Evidence for a Cluster of Collective 1^+ States in ^{150}Nd near 3 MeV

B. Kasten,(1) R. D. Heil,(2) P. v. Brentano,(3) P. A. Butler,(4) S. D. Hoblit,(5) U. Kneissl,(2) S. Lindenstruth,(2) G. Müller,(1) H. H. Pitz,(2) K. W. Rose,(2) W. Scharfe,(1) M. Schumacher,(1) U. Seemann,(2) Th. Weber,(2) C. Wesselborg,(2,3) and A. Zilges(3)

(1) *II. Physikalisches Institut, Universität Göttingen, D-3400 Göttingen, Germany*

(2) *Institut für Kernphysik, Universität Giessen, D-6300 Giessen, Germany*

(3) *Institut für Kernphysik, Universität zu Köln, D-5000 Köln, Germany*

(4) *Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 3BX, England*

(5) *Nuclear Physics Laboratory, University of Illinois, Urbana-Champaign, Urbana, Illinois 61801*

(Received 6 March 1989)

Compton polarimeters have been used to measure the linear polarization of resonantly scattered photons. In the deformed nucleus ^{150}Nd the first direct and model-independent evidence has been obtained that in a cluster of enhanced dipole excitations near 3 MeV the three strongest transitions are of the same, *positive* parity.

PACS numbers: 21.10.Re, 23.20.Qz, 25.20.Dc, 27.70.+q

Recently, an increased interest has been shown in the study of low-lying, enhanced dipole excitations of both magnetic and electric multipolarity. A new *magnetic* dipole excitation in deformed nuclei has been discovered by Bohle and co-workers[1] in electron-scattering experiments. This collective mode is closely related to the orbital motion of the neutrons with respect to the protons. This so-called "scissors mode" has been investigated in a large number of experimental and theoretical studies.[2] The existence of this predominantly orbital excitation has been established in rare-earth nuclei,[1-6] in actinide nuclei,[7] and in medium heavy *f-p* nuclei[8] as well. Therefore, this mode seems to be a rather general phenomenon in deformed nuclei. On the other hand, there are also experimental indications[9-11] for the predicted, enhanced electric dipole transitions,[12-15] due to the excitation of α-cluster modes and/or reflection-asymmetric deformations. In order to discriminate unambiguously between these dipole excitation modes parity assignments are of crucial importance.

Up to now, in the recent studies of the new magnetic dipole modes, parity information *entirely* came from electron-scattering data,[4,7] where parity was not directly measured, but was inferred from the electron-scattering form factor of the excited state, by measuring under such kinematic conditions, which strongly favor magnetic excitations over electric excitations. In combining the precisely known excitation energies from our high-resolution nuclear-resonance-fluorescence (NRF) experiments with the electron-scattering data,[4,7] the form factors of some weaker dipole excitations were also obtained also, which indicated that these are also magnetic excitations. Because of the lower absolute energy resolution of inelastic electron scattering compared to NRF this method was restricted to a few favorable cases,[4,5,16] rendering it infeasible for the assignment of parities to individual members of the clusters of dipole excitations.

The present Letter reports on the first successful experiment where Compton polarimeters have been used to measure the parities of the new dipole excitations near 3 MeV and to definitely prove that several members of a cluster of dipole transitions are of the same, positive parity. These excitations are located in ^{150}Nd at an excitation energy of about $E_x = 66\delta A^{-1/3}$ MeV (δ=deformation parameter, A=mass number), where the scissors mode is expected to occur.[1,2] In the same energy region, no strong $E1$ transitions have been observed in our experiments.

The experiment was carried out at the bremsstrahlung facility[6] installed at the Stuttgart Dynamitron. Electrons with a maximum energy of 4.1 MeV and a current of 0.4 mA were stopped in a water-cooled gold radiator target of 2 cm diam and a thickness of 3 g/cm^2. The bremsstrahlung photon beam having intensities of up to $10^9\ \gamma s^{-1} MeV^{-1}$ at energies around 3 MeV was collimated by a 1-cm-diam Pb collimator. In order to avoid background produced by photon interaction with air, the bremsstrahlung beam and the scattering targets were located in an evacuated aluminum beam tube, closed at both ends by thin Kapton foils. The scattering targets consisted of cylindrical disks of enriched isotopes having diameters of 2 cm and masses of 8.4 g (^{142}Nd) and 9.7 g (^{150}Nd). Plates of aluminum were located on both sides of the scattering material in order to excite the 2.981-MeV state in ^{27}Al by resonant scattering. This transition is known to be essentially unpolarized and serves as a test of the performances of the polarimeters.

Two polarimeter setups have been used simultaneously. Setup 1 is a five-detector polarimeter with a central Ge detector and four peripheral Ge or Ge(Li) detectors located below the scattering target (Θ=90°). The central detector serves as the Compton-scattering target. The outer four detectors are aligned pairwise parallel and perpendicular to the vertical scattering plane. Setup

TABLE I. Experimental excitation energies, asymmetries $\epsilon=(N_\perp-N_\parallel)/(N_\perp+N_\parallel)$, width ratios Γ_0^2/Γ (Γ_0 and Γ are the ground-state and total widths), reduced transition probabilities $B(M1)\uparrow$, and spin-parities J^π of observed nuclear levels. Errors are given in parentheses. The width ratios, $B(M1)\uparrow$ values, and spins have been determined in separate NRF experiments at the Stuttgart facility (Ref. 20).

Nuclide	Energy (keV)	Asymmetry ϵ (%) a	b	Γ_0^2/Γ (meV)	$B(M1)\uparrow$ (μ_N^2)	J_f^π
^{142}Nd	3425(1)	−9.0(5.6)	−16(8)	229(25)		1^-
	2895(1)	+39(26)		8.4(1.1)	0.13(2)	1^+
^{150}Nd	2994(1)	+19.5(6.4)	+20(14)	44.9(4.7)	0.65(7)	1^+
	3058(1)	+13.3(9.1)		26.9(13.0)	0.35(4)	1^+

[a]Measured with the five-detector polarimeter.
[b]Measured with the single-crystal polarimeter.

2 consists of a sectorized true coaxial Ge(Li) polarimeter[17] installed in a horizontal scattering plane under a scattering angle of $\Theta=95°$. Further details will be given in a forthcoming paper.[18]

Parity information is obtained from photon spectra registered as true coincidences, generated via Compton scattering in one of the detectors (i.e., the central detector in case of the five-detector polarimeter) and detection of the scattered photon in one of the other detectors. In the case of linearly polarized photons the count rates $N_\parallel$ and $N_\perp$ of summed events from Compton scattering in planes parallel and perpendicular to the NRF scattering plane, respectively, are different. The asymmetry

$$\epsilon=\frac{N_\perp-N_\parallel}{N_\perp+N_\parallel} \tag{1}$$

is positive for magnetic and negative for electric dipole transitions.

The performances of both polarimeter setups have been tested by investigating the known, strong 3.425-MeV $E1$ transition in ^{142}Nd.[19] The technique of using Compton polarimeters in NRF experiments has formerly been applied by Metzger.[19] His polarimeter was a low-detector-efficiency two-slab Ge(Li) arrangement. His result for the ^{142}Nd transition of $\epsilon=(-1.9\pm1.6)\%$ strongly favored an $E1$ multipolarity of this transition. The present measurements confirm this parity assignment. Furthermore, the much higher polarization sensitivity of modern polarimeters is evident (see Table I). The progress in detector technology with an increased polarization sensitivity *and* detection efficiency of the setups enabled the present investigations to be done.

A singles spectrum of photons resonantly scattered off ^{150}Nd is shown in Fig. 1. New states, candidates for a parity determination, are seen at 2.895, 2.994, 3.058, 3.096, and 3.103 MeV, corresponding to dipole ground-state transitions in ^{150}Nd. The transition probabilities, spins, and decay branching ratios of these states have been measured in a separate NRF experiment within a systematic study of the Nd isotopes ^{142,146,148,150}Nd.[20]

The results obtained for the asymmetry ϵ using the five-detector polarimeter are depicted in Fig. 2. The

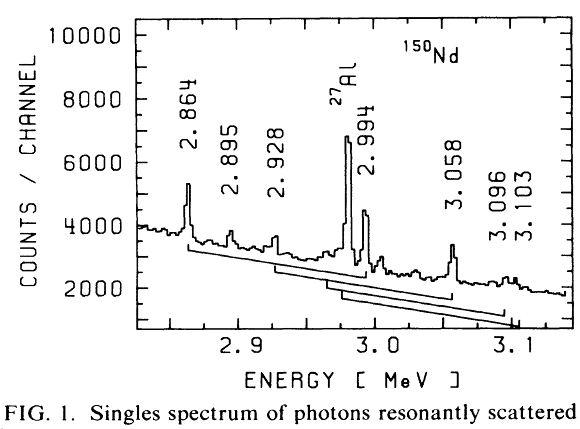

FIG. 1. Singles spectrum of photons resonantly scattered off ^{150}Nd registered by the central detector of the five-detector polarimeter. Brackets underneath the spectrum denote pairs of transitions to the ground and the 2_1^+ state.

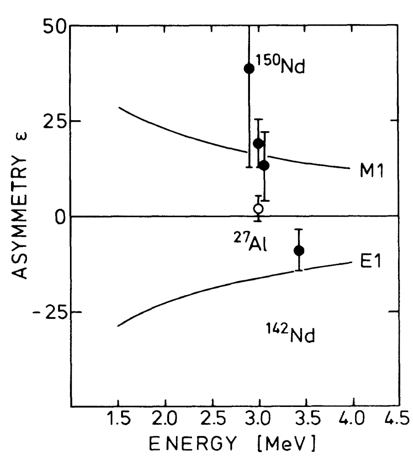

FIG. 2. Experimental asymmetries $\epsilon=(N_\perp-N_\parallel)/(N_\perp+N_\parallel)$ determined by the five-detector polarimeter. The experimental data are compared with the calculated polarization sensitivity of the setup given by the solid lines.

data points for ^{142}Nd and ^{150}Nd are nicely grouped either in the upper or lower part of the figure, thus making an unambiguous parity determination possible. On the other hand, the data due to the resonant 2.981-MeV line in ^{27}Al are in agreement with $\epsilon=0$, as expected for unpolarized radiation. This again proves the good performance of the experimental procedure. The solid lines represent asymmetries calculated for the geometry of the five-detector polarimeter. There is clear agreement between the experimental findings and the calculated polarization sensitivity of the setup. Furthermore, these results are in good agreement with the measurements simultaneously performed using the sectorized Ge polarimeter. In Table I the results for the measured transition energies, the asymmetries, the transition probabilities, spins, *and* parities are summarized. It is obvious that of the five candidates in ^{150}Nd for a parity determination seen in Fig. 1 it was possible to definitely establish the positive parity of three of them. No candidate for strong collective $E1$ excitations as predicted in ^{150}Nd due to α clustering or octupole deformations[13] could be observed in the present experiments near an excitation energy of 3 MeV.

Our experiments provided, for the first time, a model-independent parity assignment to a cluster of new, low-lying dipole transitions in the deformed nucleus ^{150}Nd. We have good reasons to attribute these transitions to the so-called scissors mode $M1$ excitations. The positive parity of the states has definitely been determined, the transition energies agree reasonably well with the $E_x=66\delta A^{-1/3}$ MeV systematics expected for these $M1$ transitions. Moreover, the summed transition strengths fit well into the systematics of the scissors mode as observed in numerous rare-earth nuclei in both photon[5,21] and electron-scattering experiments.[2] The branching ratios for the decay of the observed 1^+ states to the ground state and the first excited 2_1^+ state are in agreement with a $K=1$ assignment to these states. Unfortunately, no (e,e') data have been published so far to get additional information on the structure of the observed transitions. However, the first high-resolution electron-scattering spectra of ^{150}Nd have been taken at Darmstadt[22] where candidates of low-lying $M1$ excitations have been found. However, there is a need for further measurements to obtain precise form factors for these states.

In conclusion, the use of high-efficiency Compton polarimeters in NRF experiments opens a new era for the study of nuclear structure phenomena. The application of this technique to new spin-1 states in the deformed nucleus ^{150}Nd near an excitation energy of 3 MeV has led to definite evidence that several states clustered within a narrow energy bin around 3 MeV are of the same, *positive* parity. An interpretation in terms of the $M1$ scissors mode and its fragmentation seems to be appropriate.

The authors from Giessen, Göttingen, and Köln thank Professor K.-W. Hoffmann and his collaborators for the kind hospitality at the Institut für Strahlenphysik of the University of Stuttgart. This work was supported by Deutsche Forschungsgemeinschaft under Contracts No. Kn 154/18 and No. Schu 222/6.

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