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Short note

Multiple octupole excitations in ^{148}Gd

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Abstract. The lifetime and the γ-decay to the 0^+ ground state of the lowest 3^- state in ^{148}Gd has been determined. The reduced strength $B(\mathrm{E3}, 3^- \to 0^+)$=41 (6) W.u. agrees well with the theoretical value from empirical shell model calculations and can be directly compared with the $12^+ \to 9^-$ two-octupole-phonon $\to$ one-octupole-phonon strength obtained in the same Recoil Distance Method lifetime measurement. The results of our search for a three octupole-phonon state built on the $(\nu f_{7/2})^2_{6^+}$ state is also reported.

PACS. 23.20.Lv Gamma transitions and level energies – 21.10.Lg Lifetimes – 27.60.+j 90≤A≤149

The nucleus ^{146}Gd, corresponding to the neutron shell and proton subshell closures $N = 82$ and $Z = 64$, has the 3^- octupole state as its lowest-lying excitation with a B(E3) strength of 37 W.u. to the ground state [1]. This large octupole collectivity is due to the coherent contribution of several $\Delta l = \Delta j = 3$ particle-hole excitations available in this nuclear region. In the one-valence-neutron nucleus ^{147}Gd the corresponding octupole state, having I^π=13/2$^+$, is built on the 7/2$^-$ ground state. Furthermore, a two-octupole phonon state with I^π=19/2$^-$, which decays to the ground state through two stretched E3 transitions, has been identified [2].

One- and two-octupole phonon states have been also identified in the even-even $N = 84$ isotones around ^{146}Gd (^{148}Gd [3], ^{144}Nd [4], ^{146}Sm [4]). Here they are not built on the ground state but instead on the aligned $(\nu f_{7/2})^2_{6^+}$ two-neutron state and have therefore spin 9^- and 12^+, respectively. Their identification as octupole states comes from the characteristic E3 γ-decay ($12^+ \to 9^- \to 6^+$) and in most cases from the measured B(E3) strengths. The 3^- octupole levels in these nuclei are formed at lower energies as in the core nucleus ^{146}Gd, but the 2^+ states of the $(\nu f_{7/2})^2$ multiplet lie at even lower energies, making so far impossible to observe the direct E3 γ-decays to the ground states due to the strong competition of the $3^- \to 2^+$ E1 transitions. A large collectivity for the 3^- states has been anyway deduced, in a model dependent way, from (p,p′) experiments in the case of ^{144}Nd [5] and ^{148}Gd [6].

A candidate for a three octupole-phonon state, an elementary excitation not yet observed in nuclei, was proposed 15 years ago in ^{148}Gd [3] at E_x=5389 keV; later on, shell model calculations have predicted a 15^- state with a large collective component of triple octupole excitation lying in that energy range (1573 keV above the 12^+ state) and decaying to the 12^+ state with an E3 strength of 98 W.u. [7].

In this short note we report the results of experiments performed with GASP and EUROBALL, devoted to the study of octupole excitations in the $N = 84$ nucleus ^{148}Gd. The γ-decay of the first 3^- state to the ground state has been identified. Through lifetime measurements the E3 strength has been deduced for the 3^- level as well as for the two-octupole phonon state built on the 6^+ state, making thus possible, from data of the same experiment, a direct comparison of the two-to-one phonon and one-to-zero phonon strength which is important to clarify the

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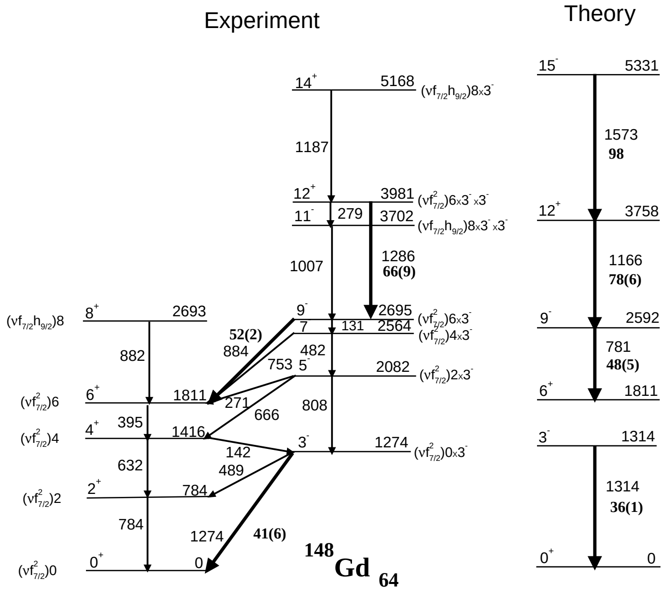

Fig. 1. Partial level scheme of ^{148}Gd. The configurations of the states are indicated. The octupole transition strengths measured in Weisskopf units are given in bold. The theoretical estimates shown on the right are taken from refs. [7,10].

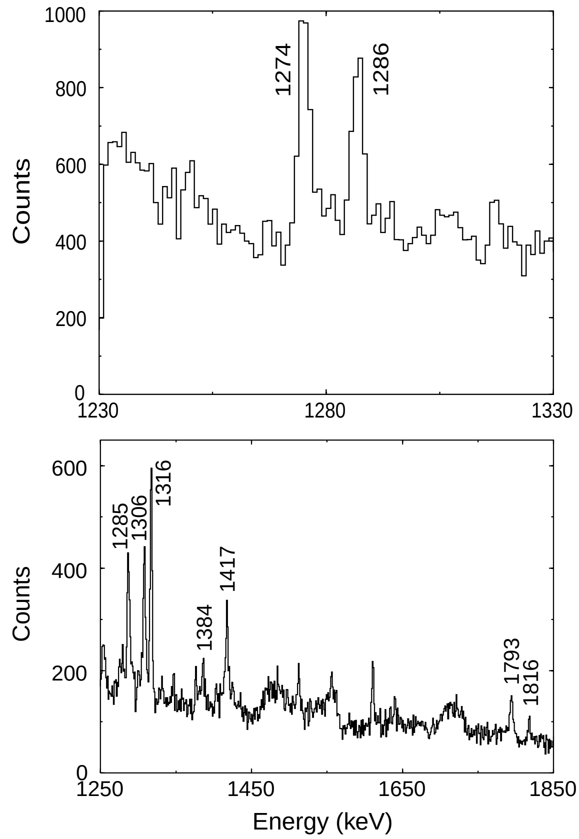

Fig. 2. Upper panel: Part of the γ spectrum in coincidence with the 808 keV transition, showing the 1274 keV ($3^- \to 0^+$) and the 1286 keV ($12^+ \to 9^-$) transitions, whose lifetimes were measured in the present experiment. Lower panel: high-energy part of the spectrum in coincidence with the 279 keV $12^+ \to 11^-$ transition. The labeled transitions feeding the 12^+ two-octupole-phonon state, have been considered as candidates for the E3 decay of the searched three-octupole-phonon state. Both spectra are from the ^{11}B+^{141}Pr reaction at a beam energy of 49 MeV.

degree of harmonicity of nuclear octupole vibrations. The elusive search for the three-octupole-phonon state is also discussed.

Excited states of ^{148}Gd have been populated in three different experiments. Two of them were standard thick target measurements using heavy (^{28}Si) and light (^{11}B) nuclei induced reactions, aimed to search for weak E3 transitions de-exciting known octupole states, possibly the three octupole phonon state, and to determine for such levels very accurate branching ratios. The third experiment was a lifetime measurement with the plunger method using the lighter beam.

The beams were delivered by the Tandem XTU accelerator of Legnaro National Laboratories and γ-rays have been detected using the GASP [8] array in the first two experiments and the EUROBALL [9] array in the lifetime experiment.

The ^{28}Si+^{124}Sn reaction at a beam energy of 125 MeV populates mainly the states along the yrast line up to spin of about $50\hbar$, whereas the ^{11}B+^{141}Pr reaction at a beam energy of 49 MeV populates the yrast and non-yrast states of ^{148}Gd, with maximum probability around $I = 15$. In both cases backed targets were employed, 3.4 mg/cm^2 ^{124}Sn on a 15.5 mg/cm^2 ^{208}Pb backing and 2.7 mg/cm^2 ^{141}Pr on 1.5 mg/cm^2 Au backing, respectively.

New levels and several new weak transitions have been identified from the analysis of the two experiments. Furthermore, the high statistics collected allowed the determination of branching ratio values much more accurate than those known previously, which is vital for the determination of accurate transition strengths. A partial level scheme of ^{148}Gd, relevant for the discussion of octupole states, is shown in fig. 1.

We could establish a weak transition with an energy of 1274 keV connecting the first 3^- state to the ground-state. Figure 2 shows the high energy part (above 1 MeV) of a spectrum obtained by gating on the 808 keV $5^- \to 3^-$ transition, where both the new 1274 keV $3^- \to 0^+$ and the known 1286 keV $12^+ \to 9^-$ E3 transitions are evident. Since the preferred decay of both the $I = 3^-$ and $I = 12^+$ octupole states is through a strong E1 transition to the $I-1$ state followed by an E2 transition to the $I-3$ state, we have to be very careful in determining the sum-up and pile-up effects which could produce a peak corresponding to the energy of the parallel E3 transition. We have therefore analysed the sum-up and pile-up of the strong 395 and 784 keV transitions ($6^+ \to 4$ and $2^+ \to 0^+$) by assuming that, if a peak appears at 1179 keV this is only due to those effects. From this analysis we could establish with great accuracy the sum-up and pile-up contribution to the 1274 keV (23% of the peak area) and 1286 keV (9%) peaks. After correction, the branching ratios are B_R=0.85(11)% and B_R= 2.6(2)%, respectively, for the 1274 keV $3^- \to 0^+$

and 1286 keV $12^+ \rightarrow 9^-$ E3 transitions. This last value compares well with the previous 2.8(2)% obtained by Piiparinen *et al.* [7]. Giving the high statistics of our experiment we have also re-analysed the E3 decay branch from the 9^- level at 2695 keV which is assigned as the stretched $\nu(f_{7/2})^2_6 \otimes 3^-$ octupole-phonon state. For the $9^- \rightarrow 6^+$ 884 keV transition we could extract a branching ratio of 39.7(10)%. This is slightly lower than the previously determined value of 42(4)% [10] and agrees well (being more accurate) with the result of ref. [7], B_R= 39(3)%. The 2695 keV 9^- state is isomeric with a mean life of τ=23.8(4) ns [11]. Taking this value we obtain a B(E3) strength of 52(2) W.u. with an error decreased by a factor two with respect to ref. [7].

As already mentioned above, one of the main aims of the experiments was to locate the three octupole-phonon state built on the $\nu(f_{7/2})^2_6$ level. The candidate proposed originally [3] for the three octupole-phonon state lies at 5389 keV energy, 1409 keV above the 12^+ state, and decays with a $\Delta I = 1$, 222 keV transition to the 14^+ at 5168 keV. We found that the 5389 keV state decays also to the 14^+ level at 5026 keV with a 363 keV transition. However, this transition has an angular distribution inconsistent with that of a stretched dipole transition, and most probably the 5389 keV level has I^π=15^+. In the ^{11}B induced reaction new non-yrast states around spin I=15 can be populated and possibly, among them, the true three-phonon state. We have therefore carefully examined, in the coincidence data of this reaction, the energy region above E_γ=1.2 MeV, to search for new transitions feeding the 12^+ two-phonon state at 3981 keV, which could deexcite the 15^- state. Seven of such transitions have been found with energies 1285, 1306, 1316, 1384, 1417, 1793 and 1816 keV, as shown in the spectrum in fig. 2. They are in coincidence with all the transitions below the 12^+ state (including the 279 keV $12^+ \rightarrow 11^-$ one, as shown in the figure) but not with the known transitions feeding the 12^+ two-phonon state. Three out of the seven transitions, namely 1316, 1417 and 1793 keV, exhibit forward peaked angular distribution, as expected for both E2 and E3 multipolarities. The most efficient way to discriminate among the two possibilities is the measurement of the level lifetime, which turns out to be more than one order of magnitude different for the two modes of de-excitation.

The lifetime of the ^{148}Gd states in the ps range was measured in ^{141}Pr(^{11}B,4n) reaction at a beam energy of 49 MeV. From the backed-target experiment it was demonstrated that this reaction populates with appreciable side-feeding the levels below the 2695 keV 9^- isomer (τ=23.8 ns), thus allowing to measure the lifetime of these states. As already stated above, the entry spin in this reaction is around spin 15 and this is confirmed by the fact that we do not see in the data the population of the I^π=20^-, $\tau \approx$2 ns isomer at 6835 keV [10], which could disturb our plunger experiment.

The target consisted of 0.48 mg/cm^2 ^{141}Pr on a 2.2 mg/cm^2 gold support. It was mounted with the Au support facing the beam in the Cologne plunger [12] in front of a 6 mg/cm^2 thick gold stopper foil. The incident beam energy of 50.5 MeV corresponded to 49 MeV at the ^{141}Pr surface, which is the same energy used in the previous experiment. Data were taken at 17 stopper-target distances between 0.7 μm and 2 mm.

The γ-rays were detected with the EUROBALL detector array [9], consisting of 15 cluster detectors (7 Ge crystals each) at backward angle, 26 clover detectors (4 Ge crystal each) around 90° and 30 tapered detectors (1 Ge crystal each) at forward angle. The 239 Ge crystals of the Ge-array were organised into six rings. Events with at least four non-suppressed Ge detectors firing in coincidence were registered on tape. For each target-stopper distance the Compton-suppressed $\gamma\gamma\gamma$ triples and higher fold events were sorted into asymmetric $\gamma\gamma$ matrices with one particular ring on each axis.

In the analysis of the data the differential decay curve method (DDCM) [13,14] was used. In this technique one gates on the shifted component of the feeding transition and analyses the stopped and shifted parts of the depopulating transition, as a function of the target-stopper distance d. The lifetime of the state is given by $\tau = I^{\rm d}_{\rm u}({\rm d}I^{\rm d}_{\rm s}/{\rm d}t)^{-1}$, where $I^{\rm d}_{\rm u}$ and $I^{\rm d}_{\rm s}$ are the intensities of the unshifted and shifted components of the depopulating transition, and $t = d/v$ is the flight time.

This method allows to determine the lifetime of the state of interest unambiguously, since the uncertainties about feeding times and intensities are avoided. To use this method one needs fully separated stopped and Doppler-shifted components. Since in our particular case the recoil velocity is very low (β = 0.541(21)%), the two components are separated only for high energy transitions and for rings far away from 90°. If the two components are not separated, and this is our usual case, when gating on the shifted component, in order to get a good statistics we could not avoid to gate on a small portion of the stopped peak, too. This encreases the intensity of the stopped part of the depopulating transition, so a correction is needed. The procedure used for the correction is detailed in ref. [15].

The lifetime of the 3^- level was determined by gating on the shifted component of the 808 keV transition and analysing the shifted and unshifted components of the strong 489 keV $3^- \rightarrow 2^+$ peak. Figure 3. shows the results of the analysis, which gives a mean life of τ=50(3) ps. With the branching ratio given above, a transition strength of B(E3) = 41(6) W.u. is obtained.

Although the 1274 keV E3 transition was observed for the first time in our experiment, the $\nu(f_{7/2})^2_0 \otimes 3^-$ character of the 3^- state was previously proved by the large cross section for the excitation of the 3^- state *via* inelastic proton scattering on radioactive ^{148}Gd target, measured by de Angelis *et al.* [6]. From these measurements a (model dependent) value of the reduced octupole strength of B(E3)=42(9) W.u. was obtained.

The lifetime of the 12^+ two-octupole-phonon state at 3981 keV has been determined as $\tau(12^+)$ = 88(9) ps. With the branching ratio of 2.6(2)% for the 1286 E3 transition, a reduced strength of B(E3)=66(9) W.u. is obtained for the two- to one-phonon decay. This is slightly lower than

Table 1. E3 strengths for octupole transitions in ^{148}Gd.

$J_i^\pi \rightarrow J_f^\pi$	E_γ (keV)	B(E3) (this work)	B(E3) (previous work) [7]	B(E3) (theory) [7,10]
$3^- \rightarrow 0^+$	1274	41(6)	-	35.9(6)
$9^- \rightarrow 6^+$	884	52(2)	52(4)	48(5)
$12^+ \rightarrow 9^-$	1286	66(9)	77(11)	78(6)
$15^- \rightarrow 12^+$	?			98

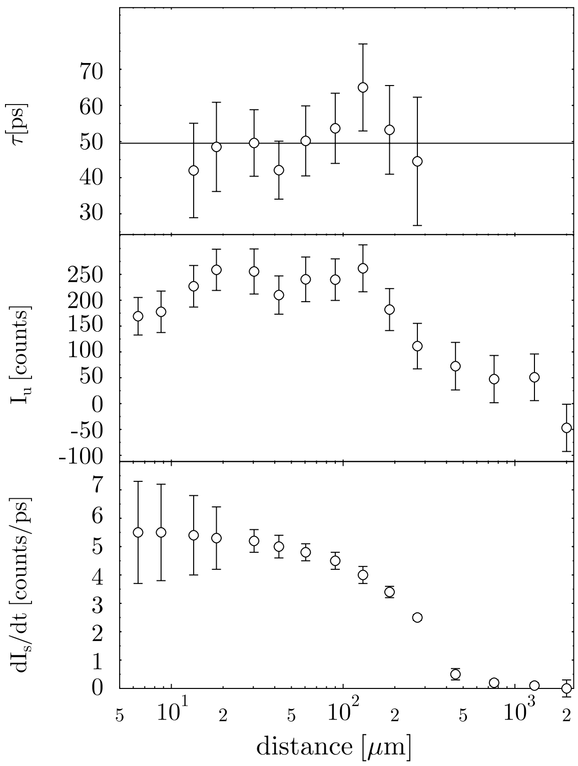

Fig. 3. Example of lifetime analysis for the 3^-, one-octupole-phonon state. For each distance, the value of the mean life (upper panel) is deduced from the intensity of the unshifted component I_u of the 489 keV transition (middle panel) and from the corresponding time derivative dI_s/dt of the shifted component (lower panel). Data refer to the counter ring at $\approx 133°$ and are in coincidence with the shifted part of the 808 keV transition taken at 35°. From these data, the "best average" for the mean life results to be $\tau = 49.5(40)$ ps. The general average, including all ring combinations, is $\tau = 50(3)$ ps.

the previously accepted B(E3)=77(11) W.u. [7]. The difference comes mainly from the lifetime measurement. The former plunger measurement, using single-γ data, gave a meanlife of τ=83(10) ps [7], where the error was mainly due to the uncertainties on the side-feeding. In the DDCM method used in this work we got rid of this problem, and the error comes mainly from the uncertainties in separating the shifted and unshifted components of the low energy 279 keV transition.

In order to obtain information on the lifetime of the states which were candidate for the $\nu(f_{7/2})^2 \otimes 3^- \otimes 3^- \otimes 3^-$ excitation a different method ought to be used, since individual feeding transitions (if any) were too weak to gate on. In addition, the transition(s) depopulating the relevant state are superimposed on a huge background, and too weak to be analysed in the individual spectra at a given target-stopper distance. Therefore, spectra obtained at three consecutive distances have been grouped together.

The 1316 keV transition deexciting the 5297 keV state presents a shifted and an unshifted component throughout the entire range of distances. The ratio of the unshifted component to the shifted one remains constant (within statistical errors) for distances $D > 30\mu$m, and increases slightly at smaller values of D. This trend can be attributed to the delayed feeding from a higher-lying isomer (probably *via* a complicated pattern of parallel cascades). From the short-distance behaviour, an upper limit $\tau < 11$ ps can be established for the mean life of the 5297 keV level.

As for the 5396 keV state, deexcited by the 1417 keV transition, with a similar procedure the meanlife was found to be less than 35 ps. We remind that the mean lives are expected in the range of 1 ns in case of enhanced E3 transitions (the predicted B(E3) being 98 W.u.) and in the range of ps in case of E2 transitions of single particle character. The two above transitions cannot have, therefore, octupole character and the two states cannot be the searched for three-octupole-phonon states.

The 5774 keV state, de-excited by the 1793 keV transition, was too weakly populated and no lifetime could be obtained. It is unlikely that this is the three-phonon state since its energy lies significantly higher than the predicted 5333 keV value (see fig. 1).

The main results, related to octupole excitations in ^{148}Gd, of the experiments described in this paper are listed in Table 1, where they are compared with previous works and with theoretical calculations from ref. [7,10]. The theoretically predicted transition strength of the stretched octupole phonons and their energies in ^{148}Gd are also shown on the right panel of fig. 1. The calculations are parameter free and use the level energy information of the neighbouring nuclei (experimental matrix elements), assuming clean single-particle configurations and their coupling to the octupole-phonon.

The B(E3) strength of the 3^- octupole state at 1274 keV, determined here directly for the first time, results to be very close to that of the ^{146}Gd 3^- state (37(2) W.u.). The microscopic structure of the states in the two nuclei is anyway different since at $N = 84$ the two valence neutrons contribute to the composition of the octupole state. A detailed analysis of the coupling of two $f_{7/2}$ neutrons to the ^{146}Gd 3^- phonon has been made in ref. [10]. The calculations reported there give 35.9 (6) W.u. for the $3^- \rightarrow 0^+$ transition strength in ^{148}Gd, which agrees quite well with our experimental result.

The other two B(E3) strengths extracted in the present work, namely the $9^- \rightarrow 6^+$ and the $12^+ \rightarrow 9^-$ ones, confirm the previous, slightly less accurate, experimental values and are in accord with the theoretical values of ref. [10].

We recall here that the lifetime of the 9^- and of the 12^+ states, lie in very different time range ($\approx$20 ns and $\approx$90 ps respectively) and cannot be measured with the same experimental setup so that when comparing the extracted B(E3) strengths systematic errors cannot be avoided. The same is valid also in ^{147}Gd where the experimental ratio between the two-phonon→one-phonon and the one-phonon→zero-phonon strengths is derived from two different experiments.

Here, for the first time, we could measure the lifetime of the 3^- and of the 12^+ states from the same experiment and therefore the experimental ratio of their B(E3) strengths, $R_{\rm exp} = 1.61(33)$, can be compared with the theoretical ratio, $R_{\rm the} = 2.17(17)$ with greater confidence. Although the errors are still large, the agreement between experiment and calculations can be considered satisfactory, even if the experimental value is definitely below 2. Recently also in the isotone ^{146}Sm the B(E3) strengths of the one-octupole and two-octupole phonon states built on the $(\nu f_{7/2})^2_{6^+}$ state have been derived from the same lifetime experiment [16]. In this case the two-phonon strength is similar to the one-phonon strength and not a factor two stronger as it is expected in the harmonic vibration limit. This fact may indicate a fragmentation of the second octupole-phonon strength among different levels in the $N = 84$ isotones ^{146}Sm and ^{148}Gd. In ^{208}Pb, recent theoretical calculations [17] in the frame of the quasiparticle-phonon model suggest that at least the 6^+ member of the two-octupole-phonon multiplet is strongly fragmented among several levels.

As far as the three-octupole-phonon state is concerned, it is predicted [7] to lie (see fig. 1.) 1573 keV above the 12^+ state, *i.e.* far away from the yrast line, where it could mix with several other 15^- states. In this case the decay properties might be determined by the non-collective part of the wave function, resulting in a short lifetime and a E3 branch comparatively small. This would explain why we could not find the stretched three-octupole state in ^{148}Gd. Another possible explanation is that we populate only weakly the non-yrast three-octupole phonon state as is the case for the not yet observed 6^+ two-phonon state in the core nucleus ^{146}Gd.

In conclusion, we have determined in ^{148}Gd the octupole transition strength for the first 3^- state, as well as for the one- and two-octupole-phonon states built on the $\nu(f^2_{7/2})6^+$ level. The obtained values are more accurate than the previous ones, and might suggest that the octupole strengths in ^{148}Gd are more fragmented than it was suggested by former calculations. The search for a three-octupole phonon state has been also reported whose results suggest that either the level, lying well above yrast, is very difficult to populate, or that its strength is fragmented among many other levels and therefore not easy to detect.

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