

In beam tests of implanted helium targets

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ABSTRACT: Targets of ${}^3,4\text{He}$ implanted into thin aluminum foils (approximately 100, 200 or 600 $\mu\text{g}/\text{cm}^2$) were prepared using intense helium beams at low energy (20, 40 or 100 keV). Uniformity was achieved by a beam raster across a tantalum collimator at the rates of 0.1 Hz (vertical) and 1 Hz (horizontal). Helium implantation into the very thin (80-100 $\mu\text{g}/\text{cm}^2$) aluminum foils failed to produce useful targets due to an under estimation of the range by SRIM code. The range in aluminum predicted by Northcliffe and Shilling and the NIST online tabulation, on the other hand, over estimate this range. An attempt to implant a second layer was also carried out, but did not significantly increase the helium content beyond the blistering limit. Rutherford Back Scattering of 1.0 and 2.5 MeV proton beams and recoil helium from 15.0 MeV oxygen beams were used to study the helium content and profile. The helium content and profile were very stable even after a prolonged bombardment (two days) with moderately intense beams of ${}^{16}\text{O}$ or ${}^4\text{He}$. Helium implanted into thin foils is a good choice, for example, for a measurement of the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction and the associated S_{34} astrophysical cross section factor (S-factor).

KEYWORDS: Accelerator modelling and simulations (multi-particle dynamics; single-particle dynamics); Targets (spallation source targets, radioisotope production, neutrino and muon sources).

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1. Introduction

Several key reactions of interest in nuclear physics and nuclear astrophysics involve light particles such as protons, deuterons, and alpha particles. The use of radioactive beams and inverse kinematics makes the availability of targets containing these elements necessary. Previous experiments in the field have used a variety of cryogenic, solid, and gas targets. One solution that has been used for hydrogen and deuterium is a thin polyethylene target. This solution cannot be used for helium, however, and some published experiments have used gas cells for helium targets. A helium gas jet target that was used in a measurement of the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction [1] was found later to have significant non-uniformity and yield a cross section which is approximately 40% smaller than measured by the same group in a later experiment [2]. Another method that has shown promise is the implantation of helium into a thin metal foil (*e.g.*, Al, Ni, Cu, Mo, Au). This has been used in a number of experiments, such as measurements of the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction cross section [3], as well as the ${}^3\text{He}(d, p){}^4\text{He}$ reaction cross section [4]. Noble gases, such as Ar and Xe [5, 6] implanted into metals were also used as targets. Indeed, noble gasses are known to form stable structures composed of bubbles with radii of approximately 100 nm when implanted into metals.

An implanted target suffers from a low number density, approximately a factor of 10 below targets commonly used in reaction studies in nuclear astrophysics, but has many advantages over a gas cell, with the most significant advantage being a well-localized target with high energy resolution. For example, a ${}^3\text{He}$ implanted target with 5×10^{17} *atoms/cm*² (just below the blistering limit) and a 1.0 MeV ${}^4\text{He}$ beam of modest intensity of 500 nA (280 pA) yield a count rate of 40 counts per hour in a HPGe detector with a 2% efficiency for detecting the resulting 2.016 MeV direct capture gamma rays at 90°. The large angular acceptance of such a detector placed close to the target results an energy spread with a FWHM of approximately 30 keV. Hence an implanted target in combination with moderately intense beams is useful for studying the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction and

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its associated astrophysical cross section factor (S_{34}) at modestly low energies of approximately $E_{cm} = 400$ keV.

One area of concern with implanted targets is the stability of the implanted gas over time, especially when used in beams. Beam heating has been cited as a problem [3]. For example it was noted [3] that the helium content in the center of the target was depleted after bombardment with an intense (2-3 μA) ^4He beam even though the implanted target was water cooled.

In this study we used helium implanted into thin aluminum foils (approximately 100, 200 or 600 $\mu\text{g}/\text{cm}^2$) in order to minimize the beam heating. We tested these thin implanted targets before and after bombardment with moderately intense beams (approximately 100 pA) of ^{16}O and ^4He . We did not observe a depletion in the helium content even after a prolonged (as much as two day) bombardment. The helium content and profile measured using back scattering of 1.0 MeV proton beams were observed to be very stable.

2. Target preparation

The targets were prepared both at the Institute of Material Science at the University of Connecticut (UConn) using a Varian CF-3000 Ion Implanter and at the 80 KV low energy (polarized ion source) facility of the Triangle University Nuclear Lab (TUNL) at Duke University. The implanter used at UConn employed a commercial dose processor and uniformity monitor to evenly distribute a precise amount of the desired ion in the target material. The TUNL implantation was performed using a beam raster in both the vertical (0.1 Hz) and horizontal (1 Hz) direction. The ^4He implanted at UConn was into an Al foil 600 $\mu\text{g}/\text{cm}^2$ thick, which corresponds to 1.33×10^{19} atoms/ cm^2 , and $^{3,4}\text{He}$ atoms were implanted in the TUNL facility into approximately 80, 100, and 210 $\mu\text{g}/\text{cm}^2$ aluminum foils. The thin aluminum foils (approximately 100 $\mu\text{g}/\text{cm}^2$) were prepared by evaporation and the 216 $\mu\text{g}/\text{cm}^2$ foils were purchased from Good Fellow Corp. They were mounted on frames with a 25 mm diameter open area and implanted area with a 12 mm diameter.

The range and straggle of the implanted ions were estimated using the code SRIM [7]. For the UConn ^4He implantation, an energy of 100 keV was chosen (which also corresponds to the lowest energy available from that implanter). At 100 keV the helium range is predicted by SRIM to be 153.6 $\mu\text{g}/\text{cm}^2$ (5688 Å). Four implantations were performed at the TUNL laboratory: 20 keV ^4He beams were implanted into 82, 94, and 120 $\mu\text{g}/\text{cm}^2$ aluminum foils; 30 keV ^3He beams were implanted into 112 and 119 $\mu\text{g}/\text{cm}^2$ aluminum foils; 25 keV ^3He beams were implanted into 100 and 102 $\mu\text{g}/\text{cm}^2$ aluminum foils; and 45 keV ^3He beams were implanted into 216 $\mu\text{g}/\text{cm}^2$ (0.0008 cm) thick aluminum foils. A majority of the results discussed in this paper were obtained using targets with 216 $\mu\text{g}/\text{cm}^2$ aluminum foils. All implantations used a fluence of approximately 4×10^{17} ions/ cm^2 — just below the blistering limit of 6×10^{17} He/ cm^2 indicated in the literature [8, 9, 10, 11, 12, 13]. The implantation fluence was measured by integrating the implanted beam. However problems with the suppression of secondary electrons prohibited us from measuring the total fluence with high accuracy.

In the implantation performed at UConn, we confirmed that the implanted helium did not remain in the aluminum foil when the areal density exceeded the blistering limit. In an attempt to increase the helium content in the foils, we prepared targets with two layers of ^4He . This was done

by two distinct methods. In the first method, a layer was implanted using an implantation energy of 160 keV followed by a second layer at 100 keV. In the second method, a layer was implanted at 100 keV and then the target was flipped so that the second layer at 160 keV was implanted from the opposite side. Although the areal density for each layer was below the blistering limit, the total for both layers exceeded the blistering limit value of $6 \times 10^{17} \text{ ions/cm}^2$. Spectra from a test of these two-layer targets showed low statistics and very broad ^4He peaks, indicating a low distributed helium ion content in the foils. This was attributed to the probability that the layers did not remain distinct, and together exceeded the blistering limit for ^4He in Al. During the TUNL implantation, we also produced one target with half of the dose implanted from one side of the foil and the second dose from the back side. The results obtained with this target are discussed below.

3. Target tests and results

Several tests of the implanted targets were performed using Rutherford Back Scattering (RBS) of 1.0 MeV proton beams extracted from the 1 MV single ended Yale Teaching Accelerator Lab, 2.5 MeV proton beams extracted from the TUNL tandem accelerator, and low energy oxygen beams extracted from the Yale ESTU tandem. The measured yield for scattering from the target material is given by:

$$Y(\Theta) = N_{beam} \times N_{target} \times \frac{d\sigma}{d\Omega_{cm}}(\Theta) \times \frac{d\Omega_{cm}}{d\Omega_{Lab}}(\Theta) \times d\Omega_{Lab}$$

Note that neglecting to consider the Jacobian $= \frac{d\Omega_{cm}}{d\Omega_{Lab}}(\Theta)$ for p + He scattering (of the order of 0.5) led to the wrong conclusion that only 50% of the implanted helium dose is retained in the target [14]. The cross section $\frac{d\sigma}{d\Omega_{cm}}(\Theta)$ is either the calculated RBS cross section when appropriate, or the measured cross section for p + ^{27}Al [15, 16], p + ^3He [17], or the cross section calculated from the measured phase shifts of the elastic scattering of p + ^4He [18].

The test at the ESTU tandem at the A.W. Wright Nuclear Structure Laboratory at Yale University used a 15 MeV ^{16}O beam. The elastic scattering of ^{16}O from the aluminum substrate was measured using detectors placed at $\Theta_{Lab} = 30^\circ$, and $= 40^\circ$ and the recoil ^4He were detected using silicon surface barrier detectors placed at $\Theta_{Lab} = 10^\circ, 15^\circ, 20^\circ, 25^\circ, 40^\circ$, and 45° ; $\Theta_{cm} = 180^\circ - 2\Theta_{Lab}$, with an aluminum absorber foil ($2.7 \mu\text{g/cm}^2$) which stopped the scattered oxygen ions and aided in the separation of alpha particles from protons. The recoil alpha particles lost about 1 MeV in the absorber foil, contributing about 100 keV to the FWHM energy resolution of the recoil alpha spectra. The detectors were also collimated to an area of 100 mm^2 , causing them to subtend an angle of $\pm 1^\circ$, contributing 270 keV to the FWHM energy resolution. We note that the measured FWHM of about 520 keV (see figure 1) is dominated by the energy loss of the ^{16}O beam traversing the implanted layer of approximately 360 keV FWHM. The measured helium recoil spectra are shown in figure 1. The extracted target content shown in figure 2 was found to be independent of scattering angle, confirming the assumption of Rutherford scattering of $^4\text{He} + ^{16}\text{O}$. The areal density of ^4He was measured to be $3.4 \pm 0.3 \times 10^{17} \text{ atoms/cm}^2$, which is equal to the implanted fluence. We do not confirm the suggested loss of helium discussed in ref. [14]. The aluminum areal density was measured using RBS of the oxygen beam to be $1.40 \pm 0.1 \times 10^{19} \text{ atoms/cm}^2$, which confirmed the manufacturer's quoted foil thickness of $600 \mu\text{g/cm}^2$.

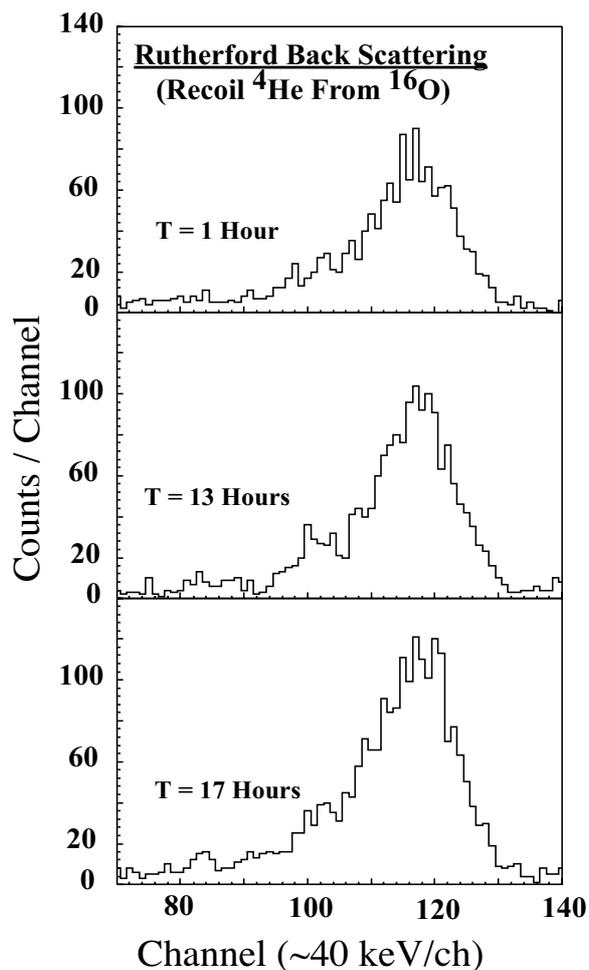


Figure 1. The measured spectra of recoil helium from 15.0 MeV oxygen beams. Spectra taken with similar integrated oxygen beams at 1, 13 and 17 hours are shown.

The helium profile was measured by measuring the FWHM of the spectra of recoil helium from a 20 MeV ^{16}O beam with an average intensity of 50 particle nA. As shown in figure 3 the FWHM remained constant over the measurement duration of 18.4 hours indicating a stable helium profile during this prolonged bombardment with an oxygen beam of moderate intensity. In figure 4 we show the ratio of the yield of recoil ^4He to elastic scattering of ^{16}O from aluminum plotted against the cumulative oxygen ions beam dose. No deterioration of the target was observed for a continuous exposure to beam up to 18.4 hours at this beam intensity.

All ^3He and ^4He implanted targets were tested prior to bombardment by the scattering of a very low intensity 2.5 MeV proton beam (approximately 30 nA) into two detectors placed at $+173^\circ$ and -173° with respect to the beam. The spectra obtained are shown in figure 5. One of the targets was implanted with 50% of the dose (2×10^{17} helium/cm²) from the front side and the same dose from the back of the target. The low energy loss of 2.5 MeV protons in aluminum did not allow separation of protons scattered off the two separated helium layers, as shown

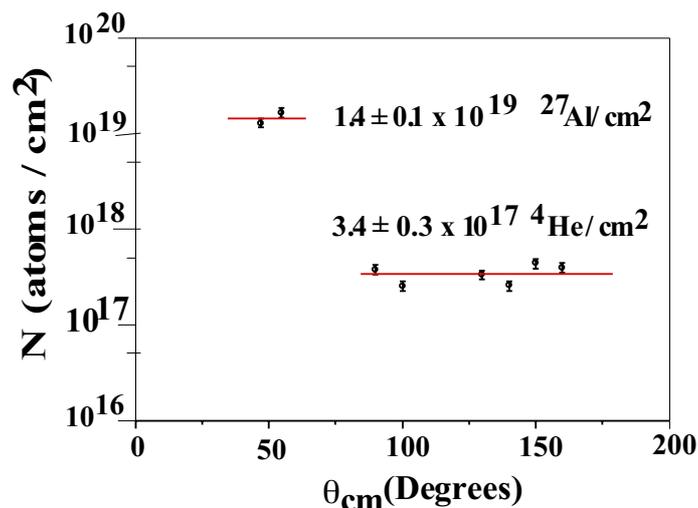


Figure 2. The ^4He content of the implanted target prepared at UConn and measured at Yale with low energy oxygen beams.

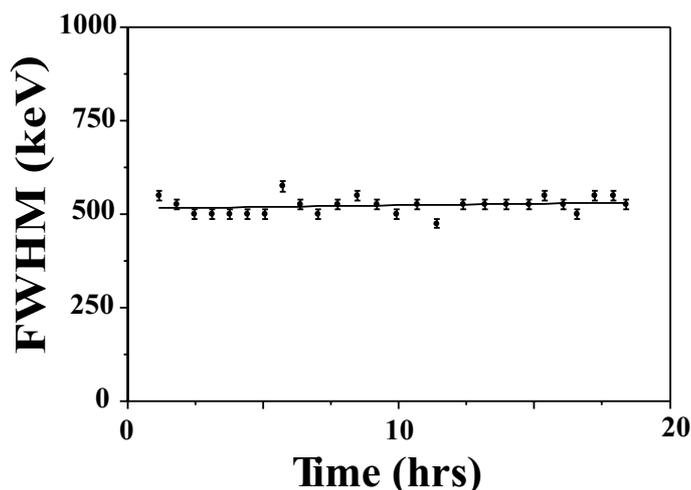


Figure 3. The measured FWHM of the recoil ^4He shown in figure 1 as a function of time.

in figure 5. But the larger energy loss of 1.0 MeV protons allowed us to observe two distinct peaks as shown in figure 6. The doubly implanted target was exposed over two days to ^4He beams having an average intensity of 80 particle nA . This two layered and all the single layered targets (that were not exposed to beams) were tested by scattering 1.0 MeV proton beams into a detector placed at 163° . The obtained spectra are shown in figure 6. We first note that the SRIM calculations [7] predict a range of $92.8 \mu\text{g}/\text{cm}^2$ (3436 A) for 50 keV ^4He in ^{27}Al . But the Northcliffe and Schilling (NS) tabulation [19] predicts a range of $142 \mu\text{g}/\text{cm}^2$ and the NIST [20] online tabulation predicts a range of $141.8 \mu\text{g}/\text{cm}^2$. Our measurements indicate that the SRIM calculations underestimate the range of very low energy alpha particles in aluminum

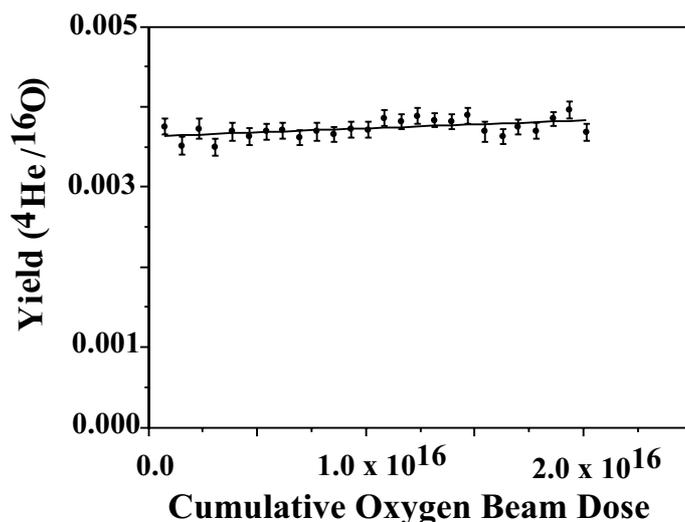


Figure 4. The ratio of the measured yield of recoil ^4He and elastic scattering of oxygen from ^{27}Al as a function of cumulative oxygen beam dose.

and the NS and NIST tabulations overestimate the range of low energy alpha-particles in aluminum.

As an example the SRIM calculations predict a range of $44.4 \mu\text{g}/\text{cm}^2$ (1645 A) for 20 keV ^4He in aluminum, but the NIST tabulation predicts a range of $83.7 \mu\text{g}/\text{cm}^2$ at this energy. The NS tabulations does not list a range for energies below 50 keV. For the TUNL implantation of 20 keV ^4He into the very thin foils (80 and $100 \mu\text{g}/\text{cm}^2$) the SRIM calculations place the implanted ^4He in the middle of the aluminum foil, but the NIST estimate places it at the end of these foils. The test of these very thin implanted targets using back scattering of a 1.0 MeV proton beam revealed that only 10% of the ^4He fluence was retained in the aluminum foil, suggesting an underestimate of the range by SRIM. For the 45 keV ^3He beam (15 keV/amu) SRIM predicts a range of $106.3 \mu\text{g}/\text{cm}^2$ (3937 A) with a straggle of $27.4 \mu\text{g}/\text{cm}^2$ (1013 A). The SRIM calculations predicts that the two sided implantation of 45 keV ^3He into the $216 \mu\text{g}/\text{cm}^2$ aluminum foil would yield two helium layers right on top of each other in the center of the doubly implanted target. The NIST tabulation predicts the larger range of $156.5 \mu\text{g}/\text{cm}^2$ thus two helium layers separated by $110 \mu\text{g}/\text{cm}^2$. In figure 6 we observe two distinct peaks from the scattering of 1.0 MeV which is at odd with the SRIM prediction. These two low energy peaks were fitted resulting in two Gaussians separated by 40 keV, corresponding to two ^3He layers separated by $45 \mu\text{g}/\text{cm}^2$ (note that at backward angles the energy loss is doubled), which is smaller than the separation predicted by the NS and the NIST tabulations. The FWHM of the second narrow peak (figure 6b) and the narrow peak of the single layer target (figure 6a) of 27 keV correspond to $31 \mu\text{g}/\text{cm}^2$ of ^{27}Al and is, in fact, consistent with SRIM prediction for the straggle of helium in aluminum.

It is also worth noting that the first peak at low energy is broader (46 keV) than the second one (27 keV). Since the first peak corresponds to the first implantation from the front, we conclude that the second implantation caused the broadening of the first implanted layer. While the first peak

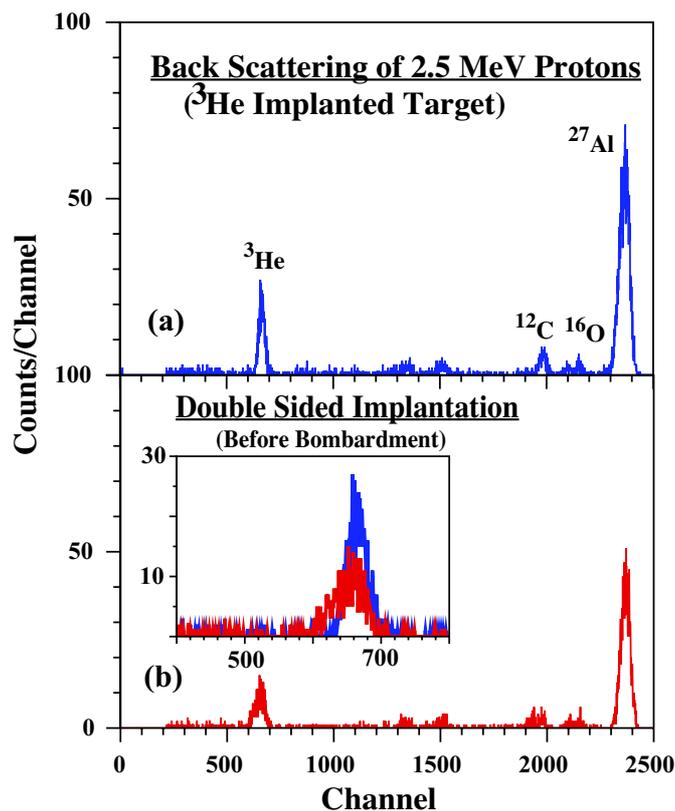


Figure 5. The measured spectra of elastic scattering of 2.5 MeV proton beams from implanted targets prepared at TUNL: (a) single implanted ^3He target before bombardment (blue color) and (b) double implanted ^3He target (red color), also before bombardment.

is broadened, the layer still contains the same amount of ^3He as the first layer, see figure 7. This observation allows us to conclude that the implantation beam of 45 keV and intensity of 2-3 μA with a beam heating of approximately 100 mW, does not remove the helium content but only causes a broadening of the profile. This observation is similar to the effect observed with the heating of a ^7Be implanted target recently reported by the Weizmann group [21]. The 1.0 MeV ^4He beams that one may use for measuring the $^3\text{He}(\alpha, \gamma)^7\text{Be}$ reaction with a $216 \mu\text{g}/\text{cm}^2$ ^3He implanted target lose 375 keV in the target (placed at 45° with respect to the beam). Hence our observations suggest that beam heating will not be a problem even for a beam with a modest intensity of 265 particle nA (approximately 500 nA). As shown above such a beam target combination yields a useful count rate for measuring the $^3\text{He}(\alpha, \gamma)^7\text{Be}$ reaction at energies as low as approximately $E_{cm} = 400$ keV. The ^3He implanted into $216 \mu\text{g}/\text{cm}^2$ foils were scanned with 1.0 MeV proton beams with a diameter of 3 mm using eight steps of 2.4 mm each. This scan across the doubly-implanted target was performed after two days of bombardment with 80 particle nA beam of ^4He with a diameter of approximately 6 mm in the center of the 12 mm implanted helium area. The results of the scan are shown in figure 7. We note that the ratio of the yield of scattered protons from ^3He and ^{27}Al does not vary across the doubly implanted target, nor does the peak position or the FWHM of the

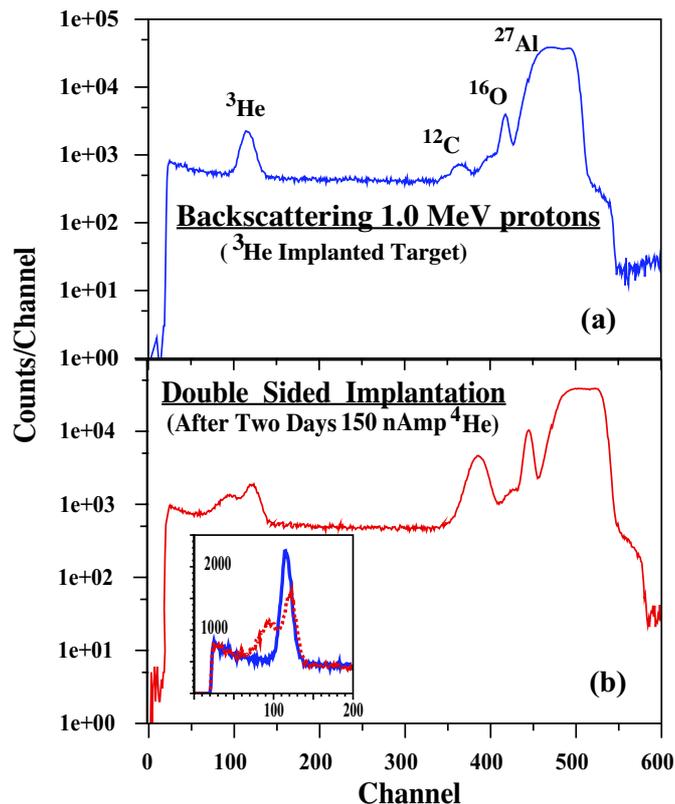


Figure 6. The measured spectra of elastic scattering of 1.0 MeV proton beams from (a) single implanted ^3He target before bombardment (blue color) and (b) double implanted ^3He target after bombardment (red color). The observed carbon buildup in spectrum (b), is approximately $5 \mu\text{g}/\text{cm}^2$ after two days of bombardment.

two observed peaks. This suggests the helium profile and content of the two layers remained stable even after the two days of bombardment.

From the known cross section for scattering of $p + ^3\text{He}$ [17], the Rutherford scattering of $p + ^{27}\text{Al}$ [15, 16], the Jacobian, and simple kinematics we calculate the yield ratio for $^{27}\text{Al}/^3\text{He}$ to be 3.99 times the atomic number ratio. The $^3\text{He}/^{27}\text{Al}$ yield ratio of 1.73% leads to $^{27}\text{Al}/^3\text{He}$ number ratio of 14.5 or a $^3\text{He}/^{27}\text{Al}$ number density of 6.9%. With an aluminum thickness of $216 \mu\text{g}/\text{cm}^2$ and number density of $4.8 \times 10^{18} /\text{cm}^2$ we derive a helium double layer including $3.3 \times 10^{17} ^3\text{He}/\text{cm}^2$, consistent with the implanted fluence (the integrated beam).

4. Conclusion

We prepared $^3,^4\text{He}$ targets by implanting low energy helium beams into thin aluminum foils and tested them using (mostly Rutherford) Back-Scattering of low energy proton and oxygen beams before, during and after bombardment with modestly intense beams of ^4He and ^{16}O . We measured the helium profile and content using (mostly Rutherford) Back-Scattering and demonstrated that these targets are robust against bombardment by modestly intense beams. No degradation in the helium profile or content was observed after a prolonged bombardment with moderately intense

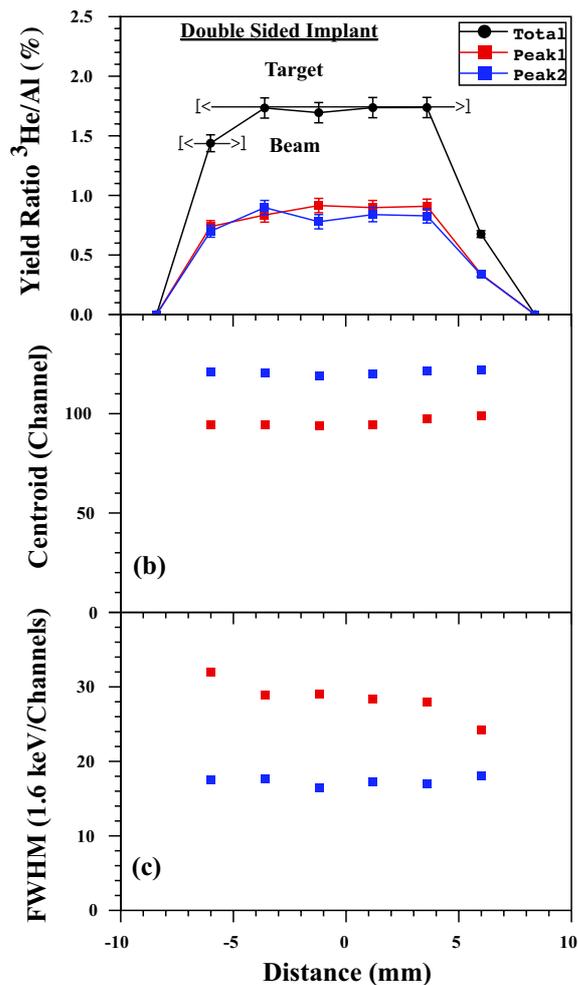


Figure 7. Results of the scan across the double sided ${}^3\text{He}$ implanted target using 1.0 MeV proton beams. We show (a) the ratio of yield of elastic scattering from ${}^3\text{He}$ and ${}^{27}\text{Al}$ for the two low energy peaks shown in figure 6b, corresponding to the two helium layers and the total sum of yield, (b) the centroid of the two peaks, (c) the FWHM of the observed peaks. The scan was performed after a two day bombardment with ${}^4\text{He}$ beams as discussed in the text. The ${}^3\text{He}$ implanted area (± 6 mm from target center), and the 1.0 MeV proton beam spot (diameter of 3 mm) are shown. Lines are drawn to connect data points and guide the eye.

beams. Such targets can be very useful for certain studies with modestly intense beams, including a measurement of the ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$ reaction at energies as low as $E_{cm} = 400$ keV.

Acknowledgments

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