucleus. As we excite states with $J = 5/2$, $7/2$, and $9/2$ one expects that the $B(E1)\downarrow$ values summed over all states found in our experiment in the energy region around 3.2 MeV should be 3 times as large as the dipole strength of the $1^- \to 0^+$ transition in the core nucleus. If we sum up the observed transition strength between 2.8 and 3.6 MeV in ^{143}Nd we obtain from the experiment a value

$$\sum_{J,n}\frac{2J+1}{8}B(E1;n,J)\downarrow = (12.8 \pm 1.6) \times 10^{-3}\,e^2\,{\rm fm}^2\,. \tag{5}$$

According to Eq. (4) this should be equal to the value $3B(E1)\downarrow(^{142}{\rm Nd}) = (16.3 \pm 2.4) \times 10^{-3}\,e^2\,{\rm fm}^2$ for the $E1$ transition from the 3425 keV state in the core nucleus ^{142}Nd. The fact that the sum rule is fulfilled is an impressive proof for the correctness of a two-phonon $\otimes$ particle structure for the excitations in ^{143}Nd.

As the experimental information on two-phonon excitations in even-even nuclei is still sparse, it is our aim to reproduce the experimentally observed levels with as simple a model as possible. The model calculation consists of two parts. First the prominent collective features of the even-even core ^{142}Nd are described so that missing experimental data such as the positions of the $2^- \cdots 5^-$ members of the $2^+ \otimes 3^-$ multiplet can be taken from theory. Then a single neutron is coupled to this core. Much work was dedicated to the study of the structure of ^{143}Nd in the past years [21–24]. We will make the following approximations: The core is described by a quadrupole phonon, an octupole phonon, and a multiplet of two phonon states $1^- \cdots 5^-$ only. The splitting of the multiplet comes from the quadrupole quadrupole interaction. The other low lying states of the core are not considered. We consider the odd neutron to be in the $f_{7/2}$ subshell only.

We describe the core by the *sdf* IBM Hamiltonian

$$H = \epsilon_2 \hat{n}_{2^+} + \epsilon_3 \hat{n}_{3^-} - \kappa (Q^{(2)} \cdot Q^{(2)})^{(0)} , \qquad (6)$$

where $\hat{n}_{2^+}$ and $\hat{n}_{3^-}$ count the number of quadrupole, respectively, octupole bosons, and Q is the usual quadrupole operator

$$\begin{aligned} Q &= Q_{sd} + Q_f \\ &= (s^\dagger \tilde{d} + d^\dagger s)^{(2)} + \chi_d (d^\dagger \tilde{d})^{(2)} + \chi_f (f^\dagger \tilde{f})^{(2)} . \end{aligned} \qquad (7)$$

Only the matrix elements Q_{22}, Q_{33}, and Q_{20} enter the calculation of the odd system and can be fixed from the experiment. Q_{ij} serves as an abbreviation for $\langle j||Q||i\rangle$. We evaluate the *sd* part and the *f* part of this Hamiltonian by using the harmonic approximation and only keep the $Q_{sd} \cdot Q_f$ part to produce the energy splitting of the $1^- \cdots 5^-$ multiplet. The parameters ϵ_2 and ϵ_3 are obtained from $E(2^+)$ and $E(3^-)$, respectively. The product $\kappa Q_{22} Q_{33}$ is extracted from the energy difference $\Delta E_{1^-} = E_{2^+} + E_{3^-} - E_{1^-}^{\text{exp}} = 0.233$ MeV of the two-phonon multiplet in ^{142}Nd.

A single $f_{7/2}$ neutron is then coupled to these excitations. The coupling calculation is performed via an interaction of the form

$$H_c = \tilde{\kappa} (Q^{(2)}_{\text{core}} \cdot q^{(2)}_{\text{s.p.}})^{(0)} + \eta (a^\dagger a)^0 \hat{n}_{2^+} \hat{n}_{3^-} , \qquad (8)$$

where $q^{(2)}_{\text{s.p.}}$ denotes the quadrupole operator of the single particle, and $a^\dagger$ is the creation operator for a $f_{7/2}$ neutron. The relevant products $\tilde{\kappa} Q_{22} q_{f_{7/2}}$, $\tilde{\kappa} Q_{20} q_{f_{7/2}}$, and $\tilde{\kappa} Q_{33} q_{f_{7/2}}$ are fixed from the experimentally observed splitting of the $2^+ \otimes f_{7/2}$ and $3^- \otimes f_{7/2}$ multiplets in ^{143}Nd. We estimated the splitting of the lower lying $2^+ \otimes f_{7/2}$ and $3^- \otimes f_{7/2}$ multiplets in ^{143}Nd from the relative positions of the first $1/2^+, 11/2^+, 5/2^+, 9/2^-, 11/2^-$ states and of the first two $7/2^-$ states and used these values as initial start parameters in the subsequent fit. Therefore all parameters of Eqs. (6)–(8) except η are fixed before the $2^+ \otimes 3^- \otimes f_{7/2}$ multiplet is calculated. The actual calculations are performed using the code COUPLIN by Dönau [25].

In a second step these fixed parameters are now used to couple the odd neutron to the $2^+ \otimes 3^-$ multiplet. The energies of all 31 multiplet states are calculated. Note that in our experiment due to the spin selection rules only the states with spins 5/2, 7/2, and 9/2 can be excited from the ground state. Therefore we shall limit our discussion to the 15 corresponding multiplet states. Figure 3 shows the calculated levels in comparison to the experiment for the two-phonon particle multiplet. The quality of the fit is very good. We found it necessary to shift the whole multiplet by approximately 10% to lower energies by adjusting the parameter η of the coupling Hamiltonian. However, this may be justified if one remembers that the nucleus ^{143}Nd is located between ^{142}Nd and ^{144}Nd where the 1^- members of the two phonon multiplet lie at 3.425 MeV and 2.186 MeV, respectively. Even a single neutron may lead to a small polarization effect responsible for the shift. The calculation yields two weak two-phonon particle excitations above the measured energy range.

To reproduce the experimentally observed transition

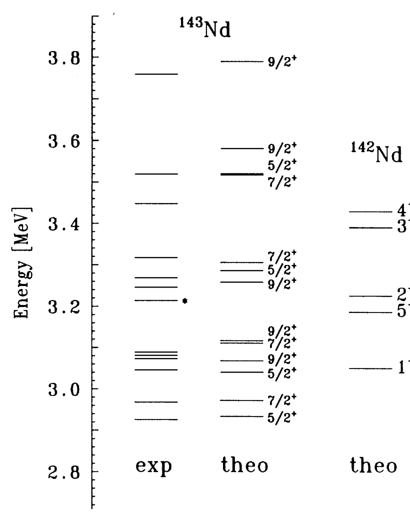

FIG. 3. The left side shows the calculated two-phonon particle states with spin $5/2^+, 7/2^+$, and $9/2^+$ in ^{143}Nd in comparison with the experimentally observed levels between 2.9 MeV and 4 MeV. The level observed in the experiment at 3.214 MeV marked with an asterisk (*) displays considerable branching to the $3/2_1^-$ state. Therefore it is believed to contain a large $p_{3/2}$ single particle amplitude and cannot be reproduced at this stage. The structure of ^{142}Nd as used in the calculation is shown on the right side. The $2^-, 3^-, 4^-, 5^-$ members of the two-phonon multiplet are not yet determined experimentally.

strengths, pure collective $E1$ transitions are assumed and consequently the transition takes place through the $|1^- \otimes f_{7/2}\rangle$ component of the wave functions only. Thus we use the sum rule Eq. (4) implying that the transition strengths from members of the two-phonon particle multiplet are given just by the $|1^- \otimes f_{7/2}\rangle$ amplitude multiplied with the experimental $B(E1; 1^- \rightarrow 0^+)$ value in the core nucleus ^{142}Nd. The calculated strength distribution is shown in the lower part of Fig. 2. The distribution is quite similar to the experimental one shown in the upper part of the same figure. This is surprising, if one recalls the drastic truncation of the theoretical model space. If we enlarge the model space, e.g., as we introduce several single-particle levels, the strength distribution is expected to smooth out even further.

We consider the agreement between the experiment and the core coupling model to be a strong argument in favor of the proposed ($2^+ \otimes 3^- \otimes$ particle) structure for the observed states around 3 MeV. Further photon scattering experiments in the $N = 82$ region are now planned to learn more about the two-phonon states.

We gratefully acknowledge valuable discussions with S. Albers, T. Belgya, A. Faessler, A. Gelberg, G. Molnar, B. R. Mottelson, A. Oros, A. Richter, L. Trache, and R. Wirowski. We thank A. Oros and L. Trache for checking our coupling program against another calculation. This work was supported in part by the Deutsche Forschungsgemeinschaft under Contracts No. Br 799–33 and No. Kn 154–21.

[1] A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2.
[2] R. F. Casten, *Nuclear Structure from a Simple Perspective* (Oxford Univ. Press, Oxford, 1990), and references therein.
[3] P. Kleinheinz, J. Styczen, M. Piiparinen, J. Blomqvist, and M. Kortelahti, Phys. Rev. Lett. **48**, 1457 (1982).
[4] M. Piiparinen *et al.*, Phys. Rev. Lett. **70**, 150 (1993).
[5] P. Vogel and L. Kocbach, Nucl. Phys. **A176**, 33 (1971).
[6] F. Iachello, Phys. Lett. **160B**, 1 (1985).
[7] D. Kusnezov and F. Iachello, Phys. Lett. B **209**, 420 (1988).
[8] I. Hamamoto, J. Höller, and X. Z. Zhang, Phys. Lett. B **226**, 17 (1989).
[9] P. A. Butler and W. Nazarewicz, Nucl. Phys. **A533**, 249 (1991).
[10] F. R. Metzger, Phys. Rev. C **14**, 543 (1976).
[11] F. R. Metzger, Phys. Rev. C **18**, 2138 (1978).
[12] F. R. Metzger, Phys. Rev. C **18**, 1603 (1978).
[13] H. H. Pitz *et al.*, Nucl. Phys. **A509**, 587 (1990).
[14] R. A. Gatenby *et al.*, Phys. Rev. C **41** R414 (1990).
[15] E. Müller-Zanotti *et al.* (to be published).
[16] G. Molnar (private communication).
[17] P. M. Endt, At. Data Nucl. Data Tables **26**, 47 (1982).
[18] A. F. Barfield *et al.*, Z. Phys. A **332**, 29 (1989).
[19] U. Kneissl, Prog. Part. Nucl. Phys. **24**, 41 (1989); **28**, 331 (1992).
[20] D. J. Rowe, *Nuclear Collective Motion* (Methuen, London, 1970), p. 35ff.
[21] L. Trache *et al.*, Nucl. Phys. **A492**, 23 (1989).
[22] J. Wrzesinski *et al.*, Nucl. Phys. **A515**, 297 (1990).
[23] L. Trache, C. Wesselborg, P. von Brentano, J. Wrzesinski, and G. P. A. Berg, Nucl. Phys. **A540**, 66 (1992).
[24] L. Trache, K. Heyde, and P. von Brentano, Nucl. Phys. A (to be published).
[25] F. Dönau and S. Frauendorf, Phys. Lett. **71B**, 263 (1977); F. Dönau, Z. Phys. A **293**, 31 (1979).