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# Shape changes in $N=Z$ nuclei from germanium to zirconium

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The first experimental results are reported on excited states in the $N=Z$ nuclei $^{68}$Se and $^{76}$Sr. These data, combined with recent results on germanium, krypton, and zirconium show the importance of deformed shell gaps in stabilizing nuclear shapes in this region, initially polarizing towards oblate then towards prolate shapes with increasing mass. The results present direct tests of a variety of nuclear models, and a clearer picture of the structure of the region now emerges.

The observation of high spin superdeformation in nuclei near $^{152}$Dy and $^{132}$Ce (Refs. 1 and 2) has focused considerable attention on the influence of gaps in the deformed single particle level sequence in polarizing nuclei to exotic shapes. In this paper we present data showing polarization effects at low spin which are caused by similar deformed shell gaps. The nuclei we have studied have mass 64–80 and have $N=Z$, as it is in these nuclides that the quantum polarization effects are predicted to be especially large due to shell effects. The shell effects occur simultaneously for both protons and neutrons and may be enhanced by strong residual proton-neutron correlations.[3] Small changes in the Fermi surface are predicted to cause rapid changes in the nuclear shape which is most stable. Consequently, an experimental determination of the shapes of these nuclei presents a sensitive and direct test of calculations predicting their underlying microscopic shell structure. The calculations discussed later in this paper predict oblate shapes in the lighter isotopes in this sequence and highly deformed prolate shapes for the heavier isotopes.

In this paper we present data on $N=Z$ germanium, selenium, and strontium isotopes which, when taken with recent results on krypton and zirconium,[4] complete a series of measurements extending from $N=Z=32$ to $N=Z=40$. The transitions in $^{64}$Ge reported previously[5,6] have been confirmed and more than 30 new decays rigorously assigned. No transitions had been reported in the other nuclei. We have made recoil-$\gamma$-$\gamma$ coincidence measurements on $^{64}$Ge and identified transitions in the other nuclei.[4] Our measurements are complementary to other recently reported studies on $N=Z+1$ neighboring odd-$A$ nuclei[5,7] which can be produced more strongly.

Experimental access to $N=Z$ nuclei is difficult. The fusion of stable nuclides to form the lightest pos le compound nucleus requires further neutron evaporation to reach the $N=Z$ line. This process is extremely unlikely as proton separation energies are small ($\leq 5$ MeV) compared to that of neutrons ($\sim 15$ MeV); consequently charged particle evaporation dominates. However, as the evaporation process is statistical, a small fraction ($10^{-4}$–$10^{-5}$) of exotic nuclei are produced. A study of these nuclei requires a reliable method of channel selection, which was achieved in this work by the Daresbury Recoil Separator.[8] The use of inverse reactions with heavy beams efficiently focused the reaction products into the separator. For the two-neutron evaporation channels used in this study, more than 70% of the recoils entered the separator. However, only one charge state could be selected, which reduced the separator efficiency to 10–20%. The high recoil velocities were crucial for determining the $Z$ resolution in the ionization chamber used to detect recoil products. Beam energies were selected by measuring the yields of strongly produced nuclides. Standard techniques of $\gamma$-ray spectroscopy were used to extract structural information.

$^{64}$Ge was produced in the $^{12}$C($^{54}$Fe,$2n$)$^{64}$Ge reaction at 165 MeV using a 450 $\mu$g/cm$^2$ $^{12}$C target and iron beams of up to 10 pnA from the NSF tandem accelerator at Daresbury. The recoil separator was operated in coincidence with any array of twenty detectors viewing the target position, mounted in rings of five counters at 143°, 117°, 101°, and 40° to the beam direction. In this study the detectors were all BGO shielded hyperpure germanium detectors. The separator was set to accept ions in the velocity range $6.3 \pm 0.2\%$ of $c$. Recoil ions were detected at the focal plane of the separator and stopped in a three electrode ionization chamber. The transport efficiency of the separator was measured for the strongly produced $^{64}$Zn and $^{64}$Ga ions by comparing photopeak intensities in recoil-$\gamma$ and singles spectra. In this study the efficiencies were measured to be $7.5 \pm 0.2\%$ and $14 \pm 1\%$, respectively. $^{64}$Ge was too weakly produced to allow a direct efficiency measurement, but it was predicted to be transported with an efficiency of 20%, determined entirely by the fraction of ions in the selected charge state, $q = 23^+$.

$^{68}$Se was produced in the $^{12}$C($^{58}$Ni,2$n$)$^{68}$Se reaction at a bombarding energy of 175 MeV. This experiment was performed with ten shielded germanium detectors and ten NE213 neutron detectors in the downstream rings. Recoil ions were detected in an ionization chamber with two electrodes. The recoil velocity was $6.5 \pm 0.2\%$ of $c$, which provided the best $Z$ resolution obtained in these studies. $^{76}$Sr was produced in the $^{24}$Mg($^{54}$Fe,2$n$)$^{76}$Sr reaction using an enriched $^{24}$Mg target of thickness 550 $\mu$g/cm$^2$ and an experimental arrangement similar to the $^{68}$Se study. In this experiment the recoil velocity was $5.40 \pm 0.2\%$ of $c$, which resulted in markedly poorer $Z$ resolution. During these experiments, the mass resolution was measured to be better than one part in 200 full width half maximum and the $Z$ resolution between one part in 35 and one part in 48 depending on the reaction.

The recoil-$\gamma$ coincidence data were sorted into a series of time random subtracted, mass selected, $\gamma$-ray spectra gated with increasing energy loss $\Delta E$ in the ionization chamber. The time-random subtraction was less than 10% in all cases. Figure 1 shows the intensity of prominent $\gamma$ rays as a function of energy loss for $A = 64$ [Fig. 1(a)], $A = 68$ [Fig. 1(b)], and $A = 76$ [Fig. 1(c)]. The reduction of $Z$ separation for the $A = 76$ study is evident. The high energy loss tails in Fig. 1 are due to pulse pileup and to recoils scattering from carbon ions in the isobutane. These tails have been reduced in size by hardware pileup rejection and, for the $A = 64$ study, suitable filtering of data from the three electrode ion chamber. The data shown in Fig. 1 can be converted into relative cross sections for two nucleon emission after correcting for $\gamma$-ray detection efficiency and recoil separator efficiency. The two-proton and proton-neutron evaporation channels were measured directly, but computer simulation was used to predict the separator efficiency for detection of two-neutron evaporation products. The relative cross sections were then put on an absolute footing by further measurements of the production rate of the stronger reaction channels. These experiments were performed in a separate study at Brookhaven National Laboratory. The computer codes CASCADE and PACE predict a smooth reduction in cross section for all two-nucleon evaporation channels with increasing mass, due to the increased Coulomb barrier in the entrance channel. In addition, a steady rise in neutron separation energy and fall in proton separation energy with mass causes further suppression of two-neutron evaporation. Table I shows that the predicted trend is followed experimentally, with the exception of $^{68}$Se which is observed about five times more weakly than anticipated.

A $\gamma$-ray spectrum can be created for each of the isotopes of interest by filtering on the energy loss and the mass of the ions, and by subtracting spectra associated with the more strongly produced nuclides. The results from these procedures is shown in Fig. 2 for $^{64}$Ge, $^{68}$Se, and $^{76}$Sr. The $^{64}$Ge study, which was performed most recently and had the largest cross section, is statistically superior and shows the quality of channel selection which can be achieved using this technique. Enough data were

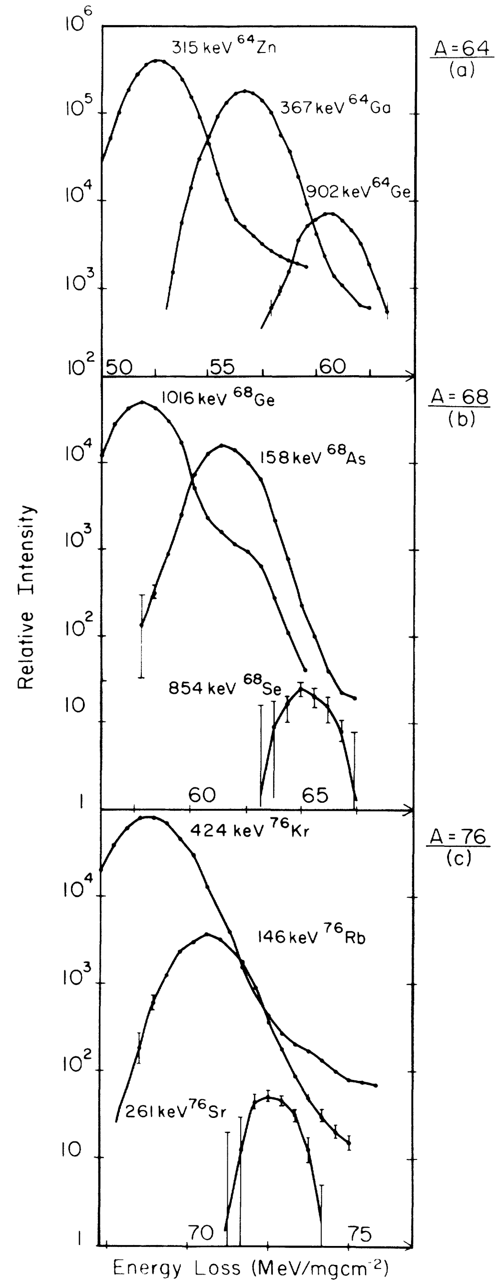


FIG. 1. The intensity of prominent photopeaks measured in $\gamma$ ray spectra which were in coincidence with (a) $A = 64$, (b) $A = 68$, and (c) $A = 76$ recoil nuclei and gated by increasing energy loss $\Delta E$ under the first electrode of the ionization chamber.

collected to permit detailed spectroscopy, and full analysis is in progress. For the purposes of this paper, we note that the high excitation energy of the previously reported[5,6] first excited state at 902 keV is not indicative of any substantial quadrupole collective deformation. Calculations[9] indicate $\beta_2 < 0.2$ and that octupole correlations are important in this nucleus at intermediate spin. For the rest of this paper, we will concentrate on the new results for $^{68}$Se and $^{76}$Sr and their implications for the structure of $N = Z$ nuclei in this region.

Shape coexistence between slightly oblate and very pro-

TABLE I. A list of the reactions used to produce $N=Z$ nuclei in this study, the observed first excited states and the production cross sections at the beam energy used. Data for $^{72}$Kr and $^{80}$Zr are from Ref. 4.

| Isotope | Reaction | $E_{\mathrm{beam}}$ (MeV) | $E(2^+)$ (keV) | $\sigma_{\mathrm{prod}}$ ($\mu$b) |
|---|---|---|---|---|
| $^{64}_{32}$Ge$_{32}$ | $^{12}$C($^{54}$Fe,2$n$)$^{64}$Ge | 165 | 902 | 500±300 |
| $^{68}_{34}$Se$_{34}$ | $^{12}$C($^{58}$Ni,2$n$)$^{68}$Se | 175 | 854 | 38±16 |
| $^{72}_{36}$Kr$_{36}$ | $^{16}$O($^{58}$Ni,2$n$)$^{72}$Kr | 170 | 709 | 60±25 |
| $^{76}_{38}$Sr$_{38}$ | $^{24}$Mg($^{54}$Fe,2$n$)$^{76}$Sr | 175 | 261 | 10±5 |
| $^{80}_{40}$Zr$_{40}$ | $^{24}$Mg($^{58}$Ni,2$n$)$^{80}$Zr | 190 | 290 | 10±5 |

late shapes has been known[10] for some time in $^{70,72}$Se and the data have recently been significantly extended.[11,12] The shape competition in these nuclei has been explained as arising from the oblate polarizing influence of a shell gap at nucleon number 34 and the strong prolate driving influence of the nucleon number 38 gap. Calculations[9,13] of nuclear potential energy surfaces for selenium isotopes indicate that the oblate minimum should increase in deformation and binding energy until it becomes the ground state configuration in $^{68}$Se, where both protons and neutrons favor an oblate shape with a deformation of $\beta_2=-0.27$. Oblate nuclear ground states are almost unknown in nuclei, so a verification of this prediction is of some importance. Recent studies[7] of $^{69}$Se have found evidence for an oblate band with a negative quadrupole moment based on a $J^\pi=\frac{9}{2}^+$ state. The final spectrum from our experiment on $^{68}$Se is shown in Fig. 2(b). Although the statistics are poor, several features are clear. The strongest transition is at 853.9±0.3 keV and is a candidate for the $2^+\rightarrow 0^+$ decay. A $T_{1/2}=37$ ns isomer is populated[14] in 20% of the $^{68}$As nuclei formed in this reaction. The isomer decays by several $\gamma$ rays, including one at 854 keV. Considerable attention was paid to the separation of arsenic and selenium recoils. The recoil of nuclei from the target and away from the $\gamma$-ray detectors reduced the efficiency for delayed arsenic radiation by an estimated factor of 97.6%, and the further excellent $Z$ separation in the ion chamber allowed a clear identification of the 854 keV transition as also being associated with $^{68}$Se [Fig. 1(b)]. Although an 854 keV first excited state is similar in energy to neighboring $^{70,72}$Se (945 and 862 keV, respectively), it is not the energy one would associate with simple collective rotation of a rigid oblate ellipsoid with $\beta_2=-0.27$. A calculation of the geometrical moment of inertia with an approximate correction for pairing would indicate a much lower first excited state nearer 425 keV. It would appear that the shape mixing observed in $^{70,72}$Se persists in $^{68}$Se. However, in $^{70,72}$Se the shape changes and particle alignment result in a strong $4^+\rightarrow 2^+$ decay at a slightly lower energy than the $2^+\rightarrow 0^+$. This does not appear to be the case for $^{68}$Se, where there is evidence of weaker transitions at higher energies which may indicate more stability of shape. Clearly, more data are needed to clarify this question.

In the $^{76}$Sr experiment, the identification of the 260.9±0.2 keV first excited state was particularly straightforward as no other $\gamma$ rays near this energy were

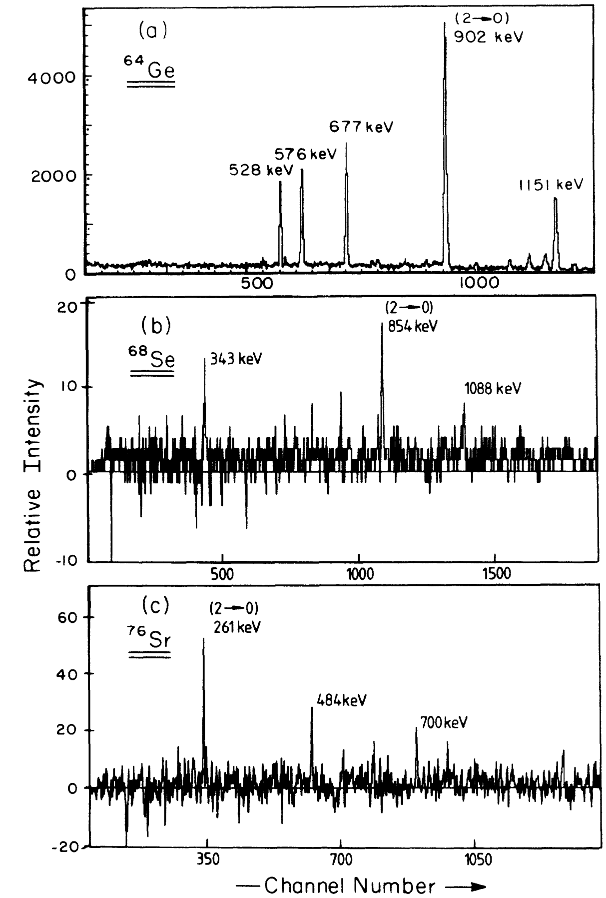


FIG. 2. The spectra of $\gamma$ rays associated with (a) $^{64}_{32}$Ge, (b) $^{68}_{34}$Se, and (c) $^{76}_{38}$Sr produced in the reactions listed in Table I.

produced in the fusion of $^{54}$Fe and $^{24}$Mg. A spectrum of transitions in $^{76}$Sr was obtained by selecting the optimum coincident time and energy loss windows to produce a strontium spectra, and subtracting known transitions from $^{76}$Kr and $^{76}$Rb. The results are shown in Fig. 2(c). It should be noted parenthetically that $^{76}$Sr was also produced in the $^{40}$Ca($^{40}$Ca,2$p$2$n$)$^{76}$Sr reaction at 135 MeV using a rolled, natural calcium target and the techniques described in Ref. 15. A two-neutron gated $\gamma$ ray spectrum clearly showed the 261, 484, and 700 keV transitions which provided a useful confirmation of these assignments through cross bombardment. The regularly spaced sequence of transitions of $^{76}$Sr are quite different from the lighter $N=Z$ nuclei $^{72}$Kr and $^{68}$Se, and indicate a drastic change in structure. The strongest transition at 261 keV continues a smooth trend in light strontium isotopes, with the first excited state decreasing in energy as $N$ approaches 38. Lifetime measurements[16] of the first excited states of $^{78-88}$Sr indicate a transition from sphericity at $N=50$ to extremely large prolate deformation at $N=40$. Laser spectroscopy[17] of nuclear ground states support these results. A correlation can be made between quadrupole moments calculated from the lifetimes and the deformation estimated from the excitation energy of the first excited states. The low first excited state in $^{76}$Sr indicated quadrupole deformation of $\beta_2>0.4$. Despite the unusually large deformation, the nucleus does not appear to be an axial rotor, for which the ratio of second to first excited states should be 3.33. Instead, the observed transitions have a ratio of 2.85 which indicates triaxiality or softness in the triaxial degree of freedom.

The center of the $A\sim80$ region, that is nuclei with $N,Z=38,40$ has been of great theoretical interest recently, as the shape of these nuclei is delicately controlled by occupancy and position of levels near the Fermi surface.[18] Many types of calculation have been performed including fully microscopic Hartree-Fock,[19–21] macroscopic-microscopic calculations with Yukawa,[22] Woods-Saxon[9,13] and various Nilsson[18,23] potentials, and interacting-boson approximation (IBA) (Ref. 24) models. Our measurements are discriminating in three respects. First they establish ${}^{76}_{38}Sr_{38}$ to be the most deformed nucleus in the region with $\beta_2>0.4$. Second, the ratio of second to first excited states of $R=2.85$ is very similar to neighboring ${}^{78}_{38}Sr_{40}$ ($R=2.81$) and ${}^{80}_{40}Zr_{40}$ ($R=2.86$) indicating that none of these nuclei are good axial rotors. Finally, they establish a drastic structural change between $N=Z=36$ and $N=Z=38$. Each of these observations provides a stringent test of these models. For example, several calculations[9,13,22] indicate the same deformation for all $N,Z=38,40$ systems. Further, microscopic calculations indicate that $^{76}$Sr should have a higher saddle[20] between prolate and oblate shapes, with a deeper potential minimum for symmetric shapes, and thus be a better axial rotor than its neighbors. Neither appear to be the case. The similarity of $N,Z=38,40$ nuclei agrees well with IBA calculations and the *P* scheme[25] of Casten *et al.*, but these models do not account for the abrupt structure change between $^{72}$Kr and $^{76}$Sr.

In conclusion, we have studied excited states of $N=Z$ nuclei from germanium to zirconium. The cross section for producing these nuclei was expected to decrease smoothly with increasing compound nuclear mass, but appears to be anomalously low for $^{68}$Se. States in $^{68}$Se have been observed but do not appear consistent with the predicted large oblate deformation. A sudden increase in deformation occurs between $^{72}$Kr and $^{76}$Sr as the $N=38$ deformed shell gap polarizes nuclei to prolate shapes with $\beta_2>0.4$.

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