PHYSICAL REVIEW C VOLUME 51, NUMBER 3 MARCH 1995

Double-octupole excitations in the $N=84$ nuclei ^{144}Nd and ^{146}Sm

L. Bargioni, P.G. Bizzeti, and A.M. Bizzeti-Sona
INFN and University of Florence, Florence, Italy

D. Bazzacco, S. Lunardi, P. Pavan, and C. Rossi-Alvarez
INFN and University of Padova, Padova, Italy

G. de Angelis, G. Maron, and J. Rico
INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy

(Received 15 December 1994)

Evidence of collective octupole excitations built on spherical shell-model states is reported for the $N=84$ isotones ^{146}Sm and ^{144}Nd. In particular, good candidates for double-octupole excitations, analog to the 12^+ state at 3981 keV in ^{148}Gd, have been identified in both nuclei.

PACS number(s): 21.10.Re, 23.20.Lv, 21.10.Hw, 27.60.+j

Nuclei around ^{146}Gd are theoretically expected to be soft with respect to octupole deformation, due to the coherent contribution of several possible $\Delta\ell=\Delta j=3$ particle-hole excitations. In some cases, particularly on the neutron-rich side of the region, this softness evolves towards a stable reflection-asymmetric deformation, while in the more spherical nuclei close to the ^{146}Gd core, states with a large component of collective octupole excitation are known to coexist, at low excitation energy, with normal shell-model states. Actually, in the core nucleus ^{146}Gd (corresponding to the neutron shell and proton subshell [1] closures $N=82$, $Z=64$) the 3^- octupole state is the lowest-lying excitation, only 1579 keV above the g.s. (to be compared with 2615 keV in ^{208}Pb). This is certainly one of the reasons why examples of two-octupole-phonon states have been unambiguously identified [2–4] only in two nuclides of this region (^{147,148}Gd) after many unsuccessful attempts around the doubly magic nucleus ^{208}Pb.

As a part of a research program on nuclear octupole excitations [5], we have investigated the two lighter isotones of ^{148}Gd, ^{146}Sm, and ^{144}Nd ($N=84$, i.e., two neutrons outside the closed $N=82$ shell). These two nuclei present a low-lying 3^- level, at energy close to that of the corresponding level of ^{148}Gd, which — at least in ^{144}Nd — has a large $E3$ transition strength [6] to the ground state.

Moreover, some states of these nuclei can be interpreted as the result of an octupole excitation built on low lying positive-parity states, such as the weak-coupling multiplet $(2^+\otimes 3^-)$ recently reported in Ref. [7].

In the present experiment, the nuclei of ^{146}Sm and ^{144}Nd have been studied with the GASP array [8] at the Tandem XTU of Laboratori Nazionali di Legnaro. The reactions used were ^{139}La(^{11}B,4n)^{146}Sm and ^{139}La(^{11}B, $\alpha 2n$)^{144}Nd at $E(^{11}\mathrm{B})=45$ MeV. At this energy, channels leading to ^{146}Sm and ^{147}Sm share the most of the reaction cross section, while the yield of ^{144}Nd corresponds to about 5% of the total. The target was a 5 mg/cm^2 thick foil of ^{139}La, and the beam current was about 10 particle nA.

The last generation of Ge-ball arrays (like GASP, EUROGAM, GAMMASPHERE), which were primarily intended to study yrast and quasiyrast states at very high angular momentum, also offer new and exciting opportunities to explore "simple" modes of excitation of complex nuclei at relatively low energy. GASP [8] consists of an almost spherically symmetric shell of 40 Compton-suppressed Ge counters with an inner multiplicity-filter of 80 BGO scintillators.

Events were collected when at least three suppressed Ge detectors and two detectors of the inner ball fired in coincidence. The event rate was about 3500 per sec. Raw data have been analyzed off-line with HP-700 series computers of the UNIX network of INFN, Florence [9]. After recalibration of the energy and time scales, we have constructed two- and three-dimensional (symmetrized) arrays ("matrices" and "cubes") of γ coincidences, of 3000 channels per dimension (and 1 keV/channel), with different sets of gates on the total multiplicity and total energy measured in the BGO filter, and on time spectra for the Ge signals.

Angular asymmetries, i.e., intensity ratios between detectors placed at 34° and 90° with respect to the beam direction (we consider together all counters between 32° and 36°, and take 34° as their average angle) have also been derived, for most of the transitions, from the coincidence data. In fact, due to the almost spherically symmetric geometry of GASP, it is possible to select γ rays (at a given angle) by proper coincidences with one or more γ transitions (summed over all angles) without altering their angular distribution. For this purpose, events with one of the Ge signals corresponding to a given angle have been selected and accumulated in asymmetric three-dimensional arrays of 2000 channels per dimension (with angle-selected data reported along the third axis of the cube, and no angle selection for the other two axes).

From the analysis of γ coincidences the yrast and near-to-yrast parts of ^{146}Sm and ^{144}Nd level schemes have been obtained, as reported in Figs. 1 and 2. These level schemes show a strict similarity with one another and, in part, with that of the $N=84$ isotone ^{148}Gd. The analogy (involving also the part of the scheme composed of rather complex states) is much deeper than it was supposed so far, and can provide a basis for a consistent treatment of the even $N=84$ isotones. We are not going to comment about this point further, as it will be the object of a forthcoming paper. We only want to

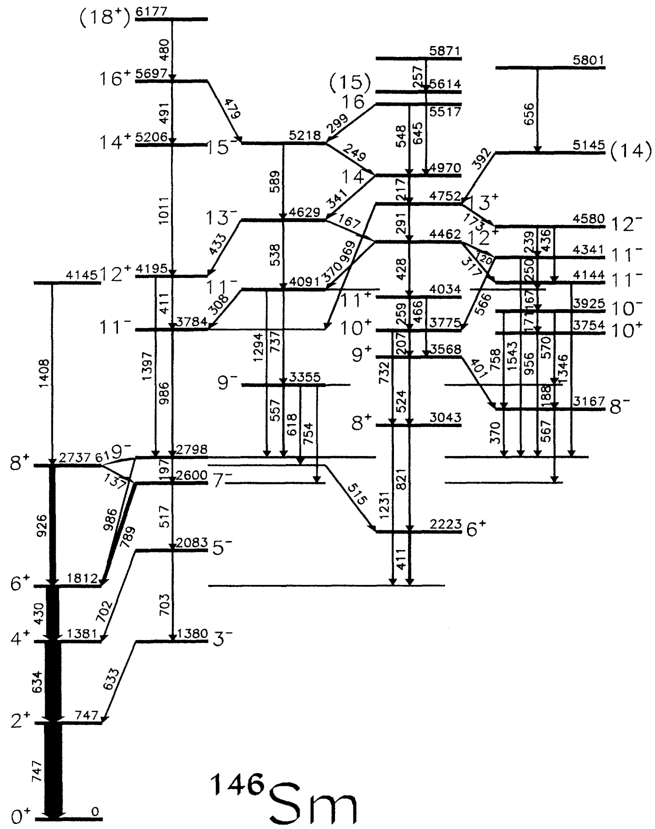

FIG. 1. Partial level scheme of ^{146}Sm, as observed with the ^{139}La(^{11}B,4n)^{146}Sm reaction.

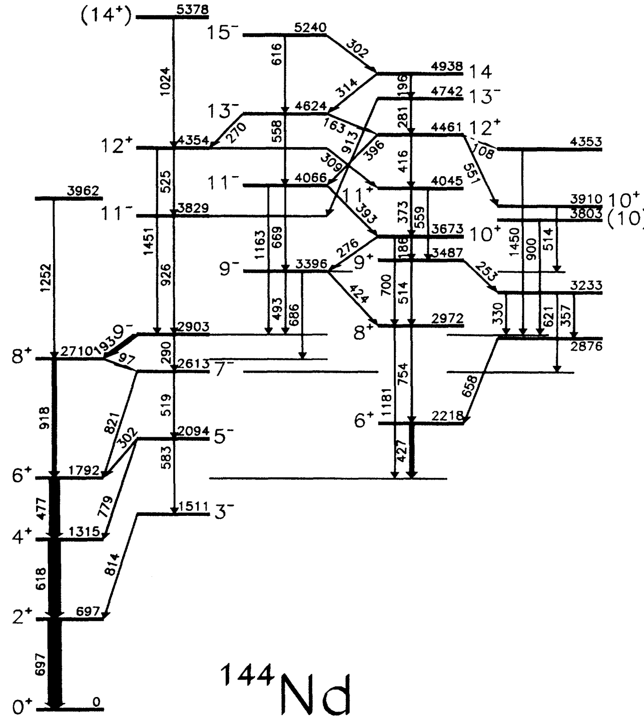

FIG. 2. Partial level scheme of ^{144}Nd, as observed with the ^{139}La(^{11}B,α2n)^{144}Nd reaction.

present here the experimental evidence for the newly proposed $E3$ transitions and the spin-and-parity attribution to the candidate double-octupole levels.

In Fig. 3, a partial level scheme of ^{146}Sm and ^{144}Nd is compared to that of ^{148}Gd. It was already known [10–12] that the sequence of states 3^-, 5^-, 7^-, 9^-, 11^-, interpreted in ^{148}Gd as due to the stretched coupling of one octupole phonon to the low lying ν^2 shell-model states (0^+, 2^+, 4^+, 6^+, 8^+) is also present in ^{146}Sm and ^{144}Nd. In ^{148}Gd, the collective nature of the 9^- state is proved by the enhanced $E3$ transition to the lowest 6^+ state. We have found that a corresponding $E3$ transition of 986 keV is present also in ^{146}Sm, in spite of the larger energy available for the competing $E1$ and $E2$ decays (61 keV and 197 keV) with respect to those of ^{148}Gd (1 keV and 131 keV). Observation of this transition was only possible with a careful selection of gates in the triple-coincidence data, due to the presence of the much stronger $11^- \rightarrow 9^-$ transition, having almost the same energy. Taking for the mean life of the 9^- level the "best value" $T_{1/2} = 0.84 \pm ^{20}_{13}$ ns adopted in Peker's compilation [10] and the branching ratio ($\approx 3 \times 10^{-2}$) deduced from the present measurement, the strength of the $E3$ transition comes

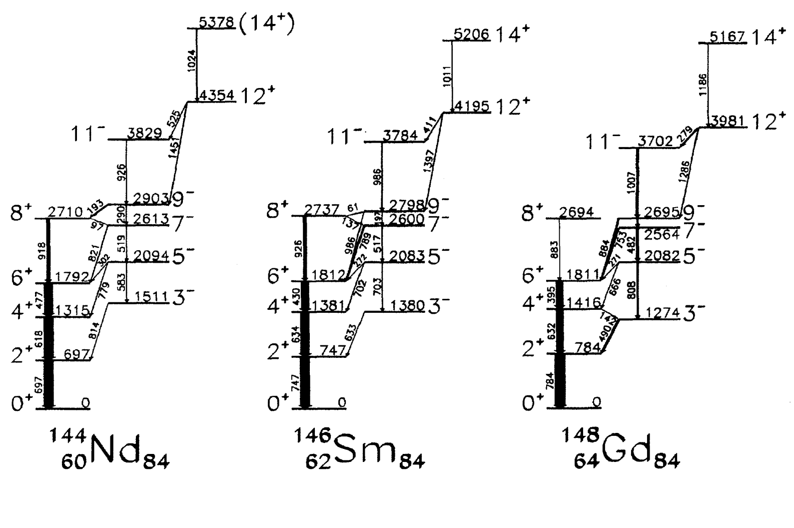

FIG. 3. Partial level scheme of the $N=84$ isotones ^{148}Gd, ^{146}Sm, and ^{144}Nd (the 12^+ state at 4354 keV in ^{144}Nd also decays to a 4045 keV, 11^+ level, not shown in the scheme). Of the three level sequences, the first (from left) is interpreted in terms of two-neutron shell-model states, the second (third) as due to stretched coupling of one (two) octupole-phonon to states of the first sequence (see text).

RAPID COMMUNICATIONS

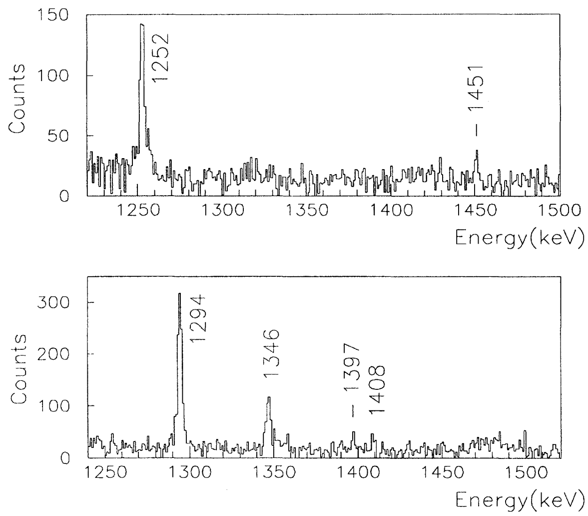

FIG. 4. Parts of coincidence spectra showing (a) the 1451 keV transition in ^{144}Nd and (b) the 1397 keV transition in ^{146}Sm (the former is actually a close doublet composed of a 1450 keV and of a 1451 keV line, see text). Data are taken from asymmetric cubes, having angle-selected counters (at $32^\circ-36^\circ$ and $144^\circ-148^\circ$) in one dimension, and no angle selection in the other two. In the case of ^{144}Nd, the triple-coincidence spectrum has been obtained with one multiple gate on three low-lying γ rays (918, 477, 618 keV) and a second gate on the 193 keV line, while, in the case of ^{146}Sm, one multiple gate selects four γ rays feeding the 12^+ level at 4195 keV and the second one selects six low-lying γ rays belonging to the main cascade from the 9^-, 2798 keV level.

out to be $B(E2)\approx 37$ W.u., i.e., very close to that of the $3^-\rightarrow 0^+$ transition [13] in the "core nucleus" ^{146}Gd and not far from that of the corresponding $9^-\rightarrow 6^+$ transition [4] in the isotone ^{148}Gd, and this proves the collective nature of the 9^- level.

In ^{144}Nd the available energy for the competing $E1$ and $E2$ transitions is even larger (193 and 290 keV) and the direct $9^-\rightarrow 6^+$ decay is no longer observed. This fact is, however, not surprising, as the branching ratio for the $E3$ transition is expected to be of the order of 2×10^{-3}, if one assumes that the relevant $E2$ and $E3$ strengths are the same for the analog transitions in ^{146}Sm and ^{144}Nd.

Moreover, as it will be proved below, likely partners of the ^{148}Gd $I^\pi=12^+$, two-octupole-phonon level at 3981 keV, have been identified at 4195 keV in ^{146}Sm and at 4354 keV in ^{144}Nd. These states are presumably characterized by a large amount of collective excitation, corresponding to the stretched coupling of two octupole phonons to the lowest $I^\pi=6^+$, and, in fact, their decay includes a direct $E3$ transition to the lowest (collective) $I^\pi=9^-$ state.

The new level at 4354 keV in ^{144}Nd is established by triple γ coincidences involving the 270 keV transition and/or one of the three gammas deexciting the level. Possible spin values for the new level are limited to $I=11$, 12, or 13, due to the presence of the two intense γ transitions of 270 and 525 keV, the first from the 4624 keV, 13^- level and the second from the 4354 keV to the 11^- level at 3829 keV, known from Ref. [12]. The angular asymmetry of both transitions is typical of a stretched dipole. Values $I=11$, 13 for the 4354 keV state are therefore excluded as, in this case, one of the two transitions would be a stretched quadrupole. This result is confirmed by the angular asymmetry, of stretched-dipole type, of a third γ transition of 309 keV, from the new $I=12$ state, that feeds, in fact, a $I^\pi=11^+$ level at 4045 keV (see Fig. 2).

A γ line of about 1451 keV, corresponding to the energy difference between the new level and the lowest 9^- state, has been observed in triple coincidences [Fig. 4(a)]. Actually this line results to be a close doublet composed of a 1450 keV transition (from the 4353 keV level) and a 1451 keV transition (from the 4354 keV level, see Fig. 2). While both transitions feed the lowest 9^- state, only the 1451 keV one results to be in coincidence with the weak γ of 270 keV feeding the 4354 keV state (and, in fact, the energy of the crossover transition $12\rightarrow 9^-$, deduced from those of the $12\rightarrow 11^-$ and $11^-\rightarrow 9^-$, is 1451.3 keV). We have checked that the expected intensity for the sum peak of the 525 and 926 keV transitions is an order of magnitude smaller than the observed effect. The branching ratio for the 1451 keV line is estimated to be about 2×10^{-2}. Since this branching ratio would be exceedingly large for a $M3$ decay in competition with $E1$ and $M1$, this transition is to be interpreted as $E3$, and the parity of the parent level as positive.

In ^{146}Sm, a state with similar properties has been identified at an excitation energy of 4195 keV. A level of this energy is reported also in Ref. [11] where, however, its spin is given as $I=(11,13)$. Our assignment $I^\pi=12^+$ is based on the observation of a new transition of 433 keV from the 13^- level at 4629 keV and on the angular asymmetry, typical of stretched dipole, of this γ ray and of the 411 keV transition to the 11^- level at 3784 keV. The same arguments used to assign $I^\pi=12^+$ to the level at 4354 keV in ^{144}Nd also hold in this case. To measure the $34^\circ/90^\circ$ asymmetry, doubly gated spectra from γ-γ-γ coincidences have been used, due to the presence of stronger γ rays of 428, 430, and 411 keV, coming from lower levels of the same nucleus (12^+ at 4462 keV, 6^+ at 1812, and 6^+ at 2223 keV, respectively). The angular distribution of the 411 keV, $6^+\rightarrow 6^+$ transition is peaked at small angles (while that of the relevant 411 keV transition is peaked at 90°), and this fact is probably at the basis of the tentative spin assignment given in Refs. [11,14] for the 4195 keV level.

Also in this case, a weak γ transition (of 1397 keV) to the lowest 9^- state is observed in double coincidence with a proper selection of gates on the three-dimensional array [Fig. 4(b)]. We can notice that its angular asymmetry is peaked at small angles, as expected for a stretched octupole transition.

The systematic trend of the $12^+\rightarrow 9^-$, $9^-\rightarrow 6^+$, $3^-\rightarrow 0^+$ transitions, from ^{148}Gd to ^{144}Nd is shown in Table

TABLE I. Energy differences (in keV) corresponding to one-octupole-phonon excitations built over the lowest 0^+, 6^+, and 9^- states in the $N=84$ isotones ^{144}Nd, ^{146}Sm, and ^{148}Gd.

Transition	^{144}Nd	^{146}Sm	^{148}Gd
$12^+\rightarrow 9^-$	1451	1397	1286
$9^-\rightarrow 6^+$	1111	986	884
$3^-\rightarrow 0^+$	1511	1380	1274

I. The excitation energy of the two-octupole-phonon above the one-octupole-phonon state remains, in all three cases, almost equal to the excitation energy of the lowest 3^- state (instead, that of the one- to zero-octupole phonon transition $9^- \rightarrow 6^+$ follows the same trend, but remains about 400 keV smaller). This fact can be considered as an additional argument (although admittedly weaker than the presence of the $E3$ transitions) in favor of our interpretation of the 12^+ state as a double octupole-phonon excitation. As long as the only example of a 12^+, two-octupole-phonon state was that of ^{148}Gd, the equality of the $12^+ \rightarrow 9^-$ and $3^- \rightarrow 0^+$ transition energies could have been considered as accidental, but this would be hard to explain for the systematic agreement in the three neighboring isotones.

In conclusion, we have identified likely candidates for the collective double-octupole-phonon excitations in ^{144}Nd and ^{146}Sm isotones, by observing the $E3$ transitions $12^+ \rightarrow 9^-$ (of 1451 and 1397 keV, respectively), and the one to zero phonon transition $9^- \rightarrow 6^+$ in ^{146}Sm. They appear completely analogue to those observed [3,4] in the $N=84$ isotone ^{148}Gd.

We are indebted to the technical staff of L.N.L. for the careful operation of the Tandem accelerator, and to Professor P. Maurenzig for stimulating discussions.

---

[1] P. Kleinheinz, R. Broda, P. J. Daly, S. Lunardi, M. Ogawa, and J. Blomqvist, Z. Phys. A **290**, 279 (1979).

[2] P. Kleinheinz, J. Styczen, and M. Piiparinen, Phys. Rev. Lett. **48**, 1457 (1982).

[3] S. Lunardi, P. Kleinheinz, M. Piiparinen, M. Ogawa, and M. Lach, Phys. Rev. Lett. **53**, 1531 (1984); M. Piiparinen, P. Kleinheinz, S. Lunardi, M. Ogawa, G. de Angelis, F. Soramel, W. Meczynski, and J. Blomqvist, Z. Phys. A **337**, 387 (1990).

[4] M. Piiparinen, P. Kleinheinz, J. Blomqvist, A. Virtanen, A. Ataç, D. Müller, J. Nyberg, T. Ransøy, and G. Sletten, Phys. Rev. Lett. **70**, 150 (1993).

[5] Preliminary results have been reported at several Conferences: P. G. Bizzeti *et al.*, in *Conference on Physics from large γ-ray detector arrays*, Berkeley, 1994 (LBL, University of California, Berkeley, CA, 1994), Vol. 1, p. 65; L. Bargioni *et al.*, Acta Phys. Pol. B (to be published).

[6] R. H. Spear, W. J. Vermeer, S. M. Barnett, G. J. Gyapong, and C. S. Lim, Aust. J. Phys. **42**, 345 (1989); M. Pignanelli *et al.*, Nucl. Phys. **A559**, 1 (1993).

[7] S. J. Robinson, J. Jolie, H. G. Börner, P. Schillebeeckx, S. Ulbig, and K. P. Lieb, Phys. Rev. Lett. **73**, 412 (1994).

[8] D. Bazzacco, in *Proceedings of the International Conference on Nuclear Structure at High Angular Momentum*, Ottawa, 1992 (AECL Research, Chalk River, Ontario, Canada, 1992), Vol. 2, p. 376.

[9] L. Bargioni, thesis, University of Florence, Italy, 1994 (unpublished).

[10] L. K. Peker, Nucl. Data Sheets **60**, 953 (1990).

[11] J. K. Tuli, Nucl. Data Sheets **56**, 607 (1989).

[12] D. D. Caussyn, S. M. Aziz, P. D. Cottle, T. Glasmacher, and K. W. Kemper, Phys. Rev. C **43**, 59 (1991).

[13] P. Kleinheinz, M. Ogawa, R. Broda, P. J. Daly, D. Haenni, H. Beuscher, and A. Kleinrahm, Z. Phys. A **286**, 27 (1978).

[14] S. Rozak, E. G. Funk, and J. W. Mihelich, Phys. Rev. C **25**, 3000 (1982); C. H. King, B. A. Brown, and T. L. Khoo, *ibid.* **18**, 2127 (1978).