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Identification of the first excited state in the $N=Z$ nucleus $^{64}_{32}Ge_{32}$

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Gamma rays from ^{64}Ge have been investigated using the reaction $^{12}C(^{54}Fe,2n\gamma)^{64}Ge$ at 150 MeV beam energy. The first excited state was found to be 901.6 ± 0.5 keV. The observation of pure neutron evaporation from a very neutron deficient compound nucleus is potentially important for the prospect of observing heavier exotic self-conjugate systems.

$N=Z$ nuclei play an important role in the understanding of nuclear structure as shell effects occur simultaneously for both protons and neutrons and are clearly manifested in observables such as nuclear binding energies and shapes. Thus, for example, the $N=Z$ systems are a natural place to look for possible superdeformation.[1] However, the curvature of the valley of stability makes self-conjugate nuclei increasingly difficult to access as A increases. Our knowledge of $N=Z$ nuclei stops abruptly at ^{60}Zn, the last nucleus to be reached by two proton transfer on a stable target. In this paper we report an advance in this experimental field by a measurement of the energy of the first excited state in ^{64}Ge.

The closure of major shells result in extremely strong binding for spherical shapes. Partial filling of shells, and completion of subshells by protons and neutrons lead to a variety of shape-driving effects which can cause the most bound shape to be deformed. The driving influence of shell effects is very finely balanced as can be seen from the many different predictions of the shape of ^{64}Ge. The deformed harmonic oscillator does not predict a shell closure for $N=32$ at superdeformation but Sheline has reported calculations in which a more realistic potential is used and pairing effects are included.[1] These calculations employ the microscopic-macroscopic method of Strutinsky[2] and propose a superdeformed shell closure at deformation parameter $\varepsilon=0.6$ for this neutron or proton number. If this were the case, the energy of the first excited 2^+ state would be about 200 keV.[3] Later calculations which include the gamma degree of freedom[4] suggest a far less deformed nucleus with a triaxial shape and more recent calculations[5] show a spherical but soft nucleus. Other workers using similar techniques but different potentials[6] predicted ^{64}Ge to be mildly deformed ($\varepsilon=0.2$) with a small hexadecapole contribution ($\varepsilon_4=0.04$). Thus, experimental measurement of the shape is very important for testing these models. This can be done by using γ-ray spectroscopy of the low-lying states.

The evaporation code CASCADE[7] was used to investigate all possible projectile-target combinations and energies, and the reaction chosen was $^{12}C(^{54}Fe,2n)^{64}Ge$ at 150 MeV incident energy. The dominant channels for this reaction were expected to be the 2p channel leading to ^{64}Zn and the pn channel leading to ^{64}Ga. The 2n channel was expected to be about 0.2% of the total cross section. Thus, the optimum conditions for the observation of ^{64}Ge were extremely unfavorable as it lies far into the proton-rich side of β stability, where charged particle evaporation dominates. The use of charged particle anticoincidence allows suppression of these reaction channels, while a kinematically inverse reaction favors the detection of neutron evaporating channels.

Four Ge(Li) γ-ray detectors were positioned at 0°, $-55°$, and $\pm125°$ to the beam axis and as close as possible to the target with the neutron detectors approximately 60 cm downstream from the target. A silicon surface barrier detector was placed immediately behind the target. A beam of ^{54}Fe at 150 MeV from the Oxford Folded Tandem struck a target of 99.9% enriched ^{12}C of thickness 100 $\mu g/cm^2$ supported on a backing of approximately 16 mg/cm^2 natural iron. The backing was thick enough to stop the beam while letting evaporation protons and alpha particles pass through to the surface barrier detector. A total of about 14 000 000 events were collected. Neutrons were detected in a large liquid (NE213) scintillation counter located behind a lead wall 6 cm thick. The scintillator was in the form of a cylinder 30 cm in radius and 16 cm thick with a hole of 5 cm radius at the center. It was divided into four independent sectors each of which was viewed by two XP1040 phototubes. A fast coincidence (20 ns) was required between the two phototubes to reduce the effects of tube noise. The central hole was filled by a smaller cylindrical liquid scintillator. The neutron events were identified by the time of flight [with respect to the Ge(Li) signals] and by pulse shape discrimination circuits.[8] Data for events in which one (or more) neutron detector fired, in slow coincidence (400 ns) with one (or more) γ-ray detector, were recorded on magnetic tape. For each event, the information stored included the γ-ray energy, the neutron pulse height, time of flight and pulse shape information for each counter, and a bit pattern which indicated if a charged particle had been observed in slow coincidence with any γ ray.

Previous searches for ^{64}Ge also used this reaction but with the conventional arrangement of light beam on a heavy target, and without a charged particle veto.[9] There are two main advantages with the present approach. First, the background is much lower because, with a carbon projectile, many of the intense γ rays come from reactions on light impurities (especially carbon) in the target. Second, the neutron detection efficiency is much higher. This occurs both because the neutrons are kinematically focused into the forward detector and because their energy is raised to a few MeV, where the detection and pulse shape discrimination are much easier.

The singles γ-ray spectrum is found to be dominated by lines from the 2p channel leading to ^{64}Zn. By applying neutron coincidence, these lines disappear to leave a spectrum dominated by ^{64}Ga, the pn channel. The intensities of the 991 keV line from ^{64}Zn in the neutron gated spectrum and singles spectrum indicate that the breakthrough of non-neutron events is at the 1% level. Figure 1(b) and 1(a) show the spectra obtained by gating on neutrons with and without charged particles, respectively. The near equivalence of these two spectra indicate a charged particle detection efficiency of ~50% while the intensities of the lines from ^{64}Ga in both the singles as well as the neutron-gated spectra yield a neutron detection efficiency of ~10%.

In order to remove the pn lines, the difference between the 1n0p and 1n1p spectra, normalized to the 367 keV line from ^{64}Ga, is taken [see Fig. 1(c)]. The peak at 128 keV, from ^{64}Ga, is the result of poor timing for low energy γ rays and so only one γ ray, at 902 keV, remains. Peaks marked with * are known to come from the 2pn channel leading to ^{63}Zn and are oversubtracted due to the higher charged particle detection probability.

When the 2n spectra are examined [Figs. 1(d) and 1(e)], they are found to be dominated by lines from ^{64}Ga which must arise from single neutrons being recorded twice. Here, the 902 keV line is enhanced with respect to the ^{64}Ga lines by a factor of about 4 and again, when the difference between the proton [Fig. 1(e)] and no proton [Fig. 1(d)] data are examined, the 902 keV line is the only strong γ line [Fig. 1(f)]. We thus conclude that the 902 keV line must come from the 2n channel as it is the only line which satisfies 2n0p requirements. To minimize the effects of neutrons scattering from one detector to another, events in which neutrons were identified in nonadjacent sectors of the main neutron detector were sorted and this

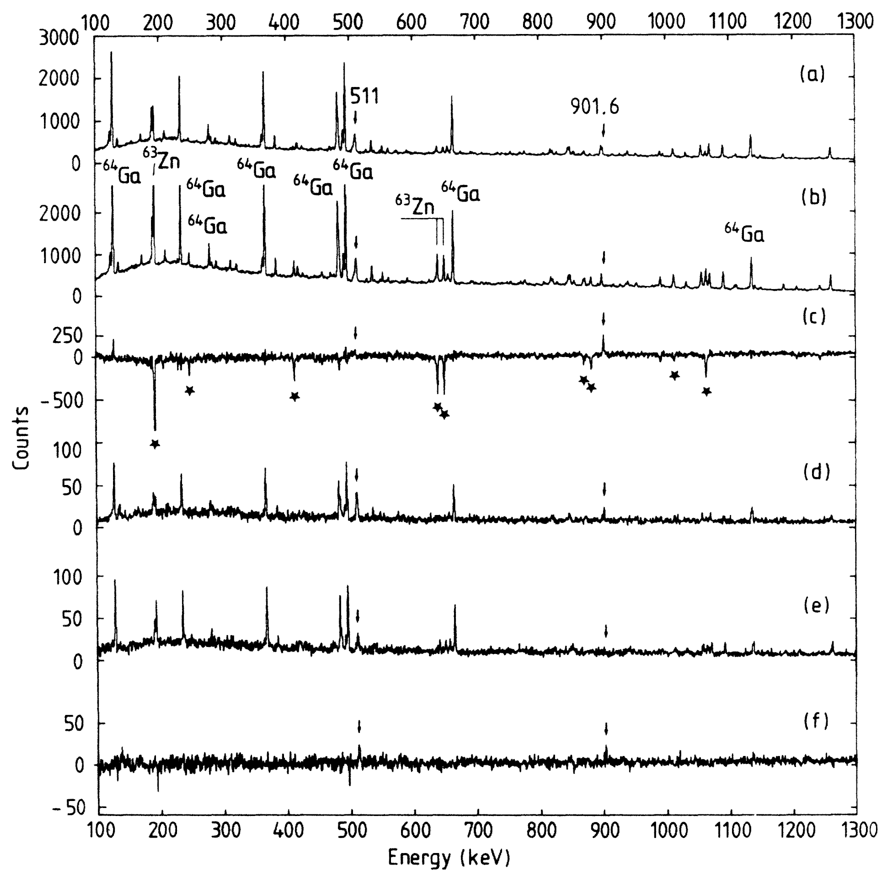

FIG. 1. Neutron gated γ-ray spectra. The coincidence requirements are as follows: (a) 1n0p, (b) 1n1p, (d) 2n0p, and (e) 2n1p. Spectrum (c) is the difference between (a) and (b) normalized to the 367 keV (^{64}Ga) line and, similarly, (f) is the difference between (d) and (e). The positions of the 511 keV annihilation γ ray and 901.6 keV line from ^{64}Ge are indicated with arrows. The stars * show the peaks from the 2pn channel due to oversubtraction.

was found to enhance the 902 keV line but in a spectrum of poorer statistical quality.

There is no evidence for another comparable γ-ray peak for energies above 0.1 MeV and up to 2.5 MeV which strongly suggests that this is the main ground state transition from the first excited state. Furthermore, this energy is consistent with the systematics of the first excited 2^+ states of the Ge isotopes. We thus conclude that the first excited state (presumably 2^+ in spin and parity) of ^{64}Ge is at an energy of 902 keV.

We can gain further confidence in the assignment of the γ ray to ^{64}Ge by noting that its intensity is what we would expect from the intensities of the ^{64}Ge beta decay γ rays. To measure this intensity we used a pulsed beam (60 s on, 120 s off) of ^{12}C ions at 35 MeV on an ^{54}Fe target and, during the beam off time, measured the intensity of γ rays at 427 and 991 keV from the decay of ^{64}Ge and ^{64}Ga, respectively. The cross sections for several evaporation channels determined by the radioactivity and in-beam γ rays and predicted by evaporation calculations, are listed in Table I. The 427 keV line lies on a large Compton background from the neighboring 511 keV annihilation line and this is reflected in the large error obtained for the β-decay cross section. The data for the in-beam cross sections are taken from a Ge(Li) detector at $\sim 55°$ (to the beam axis), where the angular distribution effect is minimized. The evaporation calculation was executed for the in-beam reaction energy[10] and it can be seen that the gross variation in the cross section is reasonably predicted by the code.

^{64}Ge is, to date, the heaviest $N=Z$ nucleus to be studied in beam. It is not surprising that previous searches for this nucleus have not been successful. In our case, the 902 keV line would only be 25% of the intensity of the nearby 899 keV line from ^{64}Ga if we did not have the charged particle veto. In addition, when using a carbon beam there is a strong contaminant line from ^{22}Na at 891 keV. This energy for the first excited 2^+ state yields[3] $\varepsilon \simeq 0.28$ which suggests that the extreme model of superdeformation can be ruled out.

TABLE I. Cross sections for two evaporation channels from the ^{54}Fe+^{12}C reaction, as determined by the radioactivity and in-beam γ rays and predicted by the evaporation code CASCADE. The experimental cross sections are normalized to the CASCADE pn cross section.

Product nucleus	Output channel	Cross section (mb) CASCADE	In beam	β decay
^{64}Ga	pn	79	79	79
^{64}Ge	2n	0.8	0.5(2)	0.3(1)

In conclusion, we have demonstrated the feasibility of using particle-γ coincidence techniques for studying the γ-ray spectra of nuclei produced in reactions with cross sections less than 1 mb. This should allow new regions of the periodic table, closer to the proton drip line, to be studied.

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[10]There is 2 MeV more in energy brought into the compound nucleus by the β-decay experiment but the variation in the CASCADE cross section for the two experiments is no more than 15% for the two-particle channels.