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Lowest 2^+ State in $^{146}_{64}Gd_{82}$ and the Energy Gap at $Z=64$

M. Ogawa,[a] R. Broda,[b] K. Zell,[c] P. J. Daly,[d] and P. Kleinheinz
Institut für Kernphysik, Kernforschungsanlage Jülich, D-5170 Jülich, West Germany
(Received 18 April 1978)

A search for the lowest 2^+ state in ^{146}Gd using $(\alpha,2n\gamma)$ excitation function measurements near threshold has located that state at 1971 keV. Its energy, more that 300 keV higher than in any other $N=82$ nucleus, provides clear spectroscopic evidence for a large gap in the single-particle spectrum at $Z=64$.

The 1579-keV first excited state in ^{146}Gd, earlier assigned[1] as $I^\pi=2^+$, has recently been shown[2] to be the 3^- octupole state instead. This finding naturally raised the question of the true location of the lowest 2^+ level, as there was no likely candidate remaining among the known[1-3] excited states of ^{146}Gd. This is an important question to settle since earlier results[2,4-6] suggest that there may be an unusually large energy gap at $Z=64$ between the $g_{7/2}$ and $d_{5/2}$ proton orbitals and the $h_{11/2}$ orbital. Moreover, estimated ground-state masses[7] for ^{147}Tb, ^{146}Gd, and ^{147}Gd, obtained by extrapolation from the known masses of less neutron-deficient nuclei, indicate that the gaps in the single-particle proton and neutron spectra at $Z=64$ and $N=82$ are comparably large.

Among the heavy nuclei, the first 2^+ states in a series of singly closed-shell isotopes or isotones are known to occur at almost equal excitation energies. Examples are the Pb and Sn isotopes, and the $N=82$ isotones. The only exceptions are the doubly closed-shell nuclei, e.g., ^{208}Pb and ^{132}Sn, where the 2^+ energies are considerably higher.[8,9] In analogy, a large gap at $Z=64$ should manifest itself in a ^{146}Gd 2^+ energy higher than in the other $N=82$ nuclei. Therefore an experiment was undertaken with the specific aim of locating that state.

The 2^+ state in ^{146}Gd must lie above the yrast line, and this probably explains why it was not found in the earlier (α,xn) measurements.[1,2] However, (p,n) or (α,n) γ-ray excitation-function measurements have often been used to locate individual states—both yrast and nonyrast—in the final nucleus. In principle this is possible when the energy thresholds for the levels are higher than the Coulomb barrier for the incident particle, but the technique is generally not applicable when more than one particle is evaporated from the compound nucleus. In the special case of the very neutron-deficient ^{144}Sm target, the (α, 2n) energy threshold for populating even the ground state of ^{146}Gd is more than 2 MeV above the Coulomb barrier; in addition the low energy-level spacings in the final ^{146}Gd nucleus are unusually large. Consequently it seemed possible that the ^{146}Gd 2^+ level could be identified by (α, 2$n\gamma$) excitation-function measurements near the reaction threshold. In a trial bombardment with 22.7-MeV α particles the 1579-keV $E3$ ground-state transition was indeed observed quite strongly, but there was no trace of the higher transitions in the yrast cascade. We were thereby encouraged to scrutinize the energy levels of ^{146}Gd in the 1.5–3-MeV region by performing detailed excitation-function measurements.

The energy threshold for populating the ^{146}Gd ground state in the (α, 2n) reaction is estimated to be 20.3 MeV from tabulated[7] masses. The excitation-function measurements were performed at the University of Köln tandem accelerator using eight different bombarding energies spanning the range $E_\alpha = 22.4$ to 25.1 MeV. The target was a 1.8-mg/cm^2 self-supporting metal foil enriched to 96.3% in ^{144}Sm. γ-ray spectra, up to 3.5 MeV, were recorded at each bombarding energy with two calibrated 70-cm^3 Ge(Li) detectors at 125° and −90° to the beam direction. The A_2 angular distribution coefficients were derived from the 125°-to-90° intensity ratio assuming $A_4 = 0$. Absolute cross sections were not determined, but the γ-ray intensities at each bombarding energy were normalized to the intensity of the 1660-keV ground-state transition of ^{144}Sm, as the (α, α') reaction cross section is expected to vary little within that energy range.

The γ-ray spectra obtained showed, in a quite dramatic way, the successive appearance of the 1579-, 1079-, and 324-keV ^{146}Gd yrast transitions as the beam energy was increased above the thresholds for the 3^-, 5^-, and 7^- states, respectively. The excitation functions for these transitions are shown in Fig. 1, together with the data for a previously unknown 1971-keV transition which was the second line to appear with an excitation function characteristic of the reaction ^{144}Sm(α, 2n). At the bottom of the figure, the associated level energies are indicated, and the

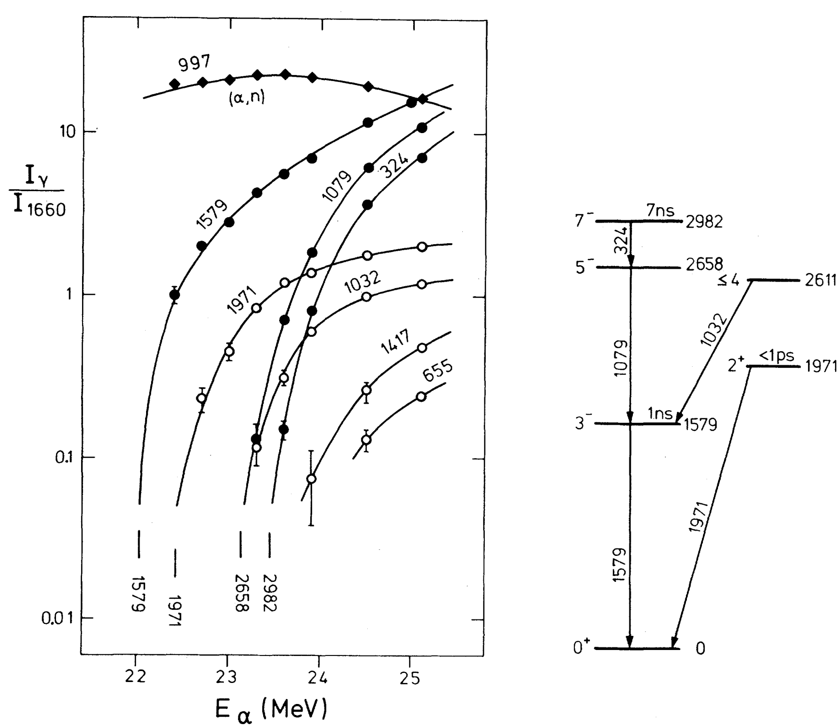

FIG. 1. (α, 2n) excitation functions near threshold for yrast transitions (dots) and nonyrast transitions (bubbles) in ^{146}Gd and the relevant portion of the ^{146}Gd level scheme.

individual thresholds for the three yrast transitions obtained by extrapolation are in satisfactory agreement with their known excitation energies. The data also show that the 1971-keV line must be a ground-state transition in ^{146}Gd.

Figure 1 also gives the data for three nonyrast ^{146}Gd γ rays which are known[3] from ^{146}Tb β decay. The estimated thresholds for the 1417- and 655-keV transitions are in agreement with their suggested[3] placements in the level scheme, and the data for the previously unplaced 1032-keV line show that it feeds the 3^- state. The negative A_2 value observed for that transition indicates a spin ≤ 4 for the previously unknown 2611-keV state. The results for the 997-keV ground-state yrast transition of ^{147}Gd populated in (α, n) are also illustrated in the figure.

The 1971-keV transition appeared particularly interesting since it was the only γ ray other than the 1579-keV line to be excited strongly at bombarding energies less than 23 MeV. The shape of its excitation function differs markedly from those of the yrast transitions, but is very similar to those of the other known ^{146}Gd nonyrast lines (Fig. 1). This observation is consistent with the view that the 1971-keV transition de-excites a level above the yrast line. Independent support for a 1971-keV state in ^{146}Gd comes from the results of a recent study[10] of the two-proton transfer reaction ^{144}Sm(^{16}O, ^{14}C)^{146}Gd. In that experiment, the population of only two excited states below 2.5 MeV in ^{146}Gd was observed at 1.58 and at 1.95 MeV. It is now evident that the lower state is the 1579-keV 3^- octupole state,[2] and almost certainly the 1.95-MeV level is identical with the 1971-keV state reported here.

The measured anisotropy of the 1971-keV γ-ray gave a positive A_2 angular distribution coefficient, about half as large as that for the parallel 1579-keV $E3$ yrast ground-state transition. This result excludes $\Delta I = 1$, but is consistent with stretched $E2$ character, or possibly higher multipolarity. At the lower bombarding energies, where only direct feeding of the 1971-keV state is possible, the main portion of the 1971-keV peak in the 125° spectra was observed to be shifted towards lower energies by 3.5 keV. This is recognized as a Doppler-shift effect indicating for the 1971-keV state a lifetime shorter than the stopping time of recoiling ^{146}Gd nuclei in the Sm target; a short check measurement with the detector at 55° showed a similar shift in the opposite direction. (In contrast, the 1579-keV line which de-excites a $T_{1/2} = 1.1$-ns state[2] was observed unshifted at all angles.) The size of the observed energy shift agrees well with the value calculated from the reaction kinematics. By considering the stopping times of Gd ions in Sm, a safe upper limit of 10^{-12} sec can be placed on the mean life of the 1971-keV state. This short lifetime excludes $M2$ and higher multipolarities. The two results together, the A_2 value and the upper limit for the mean life, establish the 1971-keV state as the lowest 2^+ level in ^{146}Gd. Its observation[10] in two-proton transfer is consistent with that conclusion.

The energy systematics of the lowest 3^- and 2^+ states in the adjacent $N = 82$ isotones are given in Fig. 2. The monotonic decrease of the 3^- energies as proton pairs are added can naturally be related to the important role of the $g_{7/2}h_{11/2}$ and $d_{5/2}h_{11/2}$ proton configurations in determining the octupole energy. In ^{146}Gd, where the Fermi surface should lie between the $d_{5/2}h_{11/2}$ orbitals, the lowest energy for the 3^- state is expected. Rather less predictable, and more revealing, are the 2^+ energies. The location of the 2^+ state in ^{146}Gd, more than 300 keV higher than in any other $N = 82$ nucleus, provides the most direct spectroscopic evidence obtained thus far for a pronounced energy gap at $Z = 64$. In contrast there is no indication of a similar gap at $N = 64$; specifically, the 2^+ energies in the even Sn nuclei including the $N = 64$ nucleus ^{114}Sn are essentially constant.

We thank I. Talmi for directiong our attention to the significance of the problem investigated here, and we acknowledge fruitful discussions with J. Blomqvist, P. von Brentano, O. Schult, and J. Speth. One of us (M.O.) acknowledges receipt of an Alexander von Humboldt fellowship. This work was supported in part by the U. S. En-

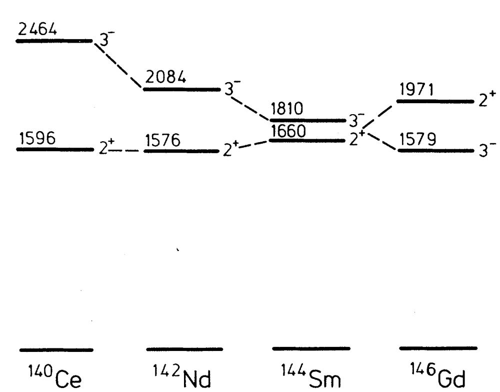

FIG. 2. Energy systematics of 2^+ and 3^- states in $N = 82$ isotones.

ergy Research and Development Administration.

[(a)] On leave from Tokyo Institute of Technology, Tokyo, Japan.

[(b)] On leave from Institute of Nuclear Physics, Cracow, Poland.

[(c)] Permanent address: Physikalisches Institute der Universität zu Köln, Köln, Germany.

[(d)] On leave from Purdue University, W. Lafayette, Indiana.

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Observation of the $T_> = \frac{45}{2}$ Components of Deep Hole States in ^{207}Pb via the (^{3}He,α) Reaction at 70 MeV

S. Gales,[(a)] G. M. Crawley, D. Weber, and B. Zwieglinski[(b)]
Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824
(Received 12 May 1978)

A number of narrow lines are observed around 20 MeV excitation energy in ^{207}Pb in the study of ^{208}Pb(^{3}He,α) at 70 MeV. Their excitation energies and relative spacing suggest that these peaks arise from the neutron pickup from the inner filled *sdhg* shell between magic numbers 82 and 50 with isospin number $T = \frac{45}{2}$. In addition, distorted-wave Born-approximation (DWBA) calculations of the angular distributions agree in shape with the data. The solution of the Lane coupled-channels equations leads to a DWBA cross section in reasonable agreement with experiment.

In the past few years a number of experiments have been carried out in heavy nuclei in order to locate the $T_<$ components of inner hole states using neutron pickup reactions.[1-9] In general, both the $T_<$ and the $T_>$ components of these inner neutron hole states are populated, the latter ($T_>$) observed as sharp peaks at high excitation energy above a continuous background.[4,5,8-10] These studies are of importance because they provide quantitative information on the spreading of simple configurations into the underlying background in a region of very high level density. A simple calculation of the Coulomb displacement energy predicts that these levels are located between 19 and 24 MeV excitation energy in ^{207}Pb and the possibility of observing the $T_> = \frac{45}{2}$ states in this nucleus is completely dependent upon the concentration of the single-hole analog strength and the ratio of such cross sections to the physical background arising from the high level density. Finally, the recent calculations of the form factor of such inner hole states[8,11] using the Lane coupled-channels equations[12] (CC), which have been fairly successful in reproducing the strength of the $T_>$ hole-analog states in heavy nuclei as compared to the usual separation-energy method (SE), could be tested in ^{207}Pb under extreme condition (binding energy of -30 MeV and high isospin number $T_> = \frac{45}{2}$).

In order to study these phenomena in more detail, the reaction ^{208}Pb(^{3}He, α)^{207}Pb was investigated at 70 MeV incident energy using a 50-cm-long delay-line counter backed by a plastic scintillator in the focal plane of the Enge spectro-

