Two- to One-Phonon $E3$ Transition Strength in ^{148}Gd

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In a plunger experiment the mean life of the $(\nu f_{7/2}^2\times 3^-\times 3^-)12^+$ state at 3.981 MeV in $^{148}_{64}$Gd$_{84}$ was measured as $\tau=83(10)$ ps, giving $77(11)B_W$ for the 1286 keV $12^+\rightarrow 9^-$ $E3$ transition rate, confirming the double-octupole character of the 12^+ state. The observed deviations in energy and transition rate from harmonic vibration are shown to be caused by the exclusion principle acting between nucleons in the two phonons and are related to the dominant contributions to the ^{148}Gd octupole phonon of the low-lying $\Delta l=\Delta j=3$ proton and neutron in-shell 3^- excitations which are of vital significance for the octupole mode in open-shell nuclei.

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The statement from 1975, "Although, at present, there is only little evidence concerning anharmonic effects in the octupole mode, these effects are potentially of considerable interest" [1], can also form an adequate summary of the present situation. Although some experimental data have been obtained [2–10] in the intervening years, the evidence is still fragmentary, and no clear picture of the degree of harmonicity of nuclear octupole vibrations has emerged.

In the radium ($Z\sim 88$, $N\sim 134$) and barium ($Z\sim 56$, $N\sim 90$) regions the existence of low $K^\pi=0^-$ bands in even-even nuclei, and other evidence, suggests [11] that these quadrupole-deformed nuclei are soft with respect to octupole shape changes. On the other hand, in spherical doubly closed-shell regions around ^{56}Ni, ^{100}Sn, ^{132}Sn, and ^{208}Pb one expects that the octupole vibrations are nearly harmonic, since the 3^- phonon is built from a large number of particle-hole excitations between well separated single-particle orbits. This contrasts with the situation for the 2^+ quadrupole mode in open-shell nuclei, where the phonon is built from a few low-energy excitations within a major shell. The quantitative analysis of the quadrupole mode within the framework of the interacting boson model shows that the interactions in general produce large anharmonic effects. Quantitative information about anharmonic characteristics can most directly be derived from the properties of two-phonon states, such as energies and transition rates. For the octupole mode in the harmonic limit the two-phonon states should form a degenerate $0^+,2^+,4^+,6^+$ multiplet at twice the energy of the one-phonon state, and the $E3$ transition rates to the one-phonon state should be twice that from the one-phonon to the zero-phonon state.

Attempts to identify two-phonon octupole excitations in nuclei have proven to be exceedingly difficult. One reason for this is that in deexcitation of the two-phonon states unspecific low-multipolarity radiation can dominate such that the configuration-specific $E3$ transitions cannot be observed. Some time ago the first case of a two-phonon state in an even-even nucleus was identified [7,10] in ^{148}Gd$_{84}$ through observation of a $12^+\rightarrow 9^-\rightarrow 6^+$ stretched double $E3$ cascade, where the 6^+ basis state is the well established yrast level formed by the maximum-spin coupling of the two valence neutrons in the $f_{7/2}$ orbit. The experimental energy ratio,

$$(E_{12^+}-E_{6^+})/(E_{9^-}-E_{6^+})=2.45\ ,$$

deviates considerably from the harmonic value of 2. A major reason for this deviation has been traced [7] to the effect of Pauli blocking on the large proton $h_{11/2}d_{5/2}^{-1}$ component in the phonon.

From the 17 ns half-life measured in these experiments for the 9^- level, significant collectivity of the $9^-\rightarrow 6^+$ one- to zero-phonon transition was established, but the $12^+\rightarrow 9^-$ two- to one-phonon $E3$ strength could not be determined since 97% of the 12^+ level decay proceeds through an $E1$ transition, which suggests a level half-life of about 100 ps. We have now determined this half-life in a plunger experiment using the Nordball multidetector array at the Niels Bohr Institute tandem accelerator.

The measurement is quite difficult since several ^{148}Gd levels above the 12^+ double-octupole state have lifetimes of comparable magnitude. In fact an earlier attempt [10] to measure the 12^+ half-life using the (^{28}Si,4n) reaction failed due to this reason since here the major population intensity proceeded through the 6.835 MeV 1.5 ns 20^- isomer. In order to optimize the sidefeeding close to the 12^+ state the present experiment was carried out using the ^{133}Cs(^{19}F,4n) reaction with a 73.5 MeV ^{19}F beam. At the target this beam energy gave an average reaction energy of 70 MeV which is essentially at the Coulomb barrier. The schematic ^{148}Gd level scheme of Fig. 1 gives the feeding intensity distribution in the present measurements. The target was prepared by evaporating a 1.3-

mg/cm^2-thick layer of undissociated natural CsJ on an 800-μg/cm^2 gold backing, and a 6-mg/cm^2 gold foil was used as a stopper. Both were stretched in normal plunger manner. Data were taken at ten distances ranging from 20 to 3000 μm.

The γ-ray spectra were measured with the Nordball array consisting of twenty Compton-suppressed Ge detectors positioned in four conical rings of five detectors each, viewing the target at 37° and 79° to the beam direction in the forward and backward hemisphere. The plunger spectra were recorded in the two 37° detector rings; for coincidence gating all twenty Nordball detectors were used. Setting gates on the nine intense ^{148}Gd transitions [10] emitted in decay of the 17 ns 9^- isomer gave highly clean spectra for the ^{148}Gd γ rays in the region of interest, free from transitions in ^{142}Sm and other reaction channels. These ^{148}Gd data were then analyzed in the standard manner of singles plunger data where in a global fit the decay-time results measured for all individual transitions are compared with the respective theoretical function for the pertinent portion of the decay chain. The experiment gave individual decay-time data for the seven stronger transitions underlined in Fig. 1 which, together with measured intensities, were the principal input data for the fit. Additional decay branches [10] involve transitions that are too weak to obtain meaningful timing data, but their measured intensities together with the associated decay properties were included in the experimental decay chain. In the analysis the sidefeeding intensity to each level was represented by two components with different effective feeding times which were fitted as free parameters. As an example, Fig. 2 shows the fit to the decay-time data for the 279 keV $12^+ \rightarrow 11^-$ transition. The data sets of the two independent measurements from the forward and backward detector rings were analyzed separately and gave the results

$$\tau_{143°}(12^+,3.981\ \text{MeV}) = 85.0(49)\ \text{ps, with}\ \chi^2 = 3.6\,,$$

$$\tau_{37°}(12^+,3.981\ \text{MeV}) = 82.1(42)\ \text{ps, with}\ \chi^2 = 2.8\,,$$

where the statistical errors are quoted. A characteristic property of the fit to the data are slow sidefeeding components for most of the levels. This is in accord with other plunger studies [12] and takes account of the fact that the ^{148}Gd sidefeeding transitions may well proceed through states of multiparticle character with half-lives comparable to those in the main decay cascade. The problems associated with sidefeeding times in principle could be avoided in a coincidence measurement through appropriate gating on the transitions feeding the 12^+ level, but limited counting statistics precluded such an analysis of our data that were measured at the Coulomb barrier where the cross section is low. We therefore investigated the stability of the fit against variations of the sidefeeding times which probably represent the largest contribution to the systematic error. From the two above determinations we adopt

$$\tau(12^+,3.981\ \text{MeV}) = 83(10)\ \text{ps}\,,$$

where the increased error covers our estimated systematic uncertainties.

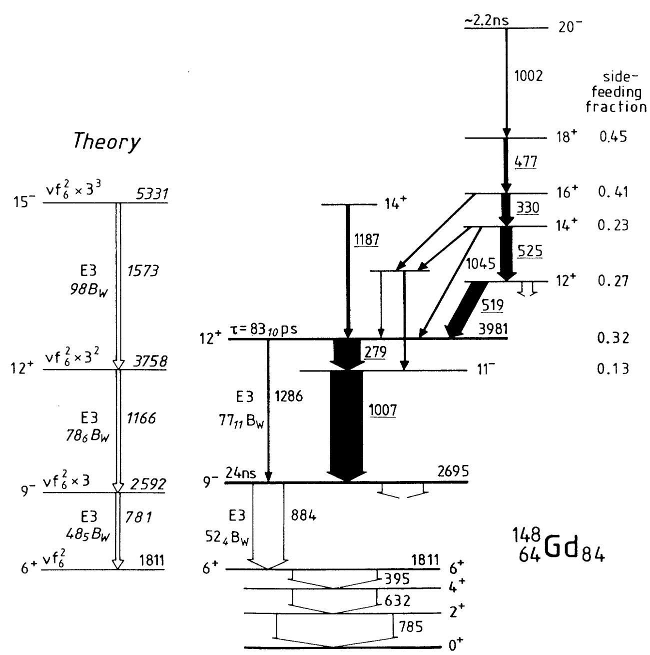

FIG. 1. Schematic partial level scheme of ^{148}Gd as observed in the present experiments. The filled γ transitions were included in the decay-time fit; individual timing data were obtained for the underlined γ's. Transitions without energies are symbolic and represent the inclusion in the fit of complex known weak branches. The theoretical results of a parameter-free calculation are from Ref. [10] except the newly calculated 15^- three-phonon state.

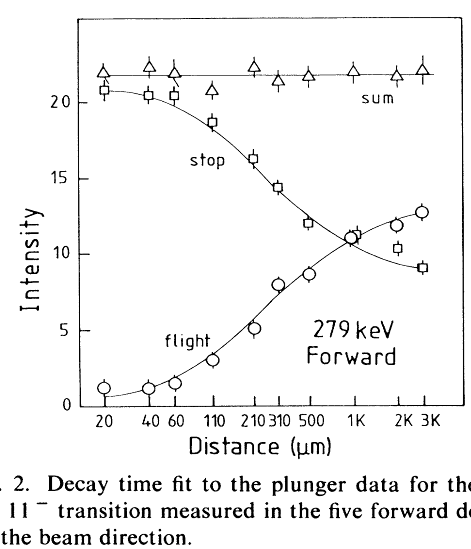

FIG. 2. Decay time fit to the plunger data for the 279 keV 12^+ to 11^- transition measured in the five forward detectors at 37° to the beam direction.

The important 1286 keV $E3$ to 279 keV $E1$ intensity ratio was not well determined from the previous experiments [10,13]. We therefore made a separate measurement with a backed target to stop the recoiling nuclei, and using 76 MeV beam energy which significantly increased the ^{148}Gd production cross section. From these data we extract the 1286 keV $E3$ decay branch as 2.8(2)%. Also for the 884 keV $E3$ decay branch from the 2.695 MeV 9^- level these new data gave a more accurate value, of 39(3)%, giving the one- to zero-phonon transition rate as

$$B(E3,9^- \to 6^+,884\text{ keV}) = 68(5)\times 10^3\, e^2\text{fm}^6 = 52(4)B_W\,.$$

For the two- to one-phonon $E3$ strength we obtain

$$B(E3,12^+ \to 9^-,1286\text{ keV}) = 100(14)\times 10^3\, e^2\text{fm}^6 = 77(11)B_W\,.$$

This is the fastest observed nuclear $E3$ transition. It firmly characterizes the 3.981 MeV 12^+ state of ^{148}Gd as a two-phonon octupole excitation.

The ^{148}Gd 12^+ two-phonon state deviates markedly from harmonic vibration where it should have twice the energy and double the $E3$ strength of the one-phonon state. While the energy of the 12^+ state was already known to be considerably higher than the harmonic value, we have now established that also the transition rate,

$$B(E3,12^+ \to 9^-)/B(E3,9^- \to 6^+) = 1.48(24)\,,$$

deviates significantly from harmonicity.

Such double-phonon anharmonicities have been the subject of intense theoretical discussion. One simple physical phenomenon that can contribute to the anharmonicity is the coupling of the two phonons through their multipole moments, in particular the quadrupole moments [14]. This interaction lowers the energy of the two-phonon $(3^-\times 3^-)6^+$ coupling. The effect was so far only discussed for ^{208}Pb, where the 3^- quadrupole moment was measured [15], but here the 6^+ two-phonon energy is still unclear. Other elementary contributions to the anharmonicity are of quantal nature, associated with the microscopic structure of the phonon. One particular effect [6] can be viewed as a correction for the Pauli principle acting between particles or holes in different phonons. As we will show this effect is dominant in the $(\nu f_6^2 \times 3^- \times 3^-)12^+$ two-phonon state in ^{148}Gd.

As mentioned above the octupole vibration is expected to be nearly harmonic in a doubly magic nucleus like ^{208}Pb. The situation is different in a nucleus like ^{146}Gd, where the neutron number is still magic, while the proton Fermi surface at $Z=64$ lies between the $\pi d_{5/2}$ and $\pi h_{11/2}$ orbitals which are connected by a large Y_3 matrix element. This orbital pair will give rise to one very low-lying 3^- particle-hole excitation in addition to the large number of particle-hole excitations at higher energy where one nucleon is lifted across a major shell gap. Consequently the ^{146}Gd 3^- phonon will have a prominent component of this specific $\pi h_{11}\pi d_{5/2}^{-1}$ particle-hole excitation. This additional component in the octupole wave function increases the collectivity, but also makes the vibration anharmonic via the aforementioned effect of the exclusion principle.

Such low-lying 3^- excitations are formed by antialigned coupling of the special orbital pairs with $j=l+\frac{1}{2}$ and $\Delta l=3$ that lie close in energy within the same major shell, namely, $g_{9/2}$-$j_{15/2}$, $f_{7/2}$-$i_{13/2}$, $d_{5/2}$-$h_{11/2}$, and $p_{3/2}$-$g_{9/2}$. They cannot contribute to the 3^- phonon in doubly magic nuclei since here they always occur on the same side of the Fermi surface. But these in-shell excitations are of crucial significance for the octupole mode in single-closed-shell and open-shell nuclei.

In ^{148}Gd the $\nu f_{7/2}\to \nu i_{13/2}$ excitation also contributes in a similar manner to the octupole vibration, resulting in the $(\nu f_6^2\times 3^-)9^-$ one-phonon energy of 884 keV and the $E3$ transition rate of $52(4)B_W$, compared to 1579 keV and $37(2)B_W$ of the 3^- state in ^{146}Gd. In a previous theoretical analysis [10] of the 12^+ double-octupole state in ^{148}Gd we have handled the effect of the Pauli principle for the protons in perturbation theory, while the contribution of the two valence neutrons to the octupole collectivity was calculated explicitly. These theoretical results are shown to the left in Fig. 1 and are in good agreement with experiment for both the energies and the transition rates. We therefore conclude that the principal cause of the anharmonicity in this case is correctly identified.

The contribution of the $\nu f_{7/2}\to \nu i_{13/2}$ transition to the octupole collectivity should increase towards higher neutron number, which is observed in the $N=88$ nucleus ^{152}Gd where the strength of the 3_1^- state is $52B_W$ compared to $42B_W$ in ^{148}Gd and $37B_W$ in ^{146}Gd [10,16]. At $N=90$ where the $f_{7/2}$ shell should be completed the nuclei have acquired static quadrupole deformation, and the associated rearrangement of the single-particle energies shifts the maximum octupole collectivity to the nuclei around $^{146}_{56}$Ba$_{90}$ and induces an octupole component in the nuclear shape. Originally such reflection asymmetric shapes have been found in the actinide nuclei [11] in the vicinity of $^{222}_{88}$Ra$_{134}$, where they result from the filling of the $\pi f_{7/2}$-$\pi i_{13/2}$ and $\nu g_{9/2}$-$\nu j_{15/2}$ orbital pairs.

The prominent role of the $\pi d_{5/2}\to \pi h_{11/2} 3^-$ excitation in the $N=82$ isotones has early become evident from the regular variation of the properties of the octupole phonon [16] which has lowest energy and maximum transition rate in Gd. There are three other regions of single-closed-shell nuclei where similar data [16] on the octupole vibration exist. They are the $Z=50$ nuclei around ^{114}Sn exploiting the $\nu d_{5/2}\to \nu h_{11/2}$ excitation, the $N=50$ nuclei around ^{90}Zr with $\pi p_{3/2}\to \pi g_{9/2}$, and the $Z=28$ isotopes close to ^{66}Ni with the $\nu p_{3/2}\to \nu g_{9/2}$ excitation. The strongest 3^- one-phonon strength, $66(9)B_W$, has recently been measured [17] in ^{96}Zr. In this spherical nucleus the $\pi p_{3/2}\to \pi g_{9/2}$ as well as the $\nu d_{5/2}\to \nu h_{11/2}$ excitations are fully contributing to the collectivity of the octupole phonon. In all these nuclei one can expect that substantial anharmonicity of the octupole vibration is brought about by the effect of the Pauli principle, causing a positive contribution to the energy shift for the two-phonon 6^+ coupling as discussed above for the Gd region.

In summary, we have measured the $12^+ \rightarrow 9^- E3$ transition rate in ^{148}Gd as $77(11)B_W$. This result confirms the identification of the 3.981 MeV 12^+ state as the $\nu f_{\frac{7}{2}}^2 \times 3^- \times 3^-$ two-phonon octupole excitation. This is the first two- to one-phonon $E3$ transition rate measured in an even nucleus. Theoretical analysis shows that the observed anharmonicities in energy and strength are due to the effect of the Pauli principle acting between nucleons in different phonons.

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