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OBSERVATION OF NEW NEUTRON-RICH ISOTOPES BY FRAGMENTATION OF 205 MeV/NUCLEON ^{40}Ar IONS*

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ABSTRACT

Yields of projectile fragments have been measured at 0° for the reaction of 205 MeV/nucleon ^{40}Ar ions on an 860 mg cm^{-2} carbon target. Mass resolution was achieved using a combination of magnetic analysis and energy loss measurements. The isotopes ^{28}Ne and ^{35}Al have been observed for the first time.

Recently, both heavy-ion transfer reactions[1] and spallation of heavy nuclei by high energy protons[2,3] have proved to be fruitful techniques for the production of neutron-rich light nuclei close to the limit of stability. In this Letter, we report the first evidence for the particle stability of ^{28}Ne, ^{35}Al and possibly ^{33}Mg produced in the fragmentation of 205 MeV/nucleon ^{40}Ar by a carbon target. In addition, we confirm the particle stability of six neutron-rich isotopes that have been observed previously only in a single experiment. The particular advantage of this novel experimental approach is that the products of a projectile fragmentation reaction move at nearly beam velocity, close to 0° in the laboratory. The exotic products are much easier to identify than in previous experiments where they emerge at low velocities. Since the method also allows the use of thick targets and enables a large fraction of the reaction cross section to be collected in a detector placed at 0°, the resultant gain in efficiency can be as much as 10^6 over a typical low energy experiment. It now becomes feasible to check the predictions of theoretical mass formulae close to the limit of stability, where the assumptions of the theories are subject to the greatest uncertainty.[4]

The projectile fragments produced in the reaction were detected in a zero degree magnetic spectrometer[5] with an entrance solid angle of 0.5 msr. Two detector telescopes were mounted in the focal plane of this spectrometer. Each telescope consisted of eight 5 mm thick lithium-drifted silicon detectors backed by a scintillator to reject particles that passed completely through the detector stack. The deflections of the particles were measured with two 1 mm resolution 3-plane multiwire proportional chambers. The maximum intensity of the ^{40}Ar beam from the Bevalac of $\sim 10^8$ particles/sec was collimated to $\sim 5 \times 10^6$ particles/sec at the target. The beam current was monitored directly using plastic scintillators and an ion chamber, and also with scintillators that measured scattered particles from the target. This technique allowed reliable monitoring of the beam from the lowest ($\sim 10^3$ particles/sec) to the highest intensities. The target used was 860 mg cm^{-2} of natural carbon in the form of graphite. The ^{40}Ar projectiles lost approximately 30 MeV/nucleon in passing through this target.

The combination of the spectrometer and the focal plane telescopes provided a system capable of two independent measurements of the particle mass.[1] First, the particles were identified by the energies deposited in the Si(Li) detectors using an extension[6] of the standard techniques for ΔE-E telescopes.[7] For each ΔE detector in the stack, a particle identification signal (PI) was calculated from the formula:

$$PI_i = \left((E_i + \Delta E_i)^{1.78} - E_i^{1.78} \right) / S_i \propto M^{0.78} Z^2 \qquad (1)$$

where ΔE_i is the energy that was lost in the i^{th} detector, E_i is the total energy deposited in subsequent detectors up to the stopping detector, S_i is the thickness of the i^{th} detector, and M and Z are the fragment mass and charge. The PI_i signals were then combined to form a weighted mean and χ^2. Cutting the tails of the χ^2 distribution allowed the mass resolution to be improved by eliminating many of the events that were misidentified because of reactions in the detectors and statistical fluctuations in the energy loss. The mass resolution obtained with this technique was typically of the order of 0.2 amu.

Secondly, the total energy, T, deposited in the telescope was combined with the particle deflection, D, in the spectrometer to form a second particle identification signal:

$$PI = k/TD^2 - T/2Z^2 \propto M/Z^2 \qquad (2)$$

where k is the spectrometer calibration constant. The mass resolution using this method was approximately 0.3 amu for all measured fragments. The independent identifications obtained using Eqs. (1) and (2) can be combined to calculate M and Z unambiguously. The final resolution obtained was typically 0.2 amu.

Calibration of the atomic number is straightforward because the charge separation is excellent and one can count down from the known charge of the beam. This procedure was also followed for the mass calibrations, but was less reliable since it was sensitive to the energy calibrations of the individual detectors. Two further methods were used to check the absolute mass scale. The first one relied on the range energy relations for different isotopes in the silicon detectors. In general, the range of the particles is not measured in this experiment. However, for the particular case of an isotope stopping at the boundary between two detectors, the range is known exactly. Since the fragments are produced with a considerable dispersion in energy, it was generally possible to determine the deflection, and hence the rigidity, for a given isotope stopping at a detector boundary. Knowing the spectrometer calibration, it is then possible to calculate the particle mass. Equivalently, one may use only the relative ranges of different isotopes without knowledge of their absolute ranges, since only the correct calibration can give a consistent set of values of range and energy. This method has an accuracy of better than 0.2 amu.

The second check used the systematics developed for fragmentation reactions that appear to be nearly independent of mass.[8] In this model the reaction Q values are given by those of projectile fragmentation and one may calculate the expected mean outgoing energy and momentum spread. These predictions have been compared with the experimental ones and allow a mass determination to better than one mass unit. In particular, a mass scale lower than the one established here is ruled out since it would place the observed mean energy in a kinematically forbidden region. We conclude that the mass scale presented is reliable and emphasize that it is based on three independent methods.

The data obtained for the neutron-rich isotopes are shown as a scatter plot in Fig. 1. Because only a small region of rigidity (±1.2%) was measured at a single detector position, the data shown are summed over several settings of the detectors. The length of the runs varied from 20 minutes to 8 hours at the setting corresponding to the largest value of A/Z. Thus, the intensities seen in the figure are not related to the relative cross sections. Projected mass spectra with a gate of ±0.2 units about charges 10, 11, 12 and 13 are shown in Fig. 2. ^{28}Ne and ^{35}Al are positively identified as particle-stable isotopes with more than 10 counts in each case. There is also evidence for the stability of ^{33}Mg, although this should be confirmed in a separate experiment before positive identification can be claimed. We also confirm the particle stability of ^{27}Ne,

^{31}Mg, ^{32}Mg, ^{34}Al, ^{30}Na and ^{31}Na, each of which has only been observed directly using a single technique.[2,3] All three new nuclides are predicted to be particle-stable,[9] although in the case of ^{33}Mg, only by 480 keV, a value that is close to the uncertainty in the theoretical predictions. It will be of particular interest to extend the present experiment since ^{29}Ne and ^{25}O are predicted to be just bound and unbound respectively. In cases such as these, even the observation of the isotope provides an important test of the mass formula used.

We have calculated the production cross sections for the sodium isotopes and list them in Table 1. Those numbers for which no error is quoted correspond to cases where the full parallel momentum distribution was not measured and an estimate has been made to correct for this effect. In addition, all the figures have an overall uncertainty of a factor of 3 because of the sensitivity of the spectrometer acceptance to the perpendicular momentum spread of the fragments. In estimating this correction, it has been assumed that the perpendicular momentum distribution is gaussian and equal in width to the parallel distributions at this energy.[10] Comparison with production cross sections for the bombardment of uranium with 24 GeV protons[11] shows that our yields have a similar variation with mass but are lower on the average by an order of magnitude. This is to be expected from the fragmentation of a lighter and less neutron-rich nucleus such as ^{40}Ar.

In conclusion, this comparatively short experiment has demonstrated the usefulness of relativistic heavy-ion beams in the production of neutron-rich nuclides. It has recently been suggested[12] that deeplyinelastic scattering of heavy ions may also be a powerful technique for this purpose. It is important that this question be investigated to determine the most appropriate energy at which to run. Whatever the answer, it seems clear that the new generation of heavy ion accelerators, capable of delivering high energy, high intensity heavy ion beams, will permit the investigation of the limits of stability in light nuclei.

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TABLE 1. Production cross sections for sodium isotopes produced in fragmentation of ^{40}Ar and in spallation of ^{238}U by 24 GeV protons.

Isotope	^{40}Ar + ^{12}C (μb)	p + ^{238}U (μb) [ref. 11]
^{26}Na	~1300	~5400
^{27}Na	325 ± 100	~2000
^{28}Na	30 ± 10	~350
^{29}Na	6.5 ± 2	~100
^{30}Na	~1.6	~ 20

FOOTNOTES AND REFERENCES

[*] This work was supported by the U.S. Department of Energy.

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FIGURE CAPTIONS

Fig. 1. Scatter plot of data obtained from the reaction of 205 MeV/A ^{40}Ar ions on a carbon target. The line running through the figure indicates the previously known limit of stability.

Fig. 2. Mass histograms for the elements Ne, Na, Mg and Al, measured by the bombardment of a carbon target by 205 MeV/A ^{40}Ar ions. The spectra are projections of the data in Fig. 1 with charge gates of ±0.2 units.

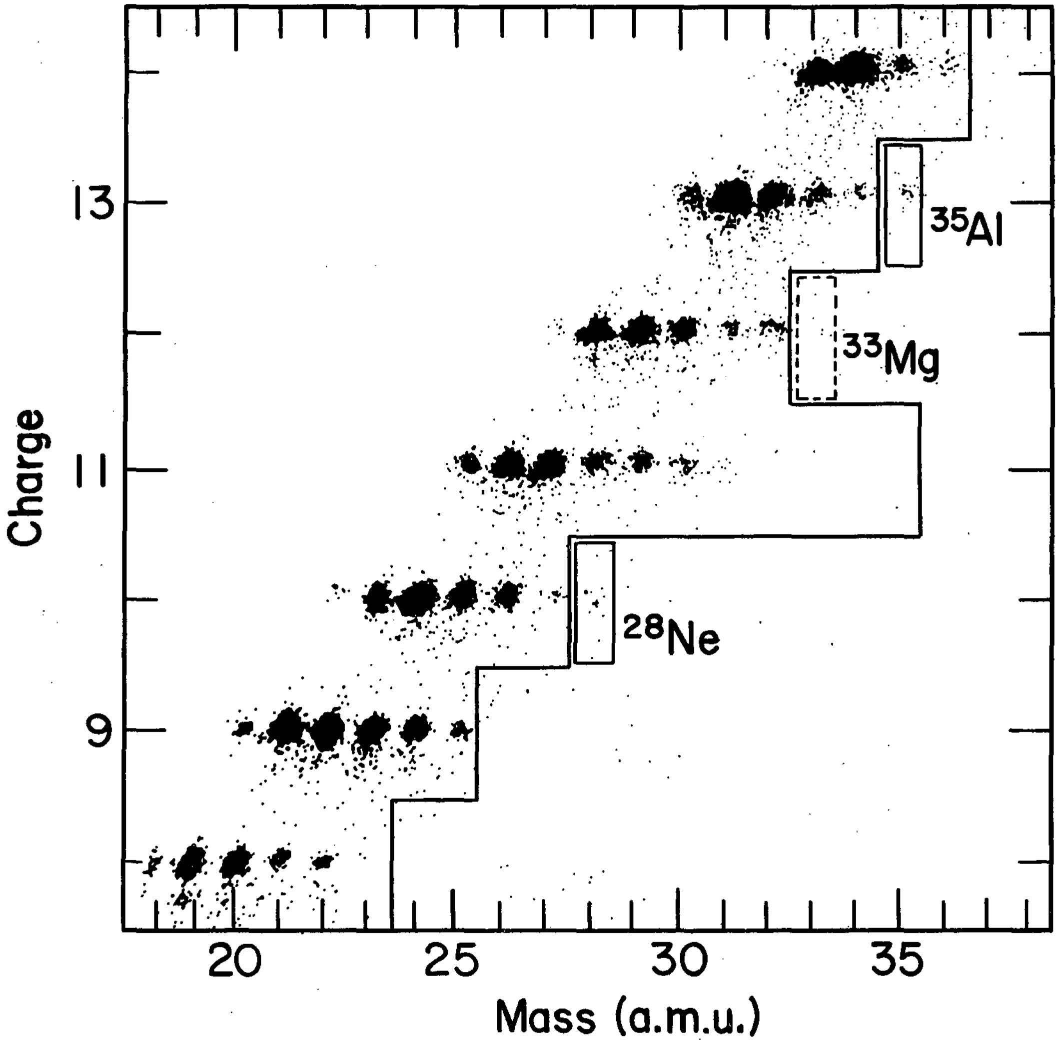

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Fig. 1

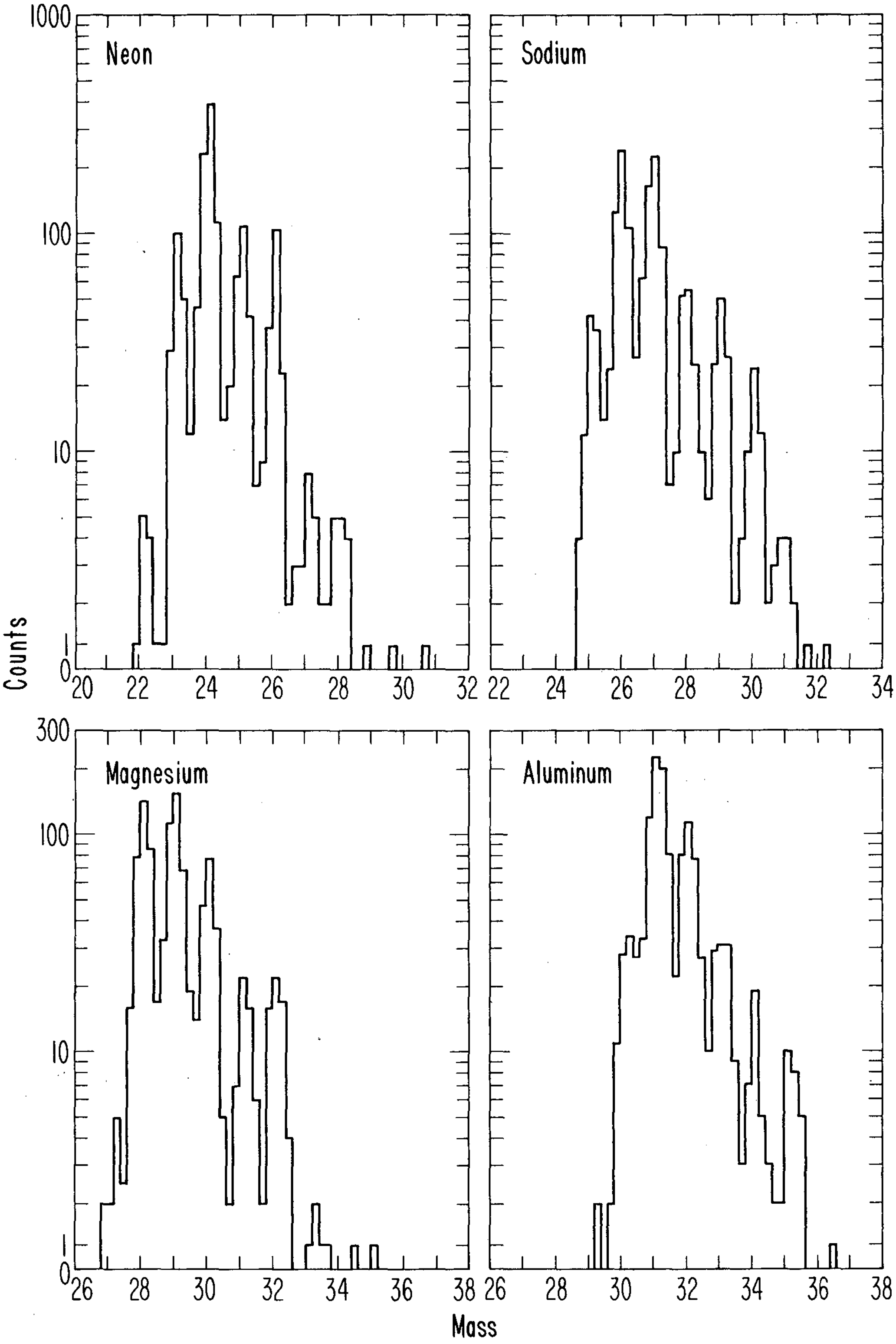
Neon
Sodium
Magnesium
Aluminum
Counts
Mass
1000
100
10
1
0
300
20
22
24
26
28
30
32
34
36
38
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Fig. 2

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