

Short Communication

Preparation of ^{20}Ne , ^{24}Mg , ^{28}Si , ^{32}S , and ^{36}Ar targets by ion implantation into thin carbon foils

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ABSTRACT

The preparation of isotopically pure 3–6 $\mu\text{g}/\text{cm}^2$ targets of ^{20}Ne , ^{24}Mg , ^{28}Si , ^{32}S , and ^{36}Ar by the implantation of 25–70 keV ions into 30 $\mu\text{g}/\text{cm}^2$ carbon foils is described.

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The precision of nuclear reaction measurements that employ high-resolution magnetic spectrographs for momentum-analysis of charged-particle reaction products to determine Q values and excitation energies is often limited by systematic effects associated with target properties that are difficult to characterize. Specifically, the energies of charged-particle reaction products depend sensitively on the target's areal density, uniformity, composition, and composition depth profile. Often the unique chemical properties of a particular element will influence one or more of these factors, complicating comparisons between spectra acquired with targets composed of different chemical elements or compounds (i.e. calibrations).

Systematic uncertainties are minimized when the targets employed are qualitatively and quantitatively similar to each other. However, it is a challenge to produce thin, solid targets composed of Ne, Mg, Si, S, and Ar that are similar. Elemental Mg foil may oxidize substantially and the oxidation profile is not necessarily a step function, nor is the oxidation necessarily uniform. Elemental S may sublime during beam bombardment under vacuum, and therefore thin S targets are usually prepared from sulphides such as CdS, AgS, HgS, and SbS. Since Ne and Ar are noble-gas elements, they cannot typically be used in a solid target geometry at room temperature

unless they are embedded in a suitable substrate. Gas targets are cumbersome and may cause problems for precision measurements due to energy loss and energy straggling in the containment windows, background from contaminant elements or isotopes in the windows and/or gas, and variation of the spatial interaction point due to the longitudinal extent of the target.

Past work has shown that it is possible to implant ions of Ne, S, and Ar into thin carbon foils, and subsequently bombard the implanted foils with another ion beam to measure nuclear reactions on the implanted material [1–7]. Kutt et al. [1], Fifield and Orr [2], and Vouzoukas et al. [3] have produced targets of up to 10 $\mu\text{g}/\text{cm}^2$ of various S isotopes by the implantation of 50–70 keV S^- into 20–40 $\mu\text{g}/\text{cm}^2$ carbon foils [2]. Smith et al. [4] and Ugalde et al. [5] have produced targets of 7 $\mu\text{g}/\text{cm}^2$ of various Ne isotopes by the implantation of Ne^+ into 40 $\mu\text{g}/\text{cm}^2$ carbon foils. Wilkerson [7] and Kaloskakis et al. [6] have produced ^{36}Ar targets by similar methods. Our literature search did not yield any information on the preparation or use of Mg- or Si-ion implanted, thin carbon-foil targets. Historically, ion-implanted targets of this kind have only been used when absolutely necessary and, even then, only for a single chemically or isotopically problematic species per experiment. However, if implemented systematically, this technique of target preparation offers the potential to reduce energy-calibration uncertainties associated with target properties to unprecedented levels.

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In the present work we describe the first systematic preparation of an entire set of isotopically pure targets by ion implantation into thin carbon-foil substrates for a single experiment [8,9]. We produced isotopically pure 3–6 $\mu\text{g}/\text{cm}^2$ targets of ^{20}Ne , ^{24}Mg , ^{28}Si , ^{32}S , and ^{36}Ar that were similar to each other despite the unique challenges that chemistry usually poses to the production of solid targets composed of these elements. Each of these targets was found to be stable under bombardment with a ≈ 400 enA, 32 MeV $^3\text{He}^{2+}$ beam for roughly 24 hours. Since the energy losses of the ^3He beam and triton ejectiles in the ($^3\text{He}, t$) experiment that employed the foils were dominated by the carbon foils, the most important characteristics of our targets (besides stability) were the similarity of the depth profile of implanted material (symmetric about the center of each foil) and the relative areal densities of the carbon foils, ahead of the areal density and uniformity of implanted material.

We used the ion sources, analyzing magnet, and injector deck of the tandem Van de Graff accelerator of The Center for Experimental Nuclear Physics and Astrophysics at the University of Washington to produce ion beams that were implanted into thin carbon foils secured in the low-energy beam line. Ion-optical elements, two orthogonal magnetic steerers, and a collimator were used to control the transverse distribution of implanted material. Beam current on the foil was monitored and integrated during each implantation to count the number of incident ions. The apparatus consisted of many of the same components used in Refs. [10,11].

A Cs sputter ion source (SPIS) and a duoplasmatron ion source (DEIS) were used. The materials used to produce MgH^+ , Si^+ , and S^+ in the SPIS were a Mg pellet with H_2 gas flowing through a 0.020 in. hole, Si powder mixed with Ag, and Li_2S , respectively. Natural-abundance Ne and Ar gases were input to the DEIS to produce Ne^+ and Ar^+ , respectively [12]. The ions were extracted from each source using a voltage of magnitude 15–50 kV, and accelerated toward an analyzing magnet. By varying the magnetic-field strength, and observing the positions of peaks on a beam-profile monitor, it was possible to identify and select peaks corresponding to particular charge-to-mass ratios. The relative intensities of the peaks were used to identify the chemical elements and compounds present in the beam based on the known isotopic abundances. In each case, this diagnostic yielded no indication of impurities at the charge-to-mass ratio of the ion of interest. The desired beam energy (in the range 25–70 keV) was achieved by combining the source extraction voltage with elevation of the injector deck.

Natural-abundance, 30 $\mu\text{g}/\text{cm}^2$ carbon foils were obtained from a commercial supplier [13] on microscope slides and floated in deionized water onto stainless steel frames with aperture dimensions of 9 mm \times 12 mm. These were allowed to dry and then secured to an electrically isolated plate centered on the beam axis. The plate was biased to +300 V to suppress the emission of electrons from the substrate during the implantation. Immediately upstream of the target, the beam passed through an element held at ground potential. Upstream of the grounded element was a 1-cm diameter collimator, also held at +300 V, to define the implanted area. The target and collimator were protected against the accumulation of impurities by a liquid nitrogen cold trap positioned approximately 14-cm upstream of the target. Vacuum in the vicinity of the target was held at $\lesssim 10^{-6}$ torr during the implantations.

The beam was initially tuned through the collimator upstream of the carbon-foil substrate by maximizing the electrical current on the substrate and minimizing the current on the collimator plate. The steerers were used to raster the beam over the open area of the circular collimator during the implantation. Limits for each dimension of the rectangular raster scan were assigned by manually adjusting the magnetic field produced by the steerers until a pre-determined fraction of the beam remained on the target. This procedure also yielded information on the beam profile, which

was typically on the order of several mm-FWHM and symmetric. The limits, a discrete step size, and a step duration were then input into a computer program that controlled the steerers throughout the implantation. There were roughly 10 steps in each dimension with durations of one second per step. The step size was typically much smaller than the width of the beam to ensure a distribution of implanted material that was uniform near the center (Fig. 1).

For a given implantation energy, the depth distribution of implanted ions is expected to be narrow in comparison to the thickness of the foil [14]. As a result, the amount of implanted material in this “layer” may be limited by saturation [4]. In order to implant more total material, the beam energy may be changed to implant multiple layers [4,5]. We chose to implant four or six layers, each of ≈ 1 $\mu\text{g}/\text{cm}^2$ thickness, into each foil. The beam energies were chosen such that the centroids of the layers were expected to be spaced by 3–4 $\mu\text{g}/\text{cm}^2$ of C [14]. Since a symmetric depth distribution of implanted material was particularly important for our application, the carbon foil was rotated by 180° after two or three layers had been implanted through one side, and then similar opposing layers were implanted through the other side. Opposing-layer pairs were controlled to be the same thickness within a tolerance of 10%. This method ensured that the targets would be symmetric to a high degree regardless of the expected ion range (Fig. 2).

Some potential complications associated with this method are thermal stress on the foils leading to breakage, sputtering of the C substrate, and self-sputtering of the implanted ions. We found that the thermal-stress problem could be avoided by observing a (very rough) limit of $\approx 10,000$ keV nA/cm² on the power per unit area deposited in the foil [4]. To investigate sputtering, we considered measuring the amount of material retained in the foil absolutely using Rutherford scattering. However, the targets were very fragile and difficult to replace, so we decided against it to minimize handling and potential damage. Instead, the targets were characterized *in situ* during the experiment that employed them. Data from the ($^3\text{He}, t$) and ($^3\text{He}, d$) reactions [8,9] initiated by a ≈ 400 enA, 32 MeV $^3\text{He}^{2+}$ beam were used, showing substantial yields from the implanted material and the carbon substrate. Yields from the ($^3\text{He}, d$) reaction indicated that the carbon thicknesses of the five foils were equal within 10% [8], and that there

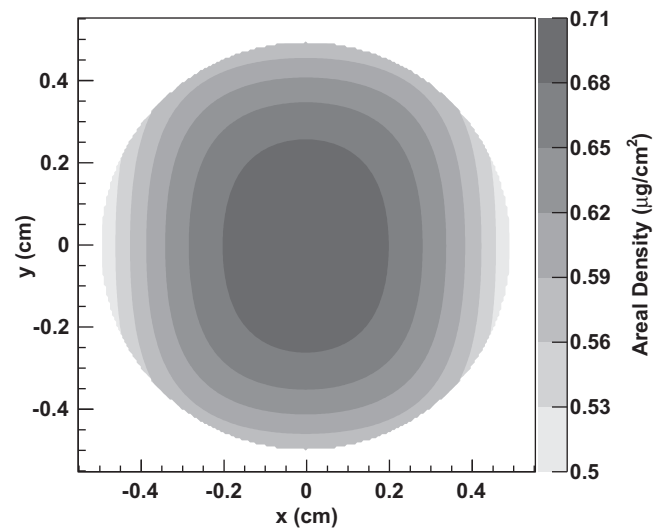


Fig. 1. Areal density of ^{24}Mg implanted at a single beam energy (i.e. in one “layer” of implanted material), simulated based on the beam-current integration, measurements of the beam width and symmetry, knowledge of the raster limits and raster-step size, and the assumption of a 2D Gaussian beam distribution. The variation in the density is less than 5% within the central region of the target where the 1×3 mm ^3He beam hit in the experiment of Refs. [8,9].

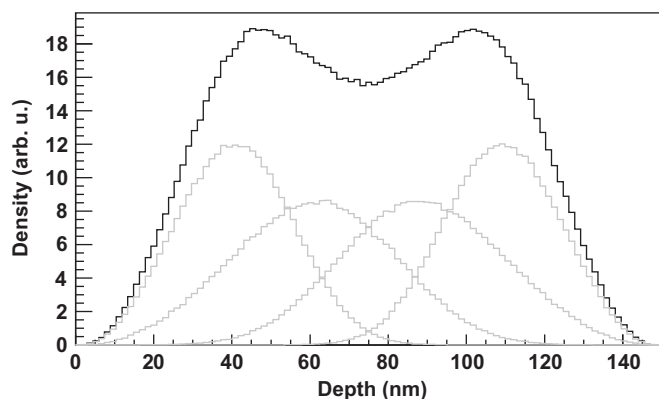


Fig. 2. Depth distribution of ^{24}Mg implanted in a 150-nm thick carbon foil substrate, simulated using the Monte-Carlo code TRIM [14], the known energies of 25-keV and 37.5-keV for the incident MgH^+ , and a C density of 2.00 g/cm^3 [13]. The gray histogram shows the contributions of the four implantation layers individually, assuming they do not interfere with each other, and the black histogram shows their sum.

was no loss of implanted material at the 10% level or greater from beginning to end of roughly one cumulative day of ^3He -beam bombardment. No indications of contaminants in the foils were evident in the spectra, except ubiquitous oxygen. These measurements provided the most precise mass values for ^{20}Na , ^{24}Al , ^{28}P , ^{32}Cl to date [8], and precise excitation energies for levels in ^{32}Cl and ^{36}K [9].

In conclusion, thin targets of ^{20}Ne , ^{24}Mg , ^{28}Si , ^{32}S , and ^{36}Ar have been prepared by ion implantation into thin carbon foils. These targets are similar despite being composed of elements that normally manifest their chemical properties in unique (and potentially problematic) ways. Such targets hold promise for reducing the system-

atic uncertainties in precision measurements of the energies of charged-particle nuclear reaction products to determine nuclear excitation energies and reaction Q values. It would also be very useful if multiple species could be implanted into a single carbon foil; based on the observed retention of Ne, Mg, Si, S, and Ar, we expect that this would work for many combinations of elements.

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References

- [1] P.H. Kutt, S.F. Pate, A.H. Wuosmaa, R.W. Zurmühle, O. Hansen, R.R. Betts, S. Saini, *Phys. Lett. B* 155 (1985) 27.
- [2] L.K. Fifield, N.A. Orr, *Nucl. Instrum. Methods A* 288 (1990) 360.
- [3] S. Vouzoukas et al., *Phys. Rev. C* 50 (1994) 1185.
- [4] M.S. Smith, P.V. Magnus, K.I. Hahn, A.J. Howard, P.D. Parker, A.E. Champagne, Z.Q. Mao, *Nucl. Phys. A* 536 (1992) 333.
- [5] C. Ugalde et al., *Phys. Rev. C* 76 (2007) 025802.
- [6] N.I. Kaloskakis, A. García, S.E. Darden, E. Miller, W. Haeberli, P.A. Quin, B.P. Schwartz, E. Yacoub, E.G. Adelberger, *Phys. Rev. C* 55 (1997) 640.
- [7] J.F. Wilkerson, Ph.D. Thesis, University of North Carolina, 1982.
- [8] C. Wrede et al., *Phys. Rev. C* 81 (2010) 055503.
- [9] C. Wrede et al., *Phys. Rev. C* 82 (2010) 035805.
- [10] T.A.D. Brown, K. Deryckx, A. García, A.L. Sallaska, K.A. Snover, D.W. Storm, C. Wrede, *Nucl. Instrum. Methods B* 267 (2009) 3302.
- [11] C. Wrede, B.W. Filippone, A. García, G.C. Harper, S. Lassell, J. Liu, M.P. Mendenhall, A.S.C. Palmer, D.I. Will, A.R. Young, in preparation.
- [12] G.C. Harper, D.I. Will, SNEAP 2009 Conference Proceedings, University of Arizona, Tucson, AZ.
- [13] Arizona Carbon Foil Co., Inc., Tucson, AZ 85719-2440, USA.
- [14] J.F. Ziegler, J.P. Biersack, SRIM 2008 and TRIM 2008. <<http://www.srim.org>>.