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Observation of an octupole$\otimes$quasiparticle band in ^{175}Lu using photon scattering experiments

R.-D. Herzberg,[1] C. Fransen,[1] R. Fischer,[1] O. Beck,[2] D. Belic,[2] J. Besserer,[2] P. von Brentano,[1] Th. Eckert,[2] U. Kneissl,[2]
B. Krischok,[2] J. Margraf,[2] H. Maser,[2] A. Nord,[2] N. Pietralla,[1] H. H. Pitz,[2] A. Wolpert,[2] and A. Zilges[1,3]
[1]*Institut für Kernphysik, Universität zu Köln, D-50937 Köln, Germany*
[2]*Institut für Strahlenphysik, Universität Stuttgart, D-70569 Stuttgart, Germany*
[3]*Institut für Kernphysik, Technische Hochschule Darmstadt, D-64289 Darmstadt, Germany*

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A nuclear resonance fluorescence (NRF) study was performed on the heavy deformed nucleus ^{175}Lu. We observe the beginning of a rotational band built on the coupling of the unpaired proton to the $K^{\pi}=0^{-}$ octupole vibration in the neighboring nucleus ^{174}Yb. The dipole strength distribution is also discussed in terms of the scissors mode. [S0556-2813(97)03111-7]

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I. INTRODUCTION

The octupole degree of freedom plays an important role in the low-lying spectrum of heavy nuclei (see, e.g., [1,2]). Its most common manifestation is in the form of dynamic octupole vibrations. In deformed nuclei four rotational bands having K quantum numbers 0, 1, 2, and 3 are formed built on the octupole vibration. The ordering of these bands depends strongly on the nucleonic structure of the nucleus in question [3]. Over the last few years, a systematic study of the low-lying $J^{\pi}=1^{-},K=0$ octupole vibrational band heads in the mass region $A=130-200$ around 1.5–2 MeV has been carried out using photon scattering experiments [4,5]. With a typical $E1$ excitation strength of $B(E1;0^{+}\rightarrow1^{-})\simeq3.5$ m W.u., these states display similar strengths as the two-phonon quadrupole-octupole 1^{-} states observed in spherical nuclei of the same mass region [6,7].

Of special interest are structures built on octupole vibrations in the neighboring odd-mass nuclei. The most prominent example are the octupole-particle multiplets in odd-mass nuclei near closed shells, e.g., ^{209}Bi [8]. As an example of a more complicated collective excitation, we mention the two-phonon-particle $(2^{+}\otimes3^{-}\otimes f_{7/2})$ multiplet in the nucleus ^{143}Nd [9,10] and the two-phonon-particle $(3^{-}\otimes3^{-}\otimes f_{7/2})$ levels in ^{147}Gd [11]. Although the weak coupling picture employed there is in general no longer valid in a well-deformed nucleus, it is still possible to treat the odd quasiparticle as a spectator even in the strong coupling regime of a well-deformed nucleus. Coupling a particle to the octupole vibrations with different K will result in band structures with similar properties in odd-even and even-even nuclei. However, the octupole-particle configurations in odd deformed nuclei have been experimentally assigned in only a few favorable cases [2,12–14]. One identifying observable will be the absolute value of the $E1$ matrix element connecting the bandhead of such an octupole-particle band to the ground state. The nuclear resonance fluorescence (NRF) method with its high selectivity in spin and excitation strength is ideally suited for such a study. In the present paper we present photon scattering data on a $K=K_0=7/2$ band in ^{175}Lu and identify it as an octupole vibrational band.

II. EXPERIMENTAL METHOD

The nuclear resonance fluorescence (NRF) method has been described in great detail in numerous publications. For a recent review see [5]. Here we describe only the methods to extract the K quantum number and the moment of inertia for a rotational band seen in NRF spectra.

The decay of a member of a rotational band characterized through its K quantum number K and spin J_i into states belonging to a different rotational band with K quantum number K' and spins J_f and J_f' is determined by the Alaga rules [15]. It is then straightforward to use the Alaga rules to get a prediction for the ratio of the excitation strengths from the ground state to different states in an excited band as well. Note, that this ratio cannot be obtained as a branching ratio but rather that the absolute transition strengths have to be known.

In ^{175}Lu the relevant expressions are

$$R_1=\frac{B(\pi1;[7/2^{\pi},7/2]\rightarrow[9/2^{+}_{\text{g.s.}},7/2])}{B(\pi1;[7/2^{\pi},7/2]\rightarrow[7/2^{+}_{\text{g.s.}},7/2])}=0.286, \quad (1)$$

$$R_2=\frac{B(\pi1;[9/2^{\pi},7/2]\rightarrow[9/2^{+}_{\text{g.s.}},7/2])}{B(\pi1;[9/2^{\pi},7/2]\rightarrow[7/2^{+}_{\text{g.s.}},7/2])}=2.784, \quad (2)$$

$$R_3=\frac{B(\pi1;[7/2^{+}_{\text{g.s.}},7/2]\rightarrow[9/2^{\pi},7/2])}{B(\pi1;[7/2^{+}_{\text{g.s.}},7/2]\rightarrow[7/2^{\pi},7/2])}=0.286=R_1, \quad (3)$$

where we use the notation $B(\pi1;[J_i,K_i]\rightarrow[J_f,K_f])$. These ratios are also indicated in Fig. 1.

From a comparison of the experimentally observed branching ratios with R_1 and R_2 it is possible to determine the spin and K quantum number of the excited state, even if a measurement of the angular correlation remains inconclusive. The Alaga rule predictions for other possible hypotheses for J and K deviate significantly from the values shown above.

Although sophisticated methods to extract the moment of inertia for a band structure exist, most of them are not appli-

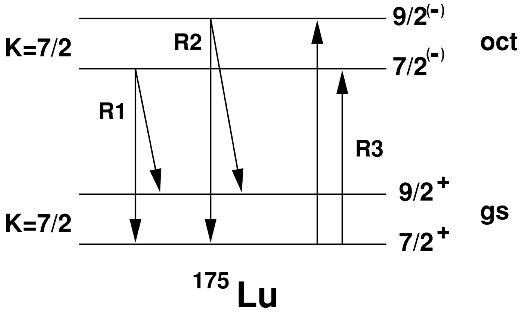

FIG. 1. Partial level scheme of ^{175}Lu. The branching ratios R_1 and R_2 are indicated. The ratio R_3 can only be determined if absolute transition strengths are measured.

cable if only two members of the band are observed. In such a case it is most convenient to employ the simple relation [8]:

$$\Theta=\frac{1}{2}\,\frac{J'(J'+1)-J(J+1)}{E(J')-E(J)}. \tag{4}$$

Obviously this can only serve as an approximation for the (possibly variable) moment of inertia of the entire band.

III. EXPERIMENTAL RESULTS

To study ^{175}Lu two different experiments have been carried out at the Dynamitron accelerator in Stuttgart. One experiment used an end-point energy of 2.6 MeV to study the low-lying octupole excited bands. The other one was carried out at a higher end-point energy of 4.1 MeV and was sensitive to the region around 3 MeV. The NRF target in both cases consisted of 2277 mg Lu_2O_3 of natural composition (97.4% ^{175}Lu).

Figure 2 shows the high energy part of the measured NRF spectrum between 2.4 and 3.6 MeV. A large number of transitions can be seen. In Fig. 3 we show the low energy part focusing on the transitions belonging to the proposed octupole band. The inset compares the spectra from the two experiments. Due to the lower background the experiment at the lower end-point energy clearly allows the detection of much weaker transitions in the region around 1.5 MeV than the experiment at the higher end-point energy [16].

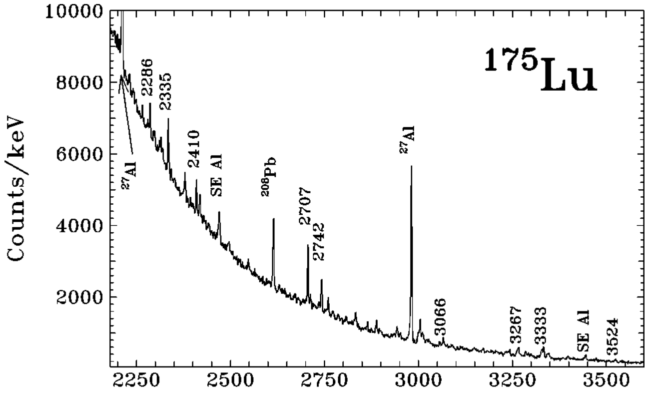

FIG. 2. A (γ,γ') spectrum off ^{175}Lu taken at an endpoint energy of 4.1 MeV. The spectra taken under three different angles have been summed up for this figure. A large number of weak transitions is visible in the high energy part of the spectrum. Only the prominent peaks are labeled.

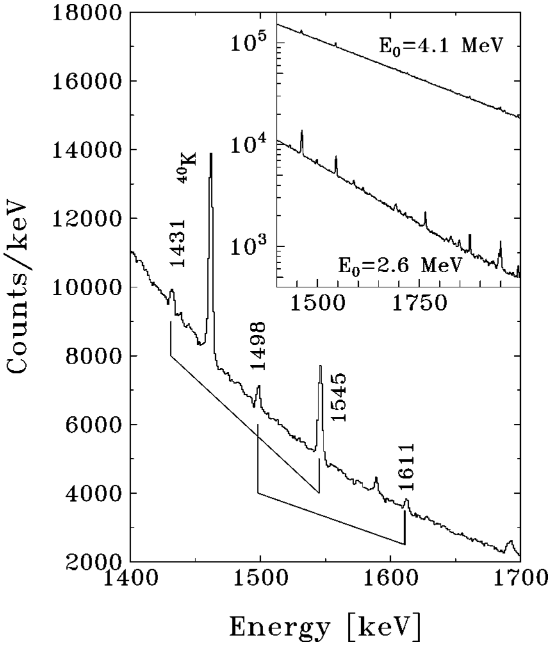

FIG. 3. The figure shows the region of the octupole-particle band. Transitions stemming from the same level are connected by brackets. The inset shows a comparison of the relevant low energy part of the spectra for the two experiments performed at a bremsstrahlung end-point energy of 2.6 MeV (bottom) and 4.1 MeV (top).

A summary of the combined experimental results is given in Table I. Here the energies, cross sections, and reduced ground-state transition widths are given. The decay transition strengths in the region above 1.5 MeV are shown in the top part of Fig. 4. Since no parity information is available on the transitions shown, the left scale gives the strengths in μ_N^2 appropriate in case of $M1$ transitions while the right hand scale gives the strengths in units of $10^{-3}\ e^2\ \mathrm{fm}^2$ appropriate for $E1$ transitions. The bottom part gives a comparison with the experimental strength distribution for the even neighbor ^{174}Yb taken from [17].

IV. DISCUSSION

A. Electric dipole excitations

The data for the low-lying octupole vibrational band are summarized in Table II. Here the level energies, transition energies, spins of initial and final states, K quantum numbers, and reduced transition probabilities are given. As was discussed above, spins and K quantum numbers were assigned through a comparison of the observed branching ratios with the predictions of the Alaga rules. Unfortunately, no direct parity information is available from the present experiment. We shall now summarize the arguments that lead to the interpretation of the hitherto unknown levels at 1545 and 1611 keV as the beginning of the octupole band with an intrinsic octupole-quasiproton structure $0^- \otimes 7/2[4\,0\,4]$.

TABLE I. Energies, branching ratios R_{expt}, cross sections I_s, and reduced ground-state transition widths $g\Gamma_0/E_\gamma^3$ for transitions in ^{175}Lu $[g:=(2J+1)/(2J_0+1)]$. Transitions marked with a are taken from the experiment at 2.6 MeV end-point energy while transitions marked b are taken from the experiment at 4.1 MeV end-point energy. The mark a,b indicates a weighted mean value from both experiments is given. $R_{\mathrm{expt.}}$ is the ratio of the reduced transition widths to the first rotational state at 113.8 keV and the ground state, respectively.

E_γ (keV)	R_{expt}	I_s (eV b)	$g\Gamma_0/E_\gamma^3$ [meV/MeV^3]	E_γ (keV)	R_{expt}	I_s (eV b)	$g\Gamma_0/E_\gamma^3$ (meV/MeV^3)
$1545^{a,b}$	0.276 (40)	19.2 (8)	4.0 (2)	2713^{b}	–	4.0 (9)	0.38 (9)
$1588^{a,b}$	–	3.2 (4)	0.53 (6)	2742^{b}	–	11.8 (8)	1.12 (8)
1611^{a}	2.8 (6)	2.1 (4)	1.09 (25)	2760^{b}	–	6.0 (9)	0.56 (8)
1689^{a}	–	1.9 (3)	0.29 (5)	2833^{b}	–	7.2 (7)	0.66 (7)
1693^{a}	–	1.9 (3)	0.29 (5)	2865^{b}	–	4.5 (7)	0.41 (7)
1715^{a}	–	1.4 (3)	0.21 (5)	2890^{b}	–	4.9 (8)	0.44 (7)
1725^{a}	–	1.1 (3)	0.17 (5)	2897^{b}	–	3.1 (7)	0.28 (6)
1816^{a}	–	1.0 (3)	0.15 (5)	2843^{b}	–	6.1 (8)	0.54 (7)
1827^{a}	–	1.9 (3)	0.28 (5)	2952^{b}	–	3.7 (7)	0.32 (6)
$1874^{a,b}$	–	5.0 (4)	0.69 (5)	2998^{b}	–	4.7 (12)	0.40 (10)
1931^{a}	–	1.0 (3)	0.14 (3)	3002^{b}	–	6.5 (13)	0.56 (11)
1945^{a}	0.33 (13)	3.0 (3)	0.51 (7)	3011^{b}	–	8.5 (20)	0.74 (17)
$1949^{a,b}$	–	6.3 (4)	0.84 (5)	3022^{b}	–	2.1 (9)	0.18 (8)
1992^{a}	–	2.1 (3)	0.28 (4)	3029^{b}	–	3.0 (10)	0.26 (9)
2012^{a}	0.69 (23)	1.8 (3)	0.36 (7)	3066^{b}	–	4.9 (10)	0.41 (8)
$2089^{a,b}$	–	3.4 (3)	0.42 (4)	3172^{b}	–	3.6 (8)	0.29 (7)
$2123^{a,b}$	–	2.3 (3)	0.28 (4)	3238^{b}	–	3.6 (7)	0.29 (6)
2286^{a}	0.51 (9)	5.0 (4)	0.81(8)	3243^{b}	–	4.5 (7)	0.36 (6)
2297^{a}	–	2.2 (3)	0.25 (4)	3267^{b}	–	6.9 (11)	0.55 (8)
2320^{a}	–	2.5 (4)	0.28 (4)	3286^{b}	–	5.3 (8)	0.42 (6)
$2335^{a,b}$	–	9.9 (5)	1.10 (6)	3293^{b}	–	4.4 (8)	0.34 (6)
2379^{a}	0.37 (10)	4.7 (4)	0.79 (8)	3300^{b}	–	4.0 (8)	0.31 (6)
2386^{a}	–	0.9 (3)	0.10 (3)	3329^{b}	–	8.8 (10)	0.69 (7)
2394^{a}	–	0.9 (3)	0.10 (3)	3333^{b}	–	10.5 (10)	0.82 (8)
$2410^{a,b}$	–	7.2 (4)	0.78 (6)	3343^{b}	–	5.9 (10)	0.46 (7)
$2419^{a,b}$	–	6.1 (4)	0.66 (5)	3347^{b}	–	6.0 (10)	0.47 (7)
2442^{a}	1.18 (27)	2.4 (4)	0.52 (10)	3398^{b}	–	5.0 (8)	0.38 (6)
2497^{a}	–	3.1 (5)	0.32 (5)	3404^{b}	–	1.9 (6)	0.15 (5)
2548^{a}	–	2.5 (4)	0.26 (4)	3524^{b}	–	7.2 (12)	0.53 (9)
2707^{b}	–	20.7 (11)	2.0 (1)				

As can be seen from Table II, the branching ratios from these levels into the members of the ground-state band are in excellent agreement with the predictions of the Alaga rules for the $J=7/2$ and $J=9/2$ members of a $K=7/2$ band establishing the spins and K quantum numbers for both levels. The ratio $R_3^{\mathrm{expt}}=0.275(65)$ of the excitation strengths is also in excellent agreement with the predicted value of $R_3^{\mathrm{Alaga}}=0.286$.

Further support for the assignment of a negative parity comes from the semiempirical rule of thumb valid in the neighboring even-even nuclei [22], that transitions with $\Delta K=0$ have $E1$ character. This rule of thumb should be valid in an odd nucleus as well, if the odd nucleon takes a pure spectator role in the transition. It is in this sense, that we assign a negative parity in the following.

It is also possible to compare the absolute transition strengths between the levels at 1545 and 1611 keV into the ground-state band. The transitions between states with the same spin ($7/2^{(-)}\to7/2^{+}$ and $9/2^{(-)}\to9/2^{+}$) shown in Table II agree within a factor of 2 with the transition strength found in the even neighbor nucleus ^{174}Yb [17]:

$$B(E1;[1^-,0]\to[0^+,0])_{^{174}\mathrm{Yb}}=4.9(1.1)\times10^{-3}\ e^2\ \mathrm{fm}^2. \tag{5}$$

If the transition is considered to proceed through the collective core via the destruction of the octupole phonon only while the odd proton takes the role of a spectator, the $B(E1)$ values for the decay of the octupole bandhead to the ground state should be roughly equal in Lu and Yb.

We shall now compare the moments of inertia for the octupole band in ^{175}Lu and ^{174}Yb. The ground-state bands of ^{175}Lu and ^{174}Yb have nearly identical moments of inertia:[1]

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[1] These values will change slightly, if the entire band is properly analyzed, but will remain similar. Here only the first two levels were taken into account.

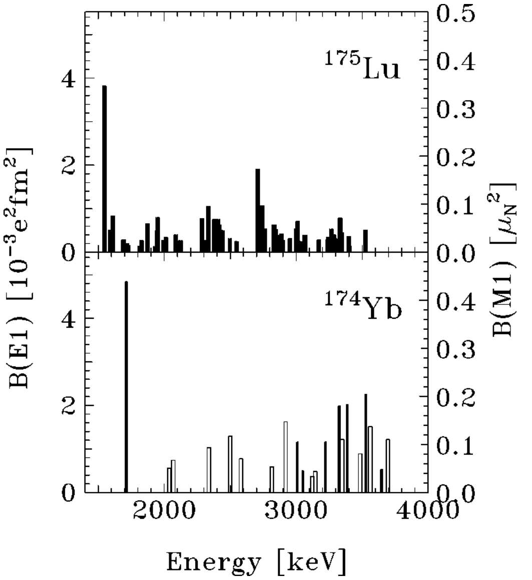

FIG. 4. Comparison of the dipole strength distributions in ^{175}Lu (top) and ^{174}Yb (bottom). Since no parity information is available, the left and right scales give the reduced transition probability for $E1$ and $M1$ transitions to the ground state, respectively. In ^{174}Yb full bars correspond to transitions with $\Delta K = 0$, open bars to transitions with $\Delta K = 1$.

$\Theta^{\text{g.s.}}_{\text{Lu}} = 39.2\,\hbar^2$ MeV^{-1} and $\Theta^{\text{g.s.}}_{\text{Yb}} = 39.5\,\hbar^2$ MeV^{-1}. It is interesting to note that this similarity holds true for the octupole bands as well: $\Theta^{\text{oct}}_{\text{Lu}} = 68.2\,\hbar^2$ MeV^{-1} and $\Theta^{\text{oct}}_{\text{Yb}} = 66.7$ $\hbar^2$ MeV^{-1}. However, as only two levels were observed, we note that these moments of inertia do not contradict the proposed interpretation as an octupole-particle band in ^{175}Lu but we will not base any further conclusions on this.

Considering these arguments, we conclude that we have indeed observed and identified the beginning of the $0^- \otimes 7/2[4\,0\,4]$ octupole vibrational band in ^{175}Lu.

The odd proton takes a spectator role during the excitation of the $K^\pi = 0^-$ octupole vibration in the core nucleus. We point out that the assignment of the structure relies heavily on the knowledge of the absolute transition strengths. This might explain why such assignments in the literature are sparse. In the cases where an assignment was made, it usually relies on the comparison with elaborate model calculations. For example, in ^{155}Sm the (tentative) assignment $0^- \otimes 3/2[521]$ was made [2], because a QPNM calculation by Soloviev *et al.* predicts a small amplitude of this state at that energy [18]. To our knowledge, the present paper presents the first assignment of a $0^- \otimes$ particle structure in a heavy odd-mass nucleus outside the actinides which was made on experimental information alone. It is highly desirable to also measure the parities of the states in question (1545 and 1611 keV) as well as the continuation of the band to higher spins. However, both these experiments are outside the scope of a NRF study.

B. Magnetic dipole excitations

We shall now also discuss the observed strength distribution in ^{175}Lu at higher excitation energies. The scissors mode is a well-established phenomenon in deformed nuclei. Since its discovery in electron scattering experiments by Richter and co-workers [19], the bulk of the experimental data has been collected using nuclear resonance fluorescence (NRF) experiments (see [5] and references therein). The systematics of the scissors mode in even nuclei is well understood [20,22] and has recently been extended to include γ-soft nuclei [23,24]. Studies of odd-mass nuclei in the same mass region also provide a large amount of systematical data. After the first experiment on ^{163}Dy [25] a rich variety of distinctly different dipole distributions has emerged. Today data are available on the odd-neutron nuclei ^{161,163}Dy, ^{155,157}Gd [26], ^{167}Er [27], and on the odd-proton nuclei ^{159}Tb [28], ^{165}Ho and ^{169}Tm [29]. With this study of ^{175}Lu we present experimental data in the upper half of the $N = 82-126$, $Z = 50-82$ major shell.

The most puzzling features of the spectra of the odd-mass nuclei are the extreme fragmentation of the observed dipole strength into as many as 90 transitions in ^{157}Gd [26] and the reduction of the observed strength of the scissors mode by more than a factor of 2 in most cases. It has been suggested that the missing strength could be shifted to higher energies [27], i.e., energies above 4 MeV which are not accessible in NRF experiments performed in Stuttgart, or that it might be distributed over a large number of unresolved weak transitions contributing a continuum to the background [30].

The problem of identifying the parities of the transitions is present in all NRF experiments on odd-mass nuclei. Since the angular correlation functions, which are essential for the measurement of parities using Compton polarimeters are nearly isotropic, the statistics obtained in a two week NRF beamtime is several orders of magnitude too low. The alternative to measuring the parities is usually the comparison with other experiments. However, the huge level density in

TABLE II. Level energies, transition energies, spins of initial and final states, K quantum numbers, reduced transition probabilities, and experimental and theoretical branching ratios for transitions between the octupole-particle band and the ground-state band are given. The negative parities given in parentheses are assigned through the interpretation as an octupole band. No experimental parity assignment could be made for these states.

E_x (keV)	E_γ (keV)	J_i,K_i	J_f,K_f	$B(E1;[J_i,K_i]\rightarrow[J_f,K_f])$ (10^{-3}e^2 fm^2)	R_{expt}	R_{theor}
1545	1545	$7/2^{(-)}$, 7/2	$7/2^+$, 7/2	3.77(19)	0.276(40)	0.286
	1431	$7/2^{(-)}$, 7/2	$9/2^+$, 7/2	1.04(16)		
1611	1611	$9/2^{(-)}$, 7/2	$7/2^+$, 7/2	0.83(19)	2.8(6)	2.784
	1498	$9/2^{(-)}$, 7/2	$9/2^+$, 7/2	2.35(73)		

odd deformed nuclei around 3 MeV renders comparison with other, nonselective experiments virtually impossible. Therefore other methods to extract the summed $M1$ strength attributable to the scissors mode in an odd-mass nucleus have to be found. We give two different values for the summed $M1$ strengths using the following criteria.

(a) All observed dipole transitions are considered $M1$. While this is obviously an oversimplification, it serves to produce a reliable upper limit for the total $M1$ strength visible in discrete lines in the nucleus.

(b) The neighboring even-even nuclei are used to estimate the ratio of the $M1$ strength to the total dipole strength. To do this, we employ the fact that the $B(E1)$ and $B(M1)$ are directly proportional to the reduced transition width Γ_0^{red}. We therefore define the quantity $\eta := \Sigma\Gamma_{0\,M1}^{\mathrm{red}}/(\Sigma\Gamma_{0\,E1}^{\mathrm{red}} + \Sigma\Gamma_{0\,M1}^{\mathrm{red}})$ and use it to extract the summed $B(M1)$ value in the odd-mass nucleus in question.

If the influence of the odd Nilsson nucleon does not polarize the core too much, as is the case for the previously discussed octupole vibration, this should give a much more reliable value. For ^{174}Yb, the even-even neighbor of ^{175}Lu, the only parity information available stems from an (e,e') experiment [21] where $M1$ excitations were observed at 3.350 MeV and 3.555 MeV, the latter of which is resolved in NRF experiments into two levels at 3.527 and 3.562 MeV. For the remaining lines we use the semiempirical rule of thumb that transitions with $\Delta K = 0$ have $E1$ character while transitions with $\Delta K = 1$ have $M1$ character in even nuclei [22]. This leads to a ratio $\eta \simeq 0.6$ for ^{174}Yb which in turn is applied to the total dipole strength in ^{175}Lu as well. It should be noted that this rule of thumb is well fulfilled for the three states for which parity information is available through an (e,e') experiment.

It has been suggested that the scissors mode strength be summed in the energy region between 2.4 and 3.7 MeV in even nuclei [22]. However, an inspection of Fig. 4 shows that the much larger fragmentation present in odd-mass nuclei renders this interval too small. We therefore include all observed dipole transitions above 1.8 MeV in the sum. Estimating the error of η to roughly 15% we find the following values:

$$\sum_{E>1.8\,\mathrm{MeV}} B(M1)\uparrow = \begin{cases} 2.18(5)\mu_N^2, & a)\ \eta = 1.0, \\ 1.3(2)\mu_N^2, & b)\ \eta = 0.6(1)\cdot \end{cases} \tag{6}$$

Clearly without the assignment of spins and parities to the observed levels, no further conclusions about their origin can be drawn. At the same time a significant part of the expected dipole strength may be distributed over a large number of extremely weak excitations effectively lying in the background. Fluctuation analysis methods with the goal to identify this missing strength in the background have been applied to several nuclei [30], but are beyond the scope of this paper.

V. CONCLUSION

To summarize, we have performed a NRF experiment on the deformed odd rare earth nucleus ^{175}Lu. Through the observed branching ratios and absolute transition strengths we were able to identify an octupole-particle vibrational band around 1.5 MeV with the structure $0^- \otimes 7/2[404]$ in this nucleus having almost the same moment of inertia as the corresponding $K = 0$ octupole vibrational band in ^{174}Yb. Further studies aiming at the identification of similar octupole-particle structures in other odd rare earth nuclei are under way. The observed dipole transition strength located between 2 and 4 MeV has been discussed in terms of the scissors mode.

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