Observation of New Neutron-Rich Isotopes by Fragmentation of 205-MeV/Nucleon ^{40}Ar Ions

T. J. M. Symons, Y. P. Viyogi,[a] G. D. Westfall, P. Doll,[b] D. E. Greiner, H. Faraggi,[c] P. J. Lindstrom, and D. K. Scott
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

H. J. Crawford and C. McParland
Space Sciences Laboratory, University of California, Berkeley, California 94720
(Received 1 November 1978)

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 particle 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 formulas 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 three-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 (I) was calculated from the formula

$$I_i = [(E_i + \Delta E_i)^{1.78} - E_i^{1.78}]/S_i \propto M^{0.78}Z^2, \qquad (1)$$

where ΔE_i is the energy that was lost in the ith detector, E_i is the total energy deposited in subsequent detectors up to the stopping detector, S_i is the thickness of the ith detector, and M and Z are the fragment mass and charge. The I_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.

Second, 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:

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

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

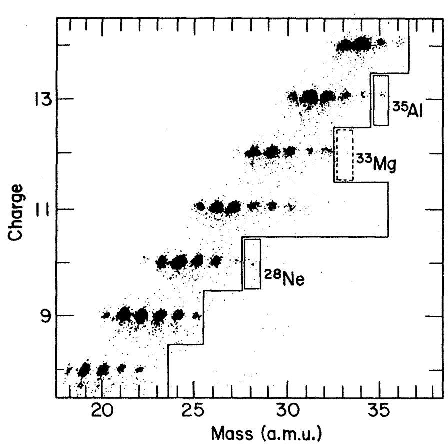

FIG. 1. Scatter plot of data obtained from the reaction of 205-MeV/nucleon ^{40}Ar ions on a carbon target. The line running through the figure indicates the previously known limit of stability.

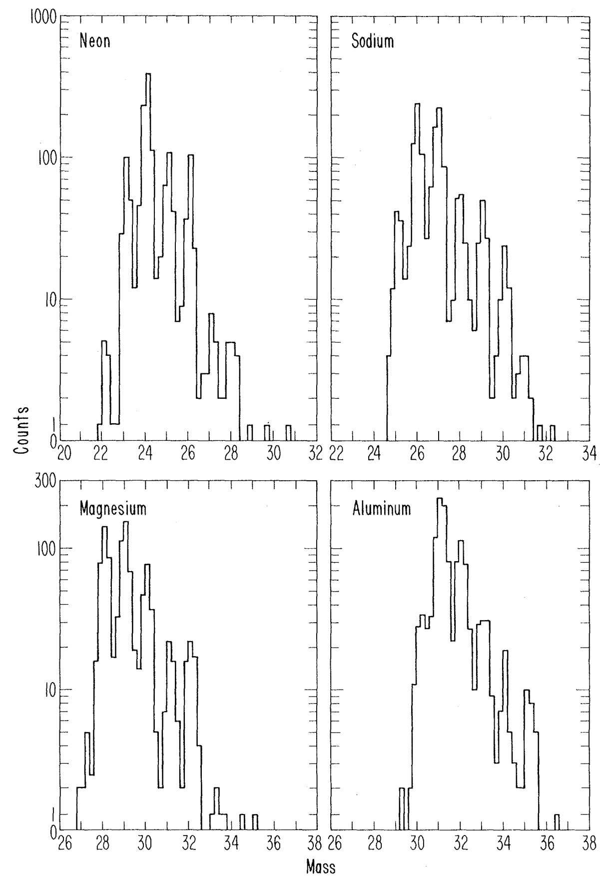

FIG. 2. Mass histograms for the elements Ne, Na, Mg, and Al, measured by the bombardment of a carbon target by 205-Mev/nucleon ^{40}Ar ions. The spectra are projections of the data in Fig. 1 with charge gates of ± 0.2 units.

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 min to 8 h 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 I. 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.

TABLE I. 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)[a]
^{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

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 deeply-inelastic 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.

We are grateful to I. Flores and F. Bieser for their help with the electronics used in this experiment and to H. H. Heckman and A. M. Poskanzer for useful discussions. We also wish to thank the Bevalac operations staff for their support. This work was supported by the U. S. Department of Energy. One of us (Y.P.V.) acknowledges receipt of an IAEA Fellowship and another (P.D.) receipt of a NATO Fellowship.

(a)On deputation from Bhabha Atomic Research Centre, Calcutta, India.

(b)Present address: Gesellschaft für Schwerionenforschung, Darmstadt, West Germany.

(c)On leave from Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France.

[1]A. G. Artukh, V. V. Avdeichikov, G. F. Gridnev, V. L. Mikheev, V. V. Volkov, and J. Wilczynski, Nucl. Phys. A176, 284 (1971).

[2]R. Klapisch, G. Thibault, A. M. Poskanzer, R. Prieels, C. Rigaud, and E. Roeckl, Phys. Rev. Lett. 29, 1254 (1972).

[3]G. W. Butler, D. G. Perry, L. P. Remsberg, A. M. Poskanzer, J. B. Natowitz, and F. Plasil, Phys. Rev. Lett. 38, 1380 (1977).

[4]G. T. Garvey, Comments Nucl. Part. Phys. V, 65 (1972).

[5]D. E. Greiner, P. J. Lindstrom, F. S. Bieser, and H. H. Heckman, Nucl. Instrum. Methods 116, 21 (1974).

[6]D. E. Greiner, Nucl. Instrum. Methods 103, 291 (1972).

[7]F. S. Goulding and B. G. Harvey, Annu. Rev. Nucl. Sci. 25, 167 (1975).

[8]C. K. Gelbke, C. Olmer, M. Buenerd, D. L. Hendrie,

J. Mahoney, M. C. Mermaz, and D. K. Scott, Phys. Rep. 42C, 311 (1978).

[9]C. Thibault and R. Klapisch, Phys. Rev. C 9, 793 (1974).

[10]Y. P. Viyogi, T. J. M. Symons, P. Doll, D. E. Greiner, H. H. Heckman, D. L. Hendrie, P. J. Lindstrom, J. Mahoney, D. K. Scott, K. Van Bibber, G. D. Westfall, H. J. Crawford, C. McParland, and C. K. Gelbke, this issue [Phys. Rev. Lett. 42, 33 (1979)].

[11]C. Thibault, in Proceedings of Third International Conference on Nuclei Far From Stability, Cargèse, France, 1976 (unpublished), p. 93.

[12]P. Braun-Munzinger and J. Barrette, Nucl. Phys. A299, 161 (1978).

Completion of the Mass-20 Isospin Quintet by Employing a Helium-Jet-Fed On-Line Mass Separator

D. M. Moltz, J. Äystö,[a] M. D. Cable, R. D. von Dincklage,[b] R. F. Parry, J. M. Wouters, and Joseph Cerny

Department of Chemistry and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

(Received 31 October 1978)

Observation of β-delayed protons from the decay of the mass-separated $T_z = -2$ nuclide ^{20}Mg ($t_{1/2} \sim 95$ ms) establishes the mass excess of the lowest $T = 2$ (0^+) state in ^{20}Na (13.42 ± 0.05 MeV), thereby completing the mass-20 isospin quintet. All members of this multiplet are bound to isospin-allowed particle-decay modes, providing the first test of the isobaric multiplet mass equation for such a quintet. Excellent agreement is observed using only the quadratic form of this equation.

Development of general experimental systems capable of mass analysis of radioactive species with half-lives as short as 50 ms and with simple application to a vast majority of the chemical elements is clearly of great interest in the study of nuclei far from stability. Such an on-line system has been completed which employs a helium jet to transport activity from the target area to a Sidenius-type hollow-cathode ion source which is coupled to a mass separator. Use of this separator[1] (termed RAMA, for recoil-atom mass analyzer) to detect the decay of ^{20}Mg represents the first discovery of the decay of such an exotic nucleus with this type of apparatus. Although one other member of this $A = 4n$, $T_z = -2$ mass series (the rare gas ^{32}Ar) has been recently observed[2] in experiments at ISOLDE, ^{20}Mg is the lightest nucleon-stable member of this new series of β-delayed proton emitters.

Detection of the decay of ^{20}Mg establishes the location of the lowest $T = 2$ state in ^{20}Na, thereby completing the second known isospin quintet[3] but the first in which all members of the multiplet are bound to isospin-allowed particle-decay modes. The mass-20 quintet thus represents an effective test for a possible deviation from the quadratic isobaric multiplet mass equation (IMME)

$$M(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2,$$

where the coefficients a, b, and c are related to reduced diagonal matrix elements of the charge-dependent part of the nuclear Hamiltonian. Deviations from the quadratic form are generally represented by additional terms $d(A, T)T_z^3$ and $e(A, T)T_z^4$. The coefficients d and e are related to off-diagonal matrix elements and can be derived from second-order perturbation theory; they are physically represented by phenomena such as isospin mixing, shifts of unbound levels, and charge-dependent many-body nuclear forces. Significant deviations from the quadratic form of the IMME have been reported for the mass-8 quintet[3,4] (in which ^{8}C is unbound to prompt nucleon emission); however, this has occurred in only one case[5] (mass 9) of some twenty complete isospin quartets.

The experimental setup for RAMA is illustrated in Fig. 1. Beams of 70-MeV ^{3}He ions from the Lawrence Berkeley Laboratory 88-in. cyclotron, of intensity 2–7 μA, were used to produce ^{20}Mg nuclei via the reaction ^{20}Ne(^{3}He, $3n$). The target employed was spark-chamber gas (90% Ne and 10% He), which for these experiments necessarily served as the stopping and the transport medium. A twelve-unit multiple capillary system collected nuclear reaction recoils from an extended reaction zone and fed a single 6-m stainless steel capillary (i.d. 1.4 mm) which transported the radioactivity to the skimmer. Ethylene glycol was employed as an additive to build up a high–

