First observation of ^{59}Ge

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First observation of ^{59}Ge

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In an experiment at the A1900 spectrometer of the National Superconducting Cyclotron Laboratory at Michigan State University the new isotope ^{59}Ge was identified and the cross section for production of the most neutron-deficient $^{59-62}$Ge isotopes in the fragmentation of a ^{78}Kr beam at 150 MeV/nucleon measured. This experimental information is relevant for the hunt of new two-proton emitters in the region above the doubly-magic ^{48}Ni.

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Introduction — Investigation of atomic nuclei located beyond the proton drip-line remains one of the frontiers in contemporary low-energy nuclear physics. Systems with strongly disturbed equilibrium between the numbers of neutrons and protons, at the limits of nuclear binding, represent an ideal testing ground for models of nuclear forces and nuclear structure. On the other hand, the interplay of the Coulomb barrier, low proton separation energies, and large β-decay Q values results in a variety of interesting phenomena specific to this region and providing new methods of experimental inquiry, not available for nuclei closer to stability [1–3]. In addition, good knowledge of nuclear properties along the proton drip-line is required for the understanding of the astrophysical *rp*-process [4].

One of the characteristic features of extremely neutron deficient nuclei is spontaneous emission of proton(s) from the ground state. While the single-proton radioactivity is a very well known process, which in the last decades provided a wealth of spectroscopic information for more than 30 nuclei, our knowledge about simultaneous emission of two protons (2p) is still scarce [2]. This decay mode, however, is predicted to be observable in almost all even-Z elements up to tellurium [5]. In the middle-mass region only three cases of 2p radioactivity have been identified: ^{45}Fe, ^{48}Ni, and ^{54}Zn [2]. The next heavier element to search for the 2p emission is germanium ($Z = 32$). A state-of-the-art prediction of proton separation energies in this region, employing Hartree-Fock calculations of the Coulomb displacement energies in combination with experimental masses of neutron-rich partners of isospin multiplets, identified ^{59}Ge as a possible candidate for 2p radioactivity [6].

A detailed study of proton-proton correlations in the 2p decay of ^{45}Fe suggested a link between the configuration of the initial state and the observed decay pattern [7, 8]. It is expected that similar studies for ^{48}Ni and ^{54}Zn may reveal the effects of the crossing of the $Z = 28$ proton shell. In this context very neutron-deficient germanium isotopes are interesting because of the closed neutron shell, $N = 28$, in ^{60}Ge. The comparison of nuclei around ^{48}Ni and ^{60}Ge may shed light on shell structure and proton correlation effects in this region.

The most neutron-deficient germanium isotope observed to date is ^{60}Ge. It was discovered in 2005 at the NSCL/MSU facility by Stolz et al. [9] among the products of the fragmentation reaction of a ^{78}Kr beam at 140 MeV/nucleon on a beryllium target. Three ions of ^{60}Ge were identified in-flight by recording the time-of-flight and the energy-loss (ToF-ΔE) of selected reaction products. The measured production cross-section of $0.38^{+0.27}_{-0.31}$ pb was found to be smaller than expected from systematics by a factor of about three [9]. Such an observation could be explained by a very short half-life, of the order of microseconds, which would indicate 2p radioactivity. However, no decay information for ^{60}Ge events was obtained. Later, in an experiment performed at GANIL, four ions of ^{60}Ge were identified in-flight following the fragmentation of a ^{70}Ge beam on a natural nickel target at 72 MeV/nucleon [10]. Again, no decay data were collected but the production cross section for ^{60}Ge was found to be ten times larger than the value obtained in Ref. [9] and consistent with the trend defined by the heavier germanium isotopes. This discrepancy in the cross section values for ^{60}Ge was attributed to the different projectile-target combinations in the two experiments. It was suggested that for the most exotic nuclei a nickel target may be a better choice than the beryllium [10].

We have undertaken an experimental attempt to ex-

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tend the knowledge on the most neutron-deficient germanium isotopes and to verify suppositions concerning their production in the fragmentation reaction. In this Rapid Communication we report on the first observation of ^{59}Ge and on the measured production cross sections for the series of germanium isotopes $^{59-62}$Ge. A complete account of this experiment, including the results of the decay spectroscopy, will be given in a forthcoming paper.

Experimental technique — The experiment was performed at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The very neutron-deficient germanium isotopes were produced in projectile fragmentation of ^{78}Kr^{34+} ions at 150 MeV/nucleon on a 200 mg/cm^2 beryllium target. The beam current over the whole experiment amounted to an average of 35 particle nA. The ions of interest were separated from the remaining reaction products according to their momentum over charge ratio by means of the A1900 spectrometer [11] and stopped in the detection set-up described below, which was placed in the experimental S2 vault at the end of a transmission line. The rigidity setting of the A1900 was optimised individually for each of the isotopes of interest, i.e. $^{59-62}$Ge. Two achromatic aluminium degraders were installed at the intermediate focal plane. A thickness of 353 mg/cm^2 was used for the most exotic ^{59}Ge setting and of 384 mg/cm^2 for $^{60-62}$Ge. For each fragment, energy loss (ΔE) in a silicon detector in front of the detection set-up was recorded. In addition, the time-of-flight (ToF) between a scintillator (FPSC) at the focal plane of the spectrometer (FP) and a scintillator (RFSC) positioned downstream from it (ToF1), and ToF between the FPSC and the ΔE detectors (ToF2), were measured by means of time-to-amplitude converters (TAC). A schematic representation of the experiment configuration is shown in Figure 1. At the end of the transmission line, the Warsaw Optical Time Projection

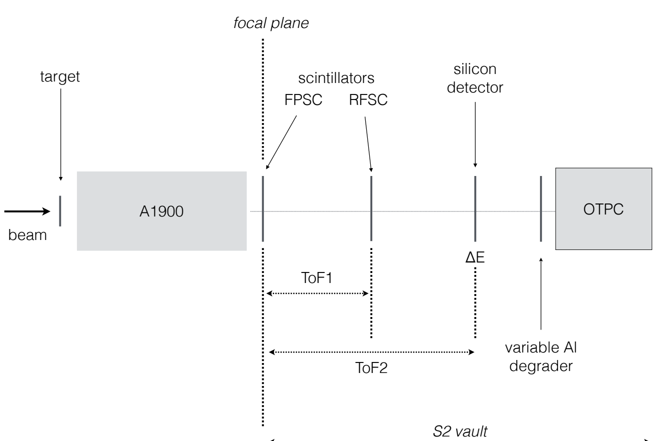

FIG. 1. Schematic diagram of the experiment configuration. Drawing not to scale. See text for details.

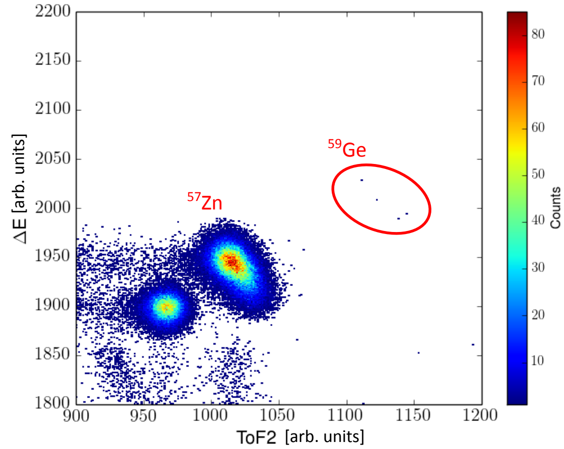

FIG. 2. (Color online) Identification plot for the ion-optics setting of the A1900 optimised for ^{59}Ge. See text for details.

Chamber (OTPC) [12] was placed in order to perform particle spectroscopy of the germanium isotopes. Results on the decay spectroscopy will be reported elsewhere.

The signals used for identification of the incoming ions were processed through two independent digital data acquisition systems. The first (trigger-less) data acquisition system (DAQ1) was based on PIXIE16 modules [13] and recorded ΔE, ToF1 and ToF2 for all ions reaching the silicon ΔE detector. A trigger was generated based on hardware gates imposed on ΔE and ToF1 to isolate only germanium ions and a limited amount of contaminants. This trigger was used in the second acquisition system (DAQ2) which was recording all the OTPC data and the waveforms of the ΔE and ToF1 signals, providing identification redundancy. After a trigger was generated, the beam was switched off for 100 ms in order to prevent additional ions from entering the system while waiting for the decay of the implanted ion. All events were time stamped and synchronicity between the two DAQ was verified.

Results and discussion — In order to firmly assign the identified events to the respective neutron-deficient germanium isotope, the event had to be identified correctly by both ΔE-ToF1 and ΔE-ToF2. In Figure 2, we display the identification plot ΔE-ToF2 for the A1900 setting optimised for ^{59}Ge, gated on the triggering ions. Four events can be identified as ^{59}Ge on the basis of their position in the plot, taking also into account the “hole” corresponding to the unbound isotope ^{58}Ga. It is important to note that no ^{59}Ge event was missed by the trigger. For the four ^{59}Ge events, in order to avoid misidentification due, e.g., to pileup of ΔE signals from lighter contaminant ions, we inspected the waveforms of the ΔE and ToF signals registered by DAQ2. Three of them are displayed in Figure 3, while the fourth one happened while DAQ2 was changing files and was therefore not recorded. As can be seen in Figure 3, the signals have

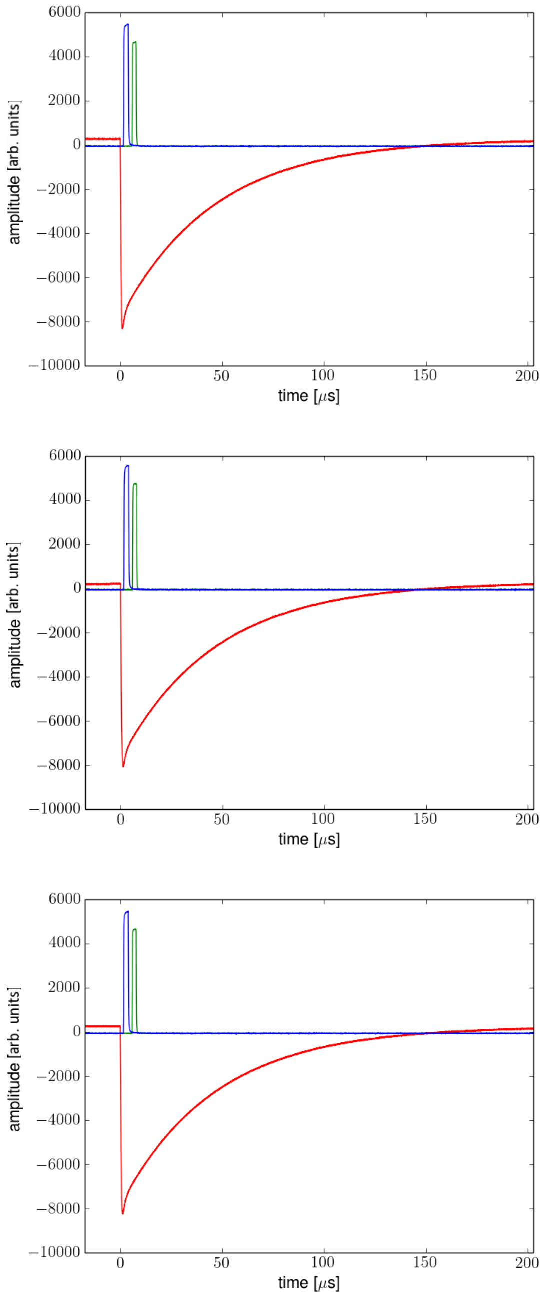

FIG. 3. (Coulor online) Waveforms of the signals giving the ΔE (red, negative), ToF1 (blue, positive, left) and ToF2 (green, positive, right) ion-identification information for the three events of ^{59}Ge acquired by DAQ2 oscilloscope. See text for details.

the shape expected for detection of a single-ion. In particular, the silicon detector ΔE signal does not show any sign of pileup. We therefore firmly assign the observed events to the new isotope ^{59}Ge.

From the number of ions in the ΔE versus ToF identification plot, the production cross-section σ could be determined according to the formula:

$$\sigma = \frac{N_{\mathrm{Ge}}}{N_{\mathrm{Beam}}} \frac{\mu}{d\, N_A} \frac{1}{T_1} \frac{1}{T_2}, \tag{1}$$

where N_{Ge} is the number of observed germanium ions, N_{Beam} is the number of beam particles impinging on the target over the whole run, μ is the atomic weight of the target, d the areal target thickness, N_A the Avogadro number, T_1 and T_2 the transmission from the target to the FP and from the FP to the ΔE detector, respectively. The number of impinging ions was determined from a Faraday cup, which periodically read the unreacted beam throughout the whole experiment. A correction to account for the beam-off time following each trigger was implemented in the calculation. The transmission T_1 was determined by means of the LISE++ ion-optics simulations [14], using the target and degrader thicknesses as measured with beam. T_2 was determined by the ratio of particle rates observed at FP and ΔE detector, see Table I. The number of ions identified for each of the germanium isotopes investigated are summarised in Table I. The cross section for production of the most neutron-deficient germanium isotopes could therefore be calculated by means of equation 1. The results are shown in Figure 4 and Table I in comparison with literature from a previous experiment at the A1900 and predictions from the EPAX3 parametrisation [15].

Our values for the production cross-sections of germanium isotopes show a smooth trend as a function of mass. In particular, there is no apparent kink at mass 60, which would indicate in-flight losses of ^{60}Ge. Our value for this

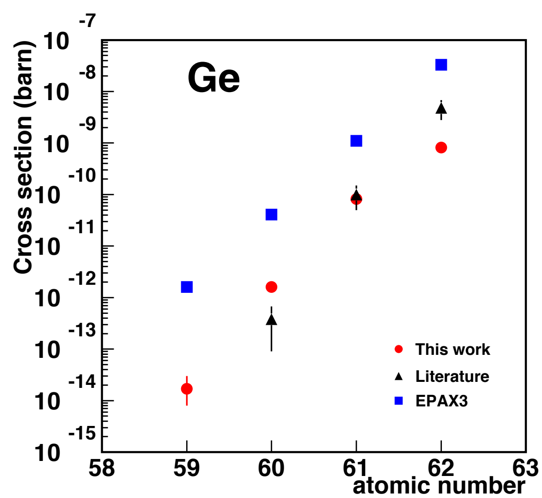

FIG. 4. (Color online) Cross section for the production of the neutron-deficient germanium isotopes in the fragmentation of a ^{78}Kr beam on a beryllium target. The data from this work (red dots) are compared to literature data from the previous A1900 experiment [9] (black triangles) and EPAX3 calculations [15] (blue squares). Only statistical uncertainties are shown for the data from this work.

TABLE I. For each of the germanium isotopes investigated, the number of observed ions, the number of beam ions (N_{Beam}), the two transmissions T_1 and T_2 and the cross sections from this work (σ_{exp}), from literature [9] (σ_{lit}) and from EPAX3 parametrisation [15] (σ_{epax}) are given. See text for details.

Setting	No. of Ions	N_{Beam}	T_1	T_2	σ_{exp} [barn]	σ_{lit} [barn]	σ_{EXPAX3} [barn]
^{59}Ge	4	1.1×10^{17}	24(5)%	70(10)%	$(17^{+13}_{-9}{}_{(stat)}\pm5_{(syst)})\times10^{-15}$	—	1.6×10^{-12}
^{60}Ge	73	2.3×10^{16}	24(5)%	60(10)%	$(1.6\pm0.2_{(stat)}\pm0.5_{(syst)})\times10^{-12}$	$(0.38^{+0.27}_{-0.31})\times10^{-12}$	41×10^{-12}
^{61}Ge	1230	6.2×10^{15}	26(5)%	70(10)%	$(8.2\pm0.2_{(stat)}\pm2.0_{(syst)})\times10^{-11}$	$10(5)\times10^{-11}$	1.1×10^{-9}
^{62}Ge	1237	5.8×10^{14}	28(5)%	70(10)%	$(0.82\pm0.02_{(stat)}\pm0.2_{(syst)})\times10^{-9}$	$4.8(20)\times10^{-9}$	33×10^{-9}

isotope is four times larger than that measured in the previous A1900 experiment, which employed a similar beam and target configuration and had large statistical uncertainty. Still, our value is lower by about a factor of two with respect to the value obtained in the GANIL experiment. The latter discrepancy can be attributed to the different beam and target combination. It shows that the usage of a nickel target is a better choice than beryllium if ^{70}Ge beam is used. Also for production of ^{59}Ge we may expect a larger production cross section in fragmentation of ^{70}Ge on ^{nat}Ni target. Nevertheless, the larger available intensity of ^{78}Kr beam and the better thermal properties of beryllium target could make their choice more advantageous.

The EPAX3 parametrisation overestimates the production cross section for germanium isotopes by one-to-two orders of magnitude. The difference increases with decreasing mass of the germanium isotopes.

Summary — In an experiment at the National Superconducting Cyclotron Laboratory we have identified the new isotope ^{59}Ge. In addition, we measured the production cross-section for the four most neutron-deficient germanium nuclei. The dependence of the cross-section on the atomic number shows a smooth behaviour, no sudden drop is observed at A=60, which could have indicated that ^{60}Ge has a half-life shorter than the flight-time through the separator. This does not seem to be the case. We observe a steeper decrease of the cross sections with respect to the EPAX3 predictions. For ^{59}Ge production, the cross section estimated by EPAX3 is a factor ∼100 larger than measured. The observation of ^{59}Ge opens the path to investigate its decay properties to answer the question whether this isotope has a seizable branching for two-proton radioactivity.

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