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Shape coexistence on the boundary of the ''island of inversion'': Exotic beam spectroscopy of ^{34}Al

B. V. Pritychenko,[1,2,*] T. Glasmacher,[1,2] B. A. Brown,[1,2] P. D. Cottle,[3] R. W. Ibbotson,[1,†] K. W. Kemper,[3]
and H. Scheit[1,2,‡]
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824*
[3]*Department of Physics, Florida State University, Tallahassee, Florida 32306*

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The $N=21$ nucleus ^{34}Al, located at the boundary of the island of inversion, was studied via intermediate-energy Coulomb excitation. A γ ray with an energy of 657 ± 9 keV has been observed in ^{34}Al and its production cross section has been measured. This γ ray may connect states which are members of the low-lying neutron $d_{5/2}$-$f_{7/2}$ multiplet.

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The ''island of inversion,'' a group of deformed neutron-rich nuclei at and near the neutron magic number $N=20$, poses an important test of our understanding of the phenomenon of shape coexistence in atomic nuclei. While shape coexistence occurs throughout the table of isotopes [1], the island of inversion seems to be unique in that the ''intruder'' configuration that is formed by promoting two neutrons across the $N=20$ shell gap becomes the ground state. To build an understanding of this phenomenon, we must not only measure nuclear structure properties of nuclei within the island (for example, see [2–4]) but also at and near the boundary of the island of inversion [3,6]. In the boundary nuclei, we expect that the intruder configurations occur at low excitation energies with normal configurations dominating the ground states.

In this Brief Report, we report the result of a measurement of the boundary nucleus ^{34}Al using the technique of intermediate-energy Coulomb excitation [7]. With $Z=13$ and $N=21$, this aluminum isotope is located between ^{35}Si, in which the ground state appears to be dominated by normal configurations [5], and the island of inversion isotope ^{33}Mg. We observe a γ ray in ^{34}Al at 657 ± 9 keV. A comparison of this result with calculations in the literature [8,9] suggests that this γ ray connects an intruder state with the normal deformed ground state.

The experiment was performed at the National Superconducting Cyclotron Laboratory. The primary beam of 80 MeV/nucleon ^{48}Ca was produced with the laboratory's K1200 cyclotron. The secondary beam of 68.1 MeV/nucleon ^{34}Al was made via fragmentation of the primary beam in a ^{9}Be production target of thickness 376 mg/cm^2 located at the midacceptance target position of the A1200 fragment separator [10].

A 702 mg/cm^2 ^{197}Au foil was used as the secondary target. The secondary beam slowed significantly in this target, and the beam energy used in the analysis of the γ-ray cross section was that of the ^{34}Al beam in the middle of the secondary ^{197}Au target, 59.70 MeV/nucleon. The ^{34}Al beam was stopped in a cylindrical fast-slow plastic phoswich detector located at zero degrees. Both energy loss in the phoswich detector and time of flight relative to the cyclotron rf signal were used for particle identification. The zero-degree detector subtended the scattering angles of 0°–2.80° in the laboratory. In total, 5.52×10^{6} ^{34}Al beam particles were detected in the zero-degree detector.

Photons were detected in coincidence with the zero-degree detector by the NSCL NaI(Tl) array [11]. The γ-ray spectrum measured in coincidence with beam particles identified as ^{34}Al in the zero-degree detector is shown in Fig. 1. The upper panel shows the background subtracted spectrum in the laboratory frame. The lower panel shows the corresponding spectrum in the projectile frame (that is, with a

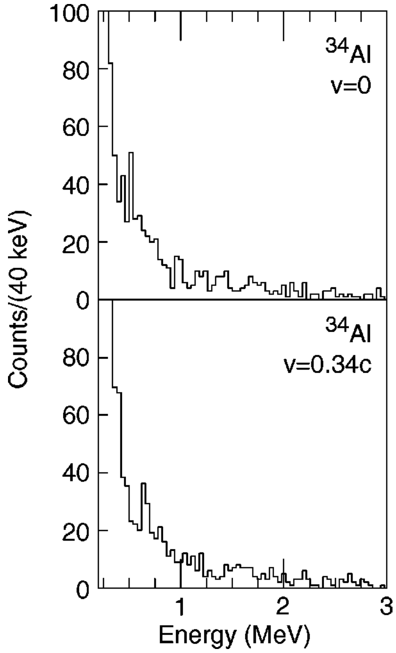

FIG. 1. Photon spectra in coincidence with ^{34}Al. The upper panel shows the spectrum measured in the laboratory and the lower panel shows the same spectrum in the projectile frame.

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[*] Present address: Plumtree Software, Inc., San Francisco, CA 94111.

[†] Present address: Brookhaven National Laboratory, Upton, NY 11973.

[‡] Present address: Max-Planck-Institut für Kernphysik, Postfach 10 39 80, D-69029 Heidelberg, Germany.

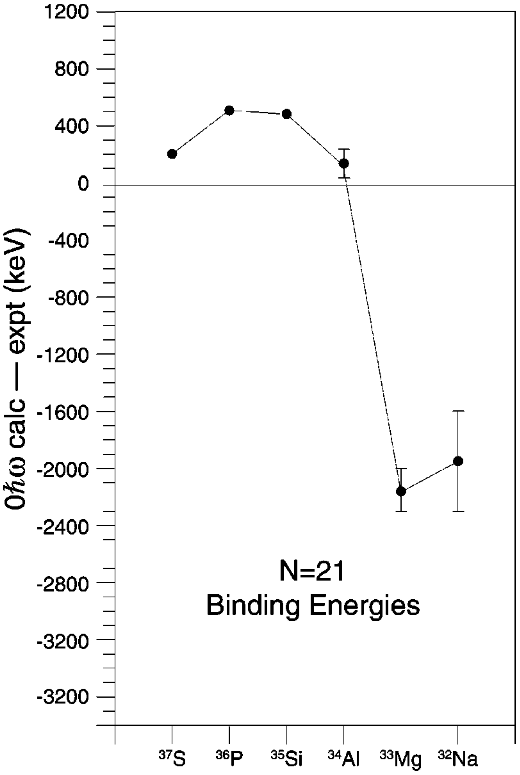

FIG. 2. Differences between binding energies calculated for ‘‘normal’’ $(0\hbar\omega)$ configurations in Ref. [8] and experimental binding energies [12,13] for the $N=21$ isotones.

Doppler correction). The 547 keV $7/2^+ \rightarrow 3/2^+_{\text{g.s.}}$ γ ray in the ^{197}Au target nucleus appears strongly in the laboratory-frame spectra. There is a single strong peak in the projectile-frame spectrum at 657 ± 9 keV. The cross section for producing this γ ray (with the projectile scattering angle integrated over the laboratory angular range of 0°–2.80°) is 24.2 ± 9.5 mb. The 657 keV γ ray reported here is the first ever observed for ^{34}Al. In fact, neither the spin nor parity of the ground state of ^{34}Al has been measured.

The binding energy of ^{34}Al can be reproduced with calculations that assume the ground state is composed of ‘‘normal’’ in-shell $(0\hbar\omega)$ excitations [8]; therefore, we can conclude that ^{34}Al is not a member of the island of inversion. A comparison of experimental binding energies [12,13] with calculations assuming normal excitations from Ref. [8] for the $N=21$ isotones is shown in Fig. 2. The nuclei that are overbound with respect to the calculations with normal configurations (^{33}Mg and ^{32}Na) are in the island of inversion; the figure makes the ‘‘boundary nucleus’’ status of ^{34}Al quite clear.

Given this conclusion, we may consider the normal ordering of shell-model orbits in this region where the unpaired proton is in the $d_{5/2}$ orbit and the unpaired neutron is in the $f_{7/2}$ orbit. The spectrum of low-lying negative-parity states (below 2 MeV) obtained in a model space with five protons in the sd shell, a filled sd shell for neutrons, and one neutron in the pf shell with the interaction used in [8] is $4^-_{\text{g.s.}}$ (ground state), 5^- (0.002 MeV), 3^-_1 (0.476 MeV), 2^-_1 (0.757 MeV), 3^-_2 (1.502 MeV), 4^- (1.769 MeV), and 2^-_2 (1.848 MeV). The lowest four states are dominated (about 80%) by the $d_{5/2}$-$f_{7/2}$ configuration (the 1^- and 2^- members of this multiplet have centroids around 3 MeV). Starting from spin 4^- or 5^- the calculated $E2$ excitation strengths are (with effective charge values of $e_p=1.35$ and $e_n=0.65$ used in Ref. [5]) $B(E2,4^-_{\text{g.s.}}\rightarrow 2^-_1)=5.3\,e^2$ fm^4, $B(E2,4^-_{\text{g.s.}}\rightarrow 3^-_1)=41.8\,e^2$ fm^4, and $B(E2,5^-\rightarrow 3^-_1)=5.6\,e^2$ fm^4. The second case $(4^-_{\text{g.s.}}\rightarrow 3^-_1)$ is closest to the experimental value of $B(E2)=100(39)\,e^2$ fm^4 obtained in the present experiment.

Using a weak-coupling model, Warburton, Becker, and Brown [8] predicted that the lowest-lying $1\hbar\omega$ (positive-parity) intruder state is in fact the ground state. Thus alternative interpretations of our result are for the $E1$ between the negative- and positive-parity states or by $E2$ excitation between positive-parity states. There is also the possibility that the state populated in the Coulomb excitation reaction is at an energy higher than 657 keV. In that case, the 657 keV γ ray would deexcite to another excited state, perhaps a member of the ground-state multiplet. The higher beam rates and more sensitive detector systems available at new radioactive beam facilities now becoming available will provide the opportunity to eliminate these ambiguities in future measurements.

To summarize, a γ ray with energy 657 ± 9 keV has been observed in the intermediate-energy Coulomb excitation of ^{34}Al and its production cross section has been measured. This γ ray may deexcite a low-lying intruder state, and its energy may correspond to the gap between normal and intruder configurations in this nucleus.

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