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Discovery of ^{60}Ge and ^{64}Se

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Abstract. Very neutron-deficient fragments were produced by projectile fragmentation of a 140 MeV/nucleon ^{78}Kr primary beam on a beryllium target. The secondary fragments were unambiguously identified after separation in the A1900 fragment separator. Three events of ^{60}Ge and four events of ^{64}Se have been observed for the first time, making ^{60}Ge the heaviest known isotone of the $N = 28$ neutron shell. No events of ^{59}Ga and ^{63}As have been observed providing very strong evidence that these nuclei are unbound with respect to proton emission.

PACS. 25.70.Mn Projectile and target fragmentation – 27.50.+e $59 \leq A \leq 89$ – 23.50.+z Decay by proton emission

1 Introduction

The proton drip line, in contrast to the neutron dripline, is not a boundary of existence [1]. Due to the Coulomb barrier, nuclei beyond the proton dripline can have very long lifetimes depending on their nuclear charge and binding energy. They can decay by either β^+ or proton emission. The observation of new isotopes at and beyond the proton dripline yields important input for the understanding of the nuclear forces [2] and the formation of the elements [3]. The location of the proton dripline as defined as $S_p = 0$ is not a critical parameter itself. The contribution to the generation of heavier elements along the astrophysical rapid-proton (rp) capture process depends on the lifetimes and binding energies of the nuclei involved. Even the pure observation or non-observation of nuclei produced in projectile fragmentation reactions yields important information about their lifetimes. Although the limits of current knowledge has already passed the region of interest for the rp-process the lifetime information of these nuclei can be used to constrain the mass models, because the proton decay lifetimes are correlated with the binding energies.

It becomes increasingly more difficult to produce new isotopes the closer one approaches the dripline. The last observation of a new isotope below mass 100 was reported more than three years ago [4]. The predominant method to discover new neutron-deficient isotopes in this mass region has been projectile fragmentation. Previous experiments were able to map a large range of new isotopes simultaneously [5,6,7]. The more exotic nuclei need to be specifically isolated in dedicated fragment separator settings [8]. Projectile fragmentation is also predicted to be the most efficient production method to extend the knowledge of neutron-deficient nuclei even further with the next generation rare isotope accelerators [9,10,11]. Measuring the production rates of the most exotic nuclei with the existing facilities is crucial for the predictions of rates for the new facilities.

2 Experimental procedure

A beam of ^{78}Kr^{34+} was accelerated to an energy of 140 MeV/nucleon at the Coupled Cyclotron Facility of the National Superconducting Cyclotron Laboratory at Michigan State University. The primary beam was fragmented in a 610 mg/cm^2 thick ^{9}Be production target located at the object position of the A1900 fragment separator [12]. The experimental setup is shown in fig. 1. Secondary fragments of a single magnetic rigidity were selected in the first half of the A1900 ($B\rho_1 = 2.4486$ Tm for ^{60}Ge, $B\rho_1 = 2.4935$ Tm for ^{64}Se). A slit system at the central dispersive focal plane (image-2) of the separator limited the momentum acceptance to d$p/p = 0.5\%$. A 240 mg/cm^2 thick wedge-shaped aluminum energy degrader was also placed at this position. Setting the second half of the separator to the magnetic rigidity of the fragment of interest ($B\rho_2 = 1.7206$ Tm and 1.7481 Tm for ^{60}Ge and ^{64}Se, respectively) allowed for further isotopic

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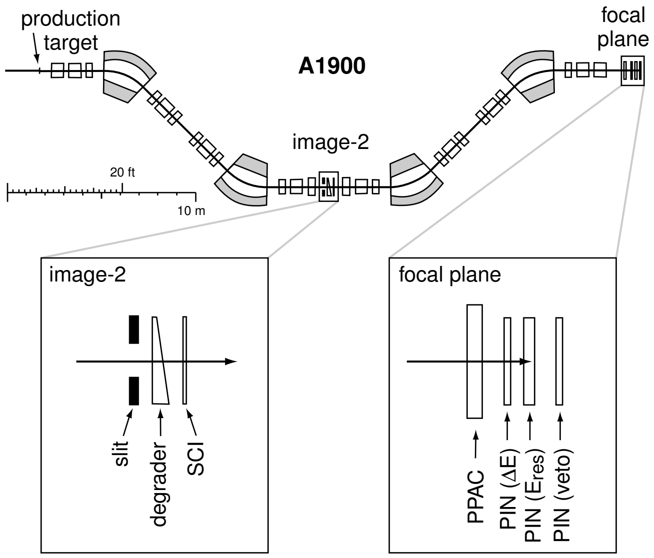

Fig. 1. Schematic view of the experimental setup at the A1900 fragment separator. The detector systems for particle identification were placed at the dispersive focal plane (image-2) and at the achromatic focal plane: a timing scintillator (SCI), a position-sensitive PPAC, and 3 silicon detectors (PIN).

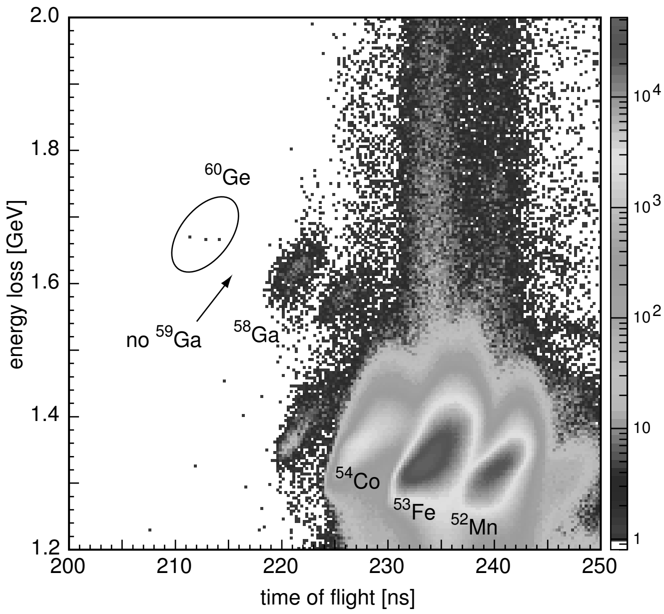

Fig. 2. Two-dimensional identification plot of energy loss in the first silicon detector *versus* the time-of-flight between the image-2 scintillator and the silicon detector at the focal plane. The fragment separator setting was optimized for ^{60}Ge.

separation. The fragments were stopped in a telescope of three silicon detectors (Si PIN diodes with an active area 50×50 mm^2) at the achromatic final focal plane of the A1900. A first detector (thickness 0.5 mm) provided an energy-loss signal for nuclear charge identification and a timing signal to start the time-of-flight (TOF) measurement. The fragments of interest were stopped in the second silicon detector (thickness 1 mm) which measured the residual energy. A third silicon detector served as veto detector to reject particles not being stopped. A 0.1 mm thick plastic scintillator (BC-400) was installed at the image-2 position. This detector was read out by two photomultiplier tubes on either end of the scintillator and provided two independent timing signals.

Several parameters were used from this detector setup to unambiguously identify implanted fragments: energy loss signals from the first two silicon detectors, a veto signal from the last silicon detector, and position information from the PPAC detector (used to veto events implanted at the edges of the active area of the silicon detectors). Three independent TOF signals were obtained by recording the time differences between the signal from the silicon detector and signals from the cyclotron RF or each of the two timimg signals of the image-2 scintillator. The resolution σ of each signal was also determined. To be accepted as a valid event, all parameters were required to lie within a 3σ interval.

3 Results and discussion

A two-dimensional identification plot of energy loss in the first silicon detector *versus* the TOF between that and the image-2 scintillator for the ^{60}Ge fragment separator setting is shown in fig. 2. During 60 hours of beam on target with an average primary beam current of 3.6 pnA a total of three events of ^{60}Ge were unambiguously identified. These events fulfill the conditions explained above. Other fragments shown in the identification plot are $N = 28$ and $N = 27$ isotones with masses $A < 60$. The group of events above ^{53}Fe are events with “pile-up” signals in the electronics of the energy loss detector. Due to the separation in time-of-flight, none of those background events can be found in the region of ^{60}Ge, The probability for random background was determined to be less than 2×10^{-9} in the vicinity of ^{60}Ge. The contribution of ^{58}Zn within the ^{60}Ge cut is even smaller. Therefore, we conclude that the new isotope ^{60}Ge has been observed for the first time. The analysis of this run is consistent with no observation of ^{59}Ga, which provides very strong evidence that ^{59}Ga is unbound with respect to proton decay.

The right panel of fig. 3 shows a two-dimensional identification plot for the ^{64}Se separator setting. The left panel shows the ^{64}Se events in a plot of energy loss *versus* the total energy measured with the silicon detectors at the focal plane. Four events of ^{64}Se were observed during 32 hours of beam on target with an average primary beam current of 13.5 pnA. This measurement shows the first observation of ^{64}Se and the non-observation of ^{63}As.

To investigate the production of neutron-deficient nuclei close to the dripline the production yields of germanium and selenium isotopes with isospin projections from $T_z = 0$ to $T_z = -2$ were measured. The maximum of the momentum distribution after the production target was determined experimentally for ^{64}Ge and compared with the prediction of the program LISE++ [13]. For other isotopes, yield measurements were perfomed at the maximum

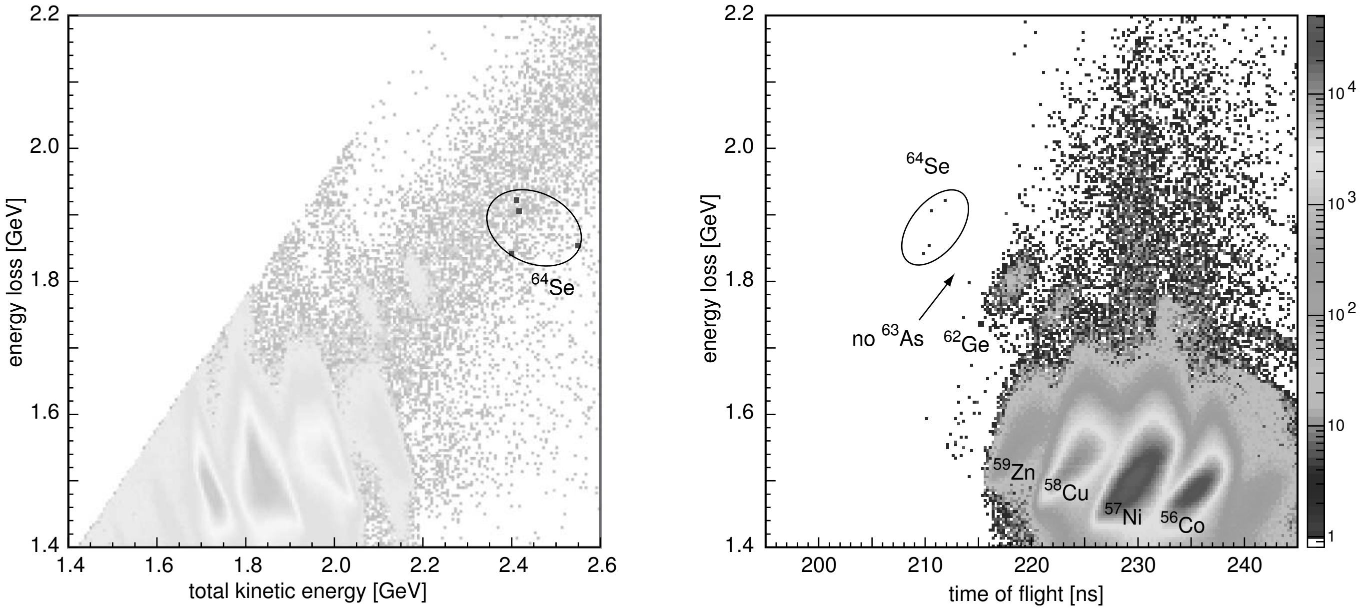

Fig. 3. Two-dimensional identification plots for a ^{64}Se setting of the fragment separator. The left panel shows the energy loss in the first silicon detector *versus* the total energy measured in both silicon detectors. The right panel shows the energy loss signal *versus* the the time-of-flight between the image-2 scintillator and the silicon detector at the focal plane.

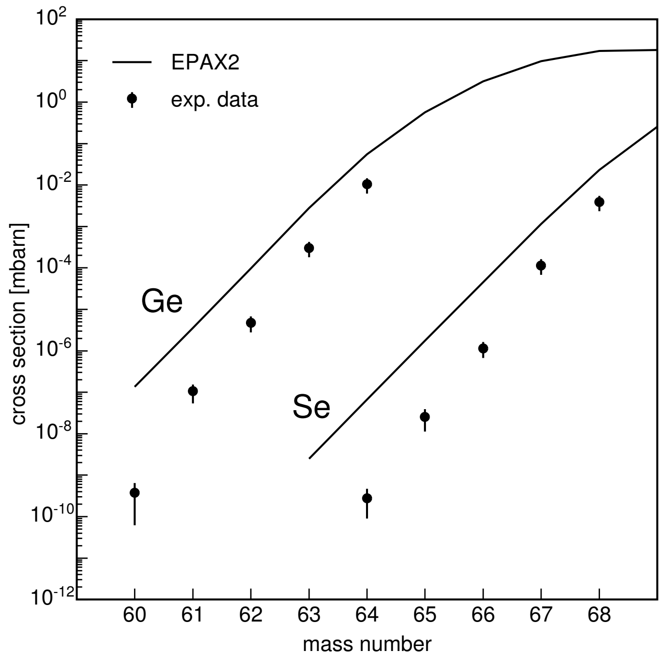

Fig. 4. Measured cross-section for germanium and selenium isotopes as a function of the mass number. The experimental values are compared with EPAX2 parametrization.

of the momentum distribution as scaled from the measured ^{64}Ge value. The transmission for these isotopes was calculated with the simulation codes LISE++ and MOCADI [14] to determine the production cross-sections. The intensity of the primary beam was monitored by a BaF_2 scintillation detector measuring secondary particles emitted from the production target.

Figure 4 shows the experimental cross-section data in comparison with the predictions of EPAX2 [15], an empirical parametrization of projectile cross-sections. EPAX2 overpredicts the the krypton fragmentation cross-sections by more than one order of magnitude. This overprediction of all isotopes towards the dripline might have significant implications for next generation rare isotope accelerators like RIA [11], where part of the rare ion beam rate estimates are based on EPAX2.

4 Conclusion

The very neutron-deficient isotopes ^{60}Ge and ^{64}Se were observed for the first time. The non-observation of ^{59}Ga and ^{63}As provides very strong evidence that these nuclei are unbound with respect to proton emission. The experimental production cross-sections of germanium and selenium isotopes close to the proton drip-line were significantly lower than the predictions by parametric EPAX2 model. This result might have major implications for predicted rates for the next generation rare isotope accelerators.

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