Production of Neutron-Rich Nuclides by Fragmentation of 212-MeV/amu ^{48}Ca

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Yields of neutron-rich projectile fragments have been measured at 0° for the reaction of 212-MeV/amu ^{48}Ca ions on an 890-mg-cm^{-2} beryllium target. Fourteen nuclides have been observed for the first time. The systematics of production cross sections are discussed.

The limits of stability for nuclei have been established up to sodium and beryllium for proton-rich and neutron-rich nuclides, respectively. Recently, the techniques of relativistic heavy-ion fragmentation,[1] deeply inelastic scattering,[2] and spallation induced by high-energy protons[3] have been used to produce neutron-rich nuclei near the limit of particle stability. In this Letter, we present the first experimental evidence for the particle stability of fourteen nuclides, ^{22}N, ^{26}F, ^{33,34}Mg, ^{36,37}Al, ^{38,39}Si, ^{41,42}P, ^{43,44}S, and ^{44,45}Cl, produced in the fragmentation of 212-MeV/amu ^{48}Ca. In addition, the recent observation[2] of ^{37}Si, ^{40}P, and ^{41,42}S is confirmed. Predictions for the masses of neutron-rich light nuclei have been made based on several methods, including iterative techniques such as the modified Garvey-Kelson relations,[4,5] the liquid-droplet model,[6,7] and large-basis shell-model calculations.[8] The energy levels of such nuclei have also been predicted using the same shell-model calculations.[8,9] From the present experiment it appears that the production cross sections for very neutron-rich light nuclei may be quite sensitive to their detailed nuclear structure.

The experimental arrangement used for the present work was similar to that described in Ref. 1. The fragments, which emerge from the reaction at nearly the beam velocity, were detected in a zero-degree magnetic spectrometer with an acceptance of 0.94 msr. A detector telescope consisting of twelve Si(Li) detectors, two position-sensitive Si(Li) detectors (PSD), and a veto scintillator was placed in the focal plane of the spectrometer. Each of the twelve Si(Li) detectors was 5 mm thick and 5 cm in diameter while the PSD's were 500 μm thick and 6 cm in diameter. The PSD's were arranged to measure horizontal and vertical position with a resolution of ~1 mm. The beam current of ^{48}Ca ions from the Bevalac was ~10^7 particles/sec and was monitored directly with plastic scintillators, an ion chamber, and a scintillator telescope that monitored particles scattered from the target. The target consisted of 890 mg cm^{-2} of beryllium and the beam lost approximately 35 MeV/amu passing through it.

Combining the spectrometry with the energy-loss measurements in the Si(Li) detectors made it possible to measure M and Z unambiguously as described in Ref. 1. The mass resolution obtained was 0.3 amu. The mass- and atomic-number scales were calibrated by use of the direct ^{48}Ca beam and also beams of ^{20}Ne and ^{40}Ar of high energy that were progressively degraded to provide a continuous spectrum of ^{20}Ne and ^{40}Ar ions stopping in each detector. Since the detector thicknesses were precisely known, it was then possible to use a range-energy table to make an accurate channel-to-energy calibration for each detector assuming accurate extrapolations to the measured neutron-rich nuclei.

The mass spectra obtained for the neutron-rich isotopes of N, F, Mg, Al, Si, P, S, and Cl are shown in Fig. 1. To improve the mass resolution, several cuts have been applied to these data including charge cuts of ±0.2 units, a χ^2 cut which eliminated 30% of the events corresponding to the highest χ^2 for each stopping detector, and a total-kinetic-energy cut which eliminated any low-energy background. The intensities of Fig. 1 do not correspond to relative cross sections because the spectra are summed over different settings of the spectrometer. Runs at each setting varied from 10 min to 9 h. There is clear evidence for the particle stability of ^{22}N, ^{26}F, ^{33,34}Al, ^{37,38,39}Si, ^{40,41,42}P, ^{41,42,43,44}Si, and ^{44,45}Cl with more than ten counts in each case. The observation of ^{33}Mg confirms the indications for the stability of that isotope in Ref. 1. The existence of ^{37}S, ^{40}P, and ^{41,42}S confirms the measurements reported in Ref. 2. The nuclide ^{22}N is predicted to be particle unstable in a modified liquid-droplet model[7] whereas modified Garvey-Kelson formulations[4,5] predict that ^{22}N is bound against neutron emission by 1.5 to 2 MeV.

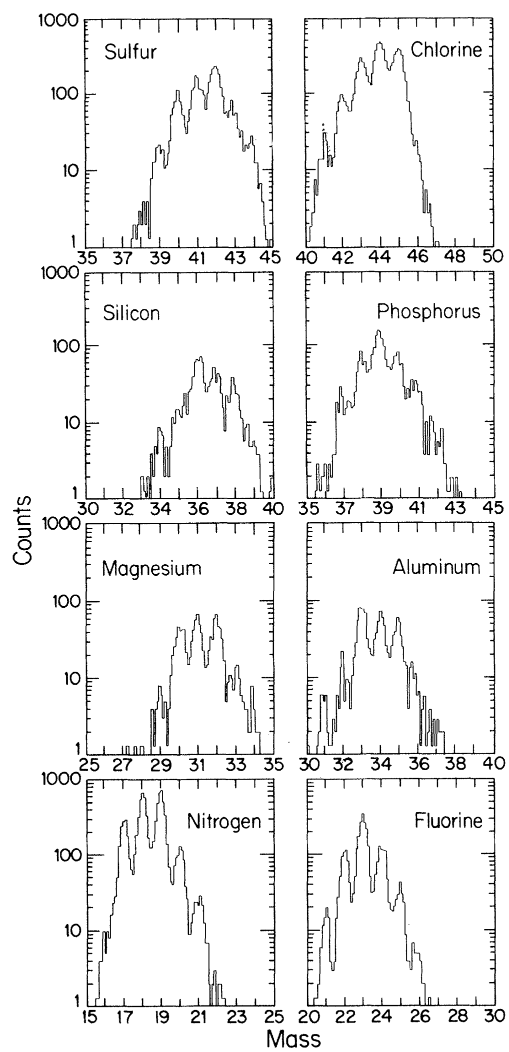

FIG. 1. Mass histograms for elements observed in the fragmentation of 212-MeV/amu ^{48}Ca by a beryllium target.

The production cross section of each isotope observed was obtained by integrating its deflection spectrum along the focal plane of the spectrometer. At each setting, the deflection spectra across the telescope were binned in five equally sized rectangular position cuts by use of the PSD's. A Gaussian momentum spectrum in the projectile rest frame, as has been observed in ^{16}O fragmentation work at higher energies, was assumed.[10] This momentum spectrum $d\sigma/dp^*$ was transformed relativistically to the laboratory and was fitted to the laboratory deflection spectra $d\sigma/dD$, with use of the form

$$\frac{d\sigma}{dD}=\frac{E^*}{E}\frac{p^2}{KZ}\frac{d\sigma}{dp^*}, \qquad (1)$$

where E^*, p^* (E, p) are the total energy and momentum in the projectile (laboratory) frame, K is the spectrometer calibration constant, and Z is the atomic number of the observed fragment. The cross sections were found by minimizing the difference between Eq. (1) and the observed spectra. The errors were assigned by use of the diagonal elements of the resulting error matrix. The cross sections were corrected for the fraction of events lost because of the transverse-momentum acceptance of the spectrometer assuming that the transverse width was equal to the parallel-momentum width.[10] The percentage ac-

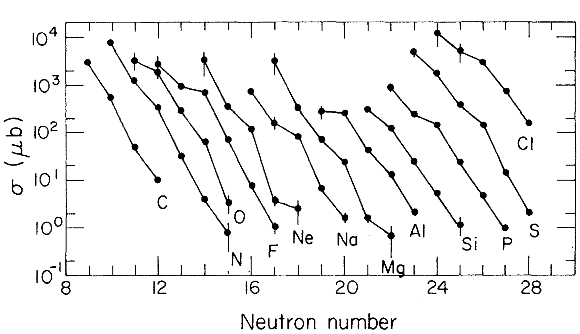

FIG. 2. Production cross sections for the elements observed in the fragmentation of 212-MeV/amu ^{218}Ca by a beryllium target. Lines are to guide the eye.

cepted varied from 15% for C isotopes to 95% for Cl isotopes. The cross sections were also corrected for the 30% χ^2 cut and a 20% loss due to the size of the vertical focus.

The measured isotopic-production cross sections are given in Fig. 2. Generally, the cross sections fall smoothly with increasing neutron number although there is a pronounced odd-even effect favoring nuclides with even neutron numbers. Our observations for N, O, F, and Ne approach to within one or two units of the predicted limit of stability, with ^{24}N, ^{25}O, ^{28}F, and ^{29}Ne predicted unstable by two or more formulas. Beyond these nuclei, the isotopes ^{26}O, ^{29}F, and ^{30}Ne are predicted to be stable. The steeply falling cross sections make it extremely difficult for us to set useful limits regarding the stability of these nuclides from this experiment. For example, the upper limit for observation of ^{29}Ne in this experiment was ~20 nb, which, when compared to the trend of the neon isotopes seen in Fig. 2, does not allow any definite states regarding the stability of this nucleus. It is clear that the question of the stability of ^{29}Ne can be answered by the present technique given increased beam intensities. The observed stability of ^{33}Mg, which is predicted bound by only 500 keV, illustrates that simply determining whether or not an isotope is particle stable can provide quantitative tests of these mass formulas.

One novel and striking feature of the yields is the rapid falloff in cross section for the oxygen isotopes, much faster than that for either nitrogen or fluorine. This is surprising since ^{24}O has been reported to be particle stable and is predicted to be so by all mass formulas. Qualitatively, an understanding of this behavior may be obtained from the predicted level schemes of these nuclei. If, as seems likely, these nuclei are formed as evaporation residues, then the number of bound states may be a more significant parameter than the binding energy in the determination of the yield. Neither ^{23}O nor ^{24}O is predicted to have any bound positive-parity states while neighboring N and F isotopes (with odd Z) are predicted to have several. Further shell-model calculations will clearly be valuable in predicting the yields of unobserved neutron-rich nuclei from the observed systematics.

In Fig. 3 the production cross sections of sodium isotopes from the present work are compared to those from 205-MeV/amu ^{40}Ar + C (Ref. 1) and 28-GeV $p + ^{238}$U reactions.[3] The cross sections from ^{48}Ca + Be and $p + ^{238}$U are nearly equal

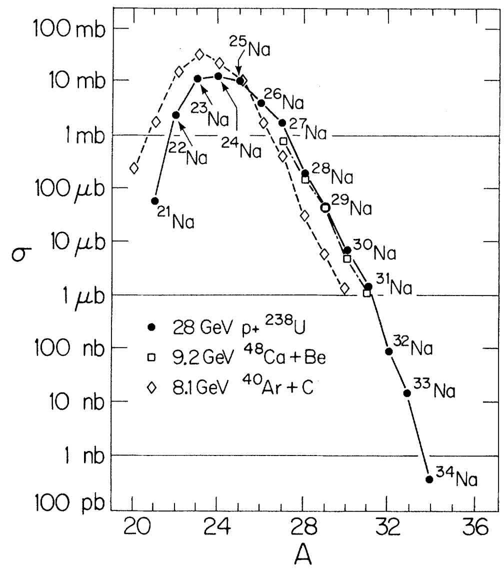

FIG. 3. Comparison of sodium production cross sections from 212-MeV/amu ^{48}Ca + Be (present work), 205-MeV/amu ^{40}Ar + C (Ref. 1), and 28-GeV p + U (Ref. 3). Lines are to guide the eye.

whereas those from ^{40}Ar + C are substantially lower. All three reactions show the same odd-even effect which is indicative of a common final stage to the process. The increase in yield in going from ^{40}Ar to ^{48}Ca projectiles is expected, but the similarity between the yields from the latter reaction and the proton-spallation results is surprising.

In conclusion, fragmentation of relativistic heavy ions seems firmly established as a practical means for the production of nuclei far from stability. The observation of these neutron-rich nuclei can be used to make quantitative tests of mass formulas. Beyond these global comparisons with mass formulas, the production cross sections appear to be sensitive to the microscopic level structure of the observed nucleus. In addition, the variations of the production cross sections indicate that, given increased beam intensities, which will be available in the near future, it is practical to determine the limit of stability up to $Z \cong 20$.

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Projectile Fragmentation Processes in 35-MeV/amu (α,xy) Reactions

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Coincidence measurements with 35-MeV/amu α particles show that at least three projectile-fragmentation processes occur. The dominant process is "absorptive" breakup, where one component of the projectile interacts strongly with the target resulting in the emission of evaporation or nonstatistical particles while the other component behaves as a spectator. The other fragmentation processes which are observed account for only a few percent of the breakup cross section.

Projectile fragmentation is a general feature of particle spectra resulting from the interaction of composite projectiles with nuclei. For energies greater than about 20 MeV/amu, the inclusive spectra of both heavy ions[1] and α-particle fragments[2-5] exhibit peaks at energies corresponding approximately to the beam velocity (when corrected for Coulomb effects). Somewhat similar models can account for the general features of the inclusive spectra for heavy-ion[1] and α-particle fragmentation.[2,3] Studies of inclusive spectra do not, however, provide a unique identification of the specific reaction mechanisms involved in fragmentation. Although some coincidence studies have been carried out with heavy ions,[6] the dominant reaction mechanisms involved in the fragmentation of tightly bound projectiles, such as the α particle, have not been clearly identified.

In order to help identify these processes we have carried out a series of coincidence experiments with 35-MeV/amu α particles. The experiments consisted of measuring p, d, and t with energies above the evaporation peaks in coincidence with $Z=1$ or $Z=2$ particles with energies from evaporation regions to the maximum, kinematically allowed, energy.

The results show that three different processes contribute to α-particle fragmentation. These processes can be characterized as (1) "final-state" breakup, where the α-target interaction leads to inelastic scattering of an excited α particle, α^*, which decays by particle emission; (2) "quasifree" breakup wherein the projectile interacts with the target nucleus through a scattering process to liberate fragments (e.g., $p+t$ or $d+d$) leaving the target in the ground state or a low-lying state with small recoil momentum[7]; and (3) "absorptive" breakup wherein a subset of projectile nucleons suffers strong interactions and fuses with the target nucleus resulting in either evaporation or nonstatistical (including preequilibrium particle emission, secondary fragmentation, and others) emission of particles from the residual nucleus, but leaves the remain-

