The ^{28}Si(d,α) reaction

V Araujo-Escalona[1, a)], L Acosta[1], E Andrade[1], L Barrón-Palos[1], C Cantó[1], F Favela[1], A Huerta[1], M E Ortiz[1], C Solís[1] and E Chávez[1, b)]

[1]Instituto de Física
Universidad Nacional Autónoma de México
Circuito de la Investigación Científica, Ciudad Universitaria
CP. 04510, Coyoacán, Ciudad de México.

[a)] vickyaraujo@fisica.unam.mx
[b)] chavez@fisica.unam.mx

Abstract. Recent techniques and experimental methods open up new ways to explore nuclear reactions relevant to nucleosynthesis at stellar combustion temperatures. In this work we focus on the case of ^{26}Al, isotope associated with the identification of active nucleosynthesis spots in the cosmos. Its presence in the solar system was unexpected until it was found in the Allende meteorite. It is now understood that cosmic rays induce nuclear reactions to produce ^{26}Al. On Earth, this process is well known and is the basis of many environmental studies. So ^{26}Al is not just the product of some high-metallicity star collapse. Natural Silicon targets were irradiated with deuteron beams of energies between 0.9 and 2.6 MeV. The produced ^{26}Al were counted later-on in an AMS facility. In this paper, we describe in detail the experimental protocol developed to quantify the number of deuterons hitting the target, as a first step to determine the total cross section.

1. Introduction

^{26}Al is a remarkable isotope from so many points of view that it is worth reminding a few. From the nuclear structure point of view, it is well known that the heaviest odd-odd stable nucleus is ^{14}N. From there on: ^{18}F, ^{22}Na, ^{26}Al, and up to heavier nuclei, they all decay by β+ emission. The ground state quantum numbers of these three consecutive listed nuclei show a curious sequence: 1+, 3+ and 5+ [1]. The unusual large spin of the ^{26}Al ground state makes the β+ transition to ^{26}Mg ground state (0+) so difficult (fourth forbidden) that it decays instead to the first excited state (1.80873 MeV, 2+), still second forbidden [2], as a result, ^{26}Al has the largest life time (7.2x10^5 y) among all odd-odd N=Z nuclei.

Moreover, the spin assignment of its five lower lying states gives the sequence: 5+, 0+, 3+, 1+ and 2+. Now Electromagnetic transitions (gamma) between these states also involve large angular momentum transfers, making all these states uncharacteristically long lived. So much so, that the first excited state 0+ at 228.305 keV has a mean life of 6.3452 s [1], which for an electromagnetic transition is extremely large. So much so that it is considered a "meta-stable" state and often referred to as ^{26m}Al which plays an important role in studies of the weak interaction (Super-allowed $0^+ \rightarrow 0^+$ transitions) and of the Cabibbo–Kobayashi–Maskawa (CKM) matrix [3].

^{26}Al is like a laboratory for multidisciplinary studies. Besides the ^{14}C/^{12}C ratio, the ^{26}Al/^{27}Al precise determination has become one of the main activities in Accelerator Mass Spectrometry (AMS) laboratories [4].

There is the still the outstanding question of its formation: how ^{26}Al is made? There are many ways in which a nucleus can be formed: Stellar Nucleosynthesis, fragmentation of heavier nuclei by high-energy cosmic particles, neutron capture and low energy nuclear reactions. Cross section measurements from nuclear physics experiments are needed to better understand all these processes.

As for cross-disciplinary sciences, the fact that this isotope is found on Earth, the solar system, the galaxy and the Universe [5], makes of it a unique tool for discovery in geology, environmental sciences, solar models, star and galactic evolution, cosmology and others.

Special interest in ^{26}Al surged with the observation of a ^{26}Mg excess of in the Allende meteorite [6] and grew with the detection of the 1.809 MeV γ-line in cosmic-rays [7]. This γ-ray is a clear indicator of the presence of ^{26}Al β-decay and allows the validation of some stellar nucleosynthesis models. According to these models, ^{26}Al is mainly produced through the ^{25}Mg(p,γ) reaction [8]–[11]. Another reaction that has been studied in this regard is ^{24}Mg(^{3}He,p)^{26}Al [12]. No information can be found in the literature about the contribution from the ^{28}Si(d,α)^{26}Al. This work is a progress report on the study of this last reaction. Deuteron irradiations are made at the 5.5 MV CN-Van de Graaff accelerator facility. The irradiated Silicon targets are taken to our Accelerator Mass Spectrometry (AMS) facility for ^{26}Al counting. The lowest concentration (^{26}Al/^{27}Al ratio) measurable at LEMA being 10^{-14} projects the lowest cross section we could measure with this technique to be around 1 nbarn.

2. Experimental setup

Our protocol is similar to that proposed by Arazi et al. [10], [13] in their study of the ^{25}Mg(p,γ)^{26}Al reaction, where Magnesium targets were first irradiated with proton beams, and after chemical separation and addition of ^{27}Al (pilot), a cathode is prepared to count the ^{26}Al isotopes in an AMS facility. In our case, no chemical preparation of the irradiated substance nor additional pilot material were necessary. The cathode itself as needed for AMS measurements was filled with a known mixture of ^{nat}Si and ^{27}Al powders and directly irradiated with deuteron beams at the 5.5 MV CN-Van de Graaff Accelerator facility. Cathodes are then taken "as is" to LEMA ("Laboratorio de Espectrometría de Masas con Aceleradores") for ^{26}Al counting.

2.1. Target preparation

High purity Silicon and Aluminum powders were mixed and tried as cathodes at the AMS isotope separator in different proportions to select the target composition that would have the most Silicon atoms and yet produce enough ^{27}Al current in the Ion Source. This "pilot" beam is needed to fine-tune the Isotope separator for mass 27 and then the necessary fields for mass 26 are easy to set. At the end, both ^{26,27}Al isotopes have to be counted precisely. The (^{26}Al/^{27}Al) ratio measured is finally compared to that of a known reference material for an absolute value [14].

In [14] is detailed the use of the copper cathode holder required for our AMS measurement. These are the same sample holders used as containers for the Al:Si mixture during deuteron irradiation. Avoiding in this way any additional chemical treatments between deuteron irradiation and AMS counting.

2.2. Deuteron Irradiation

After selecting the Si/Al ratio, fresh cathodes were prepared and taken to the 5.5 MV Van de Graaff accelerator laboratory to be irradiated with deuteron beams.

Two 300 μm thick *PIPS* (Passivated Implanted Planar Silicon) [15], [16], detectors were placed at 150° relative to the beam direction left and right to detect back-scattered particles, arrangement known as Rutherford Backscattering Spectrometry (RBS). Both detectors used 1.8 mm diameter collimators [14]. Since there is no significant difference between the data from both detectors, in this report only data from one detector will be shown for simplicity. At these low energies, far below the Coulomb barrier for this system (3.91 MeV), reaction yields are extremely small and strongly energy dependent.

3. Data analysis and preliminary results

Figure 1 shows the energy spectrum of particles reaching one of our detectors at 150° during an irradiation at E_d = 2.2 MeV. The well-known elastic scattering contribution from an infinite thick target has been simulated using SIMNRA [17], a fully graphical user interface program that can simulate and fit elastic scattering and nuclear reaction data. A higher energy yield from positive Q-value (d,α) and (d,p) reactions is observed. At some point, it was suggested the idea to use this high-energy yield for normalization, however, as the beam energy is reduced this yield disappears, as it should, and since our final goal is to extend our cross section measurements at energies as low as possible, we decided to use the elastic yield.

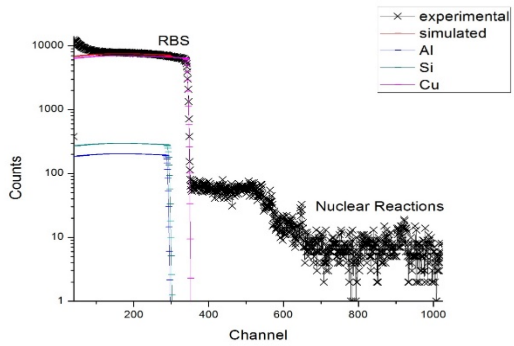
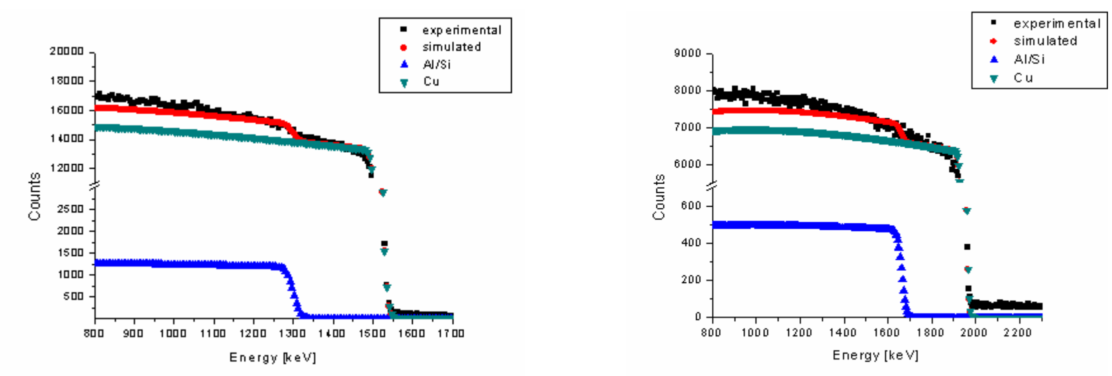


Figure 1. Energy spectrum and simulation by SIMNRA from the deuteron irradiation of the target at E_d = 2.2 MeV

In figure 2 we zoom-in the low energy section (elastic) of two spectra corresponding to deuteron beam energies of 1.7 (a) and 2.2 (b) MeV. Since our energy resolution does not allow the separation from the contribution of mass 27 to that of mass 28, the Al/Si target mixture contribution is taken together as one (mass 28) for the SIMNRA simulations. These simulations allow us to identify the contributions to each spectrum from deuterons scattered off Copper and those off Al/Si. The quality of the fit is clearly not the same for both energies; this fact led us to conclude that there was a misalignment between the beam axis and the center of the target. This misalignment was extensively addressed in a previous report [18]. There we showed how critical beam optics and alignment are when you deal with a 650 µm radius.



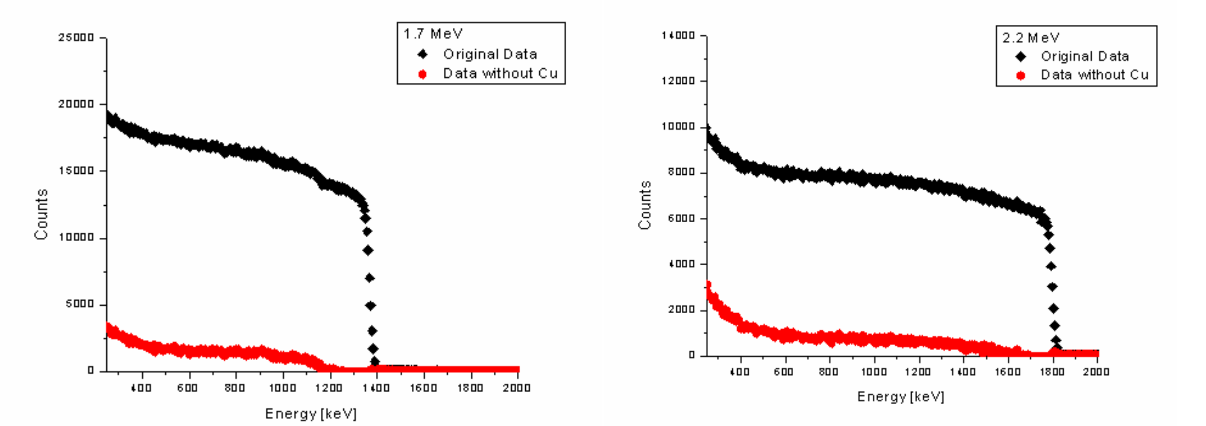
(a) *(b)*

Figure 2. Data simulation from RBS spectra from deuteron irradiation of two targets: E_d= 1.7 (a) and 2.2 (b) MeV bombarding energy.

Journal of Physics: Conference Series **730** (2016) 012003 doi:10.1088/1742-6596/730/1/012003

Determination of the total number of incident deuterons is made by simulating the RBS spectrum with SIMNRA.

The RBS spectra (see Figure 3) show that there is a significant interaction of the beam with the copper holder. The first part of the analysis focuses on the fit of the RBS contribution from Copper. Once a good fit is reached, we subtract this contribution to the original data. The result is considered the contribution to the RBS spectrum from deuteron scattered from the Al/Si mixture. A second fit to this subtracted spectrum with SIMNRA yields the desired number of incoming deuterons during irradiation.



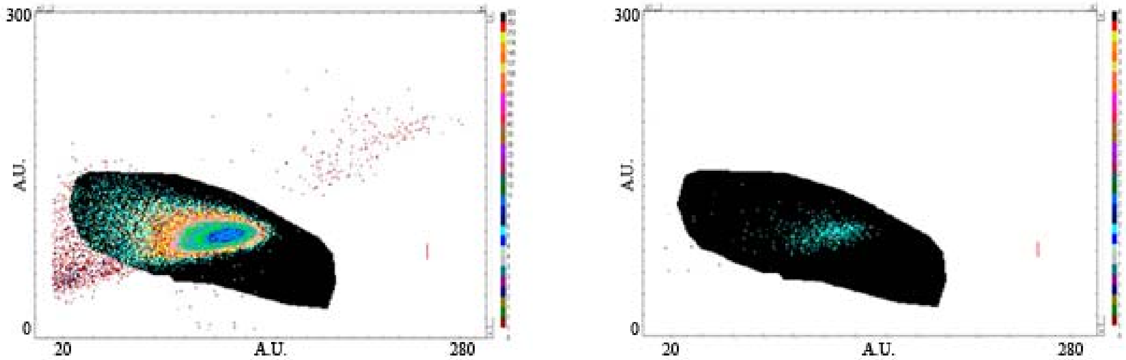
(a) *(b)*

Figure 3. RBS spectra for two different irradiation energies (a) 1.7 MeV and (b) 2.2 MeV. Squares represent the original data and circles represent only the interaction of the deuteron beam with Si/Al.

3.1. ^{26}Al counting

Irradiated and non-irradiated cathodes were taken to *LEMA* for Aluminum counting. Figure 4 shows typical E-ΔE maps from the split-anode of the ionization chamber detector in the Isotope Separator of *LEMA*. Counts in the shaded region correspond to ^{26}Al events. The pilot beam (^{27}Al) is stopped and quantified in a Faraday Cup. These measurements are compared with those from a reference material to obtain an absolute determination of the excess ^{26}Al produced.

In some of our measurements, data deviated significantly from the "typical" map, as shown in Figure 4 (a). The large unidentified background could be eliminated by using 5 mm collimators all along the isotope separator in LEMA, both for tuning and data taking. Reducing the count-rate, but making sure to exclude unexpected contributions, see Figure 4 (b).



(a) *(b)*

Figure 4. E-ΔE maps from the ionization chamber at LEMA. The dark region corresponds to ^{26}Al ions (a) Maximum acceptance. (b) 5 mm diameter collimation throughout the system, limiting detection of just the central trajectories.

Journal of Physics: Conference Series **730** (2016) 012003 doi:10.1088/1742-6596/730/1/012003

It is worth stressing at this point that the compound normally used for AMS work with Aluminum, is Aluminum oxide (Al_2O_3) and that we are using a simple mixture of Al/Si.

To better understand the origin of our background, we did a mass analysis of our beam at the injector magnet by using a beam current integrator and slowly changing the magnetic field, see Figure 5. The arrow shows the magnetic field corresponding to mass 27. To the right, at higher magnetic fields, the very large contribution of mas 28 is visible. One can see that mass 27 is "mounted" on some continuous background when the collimators are out, making tuning difficult and eventually leading to inaccurate measurements of the ^{26}Al/^{27}Al ratio (we will call it ΔAl in the following).

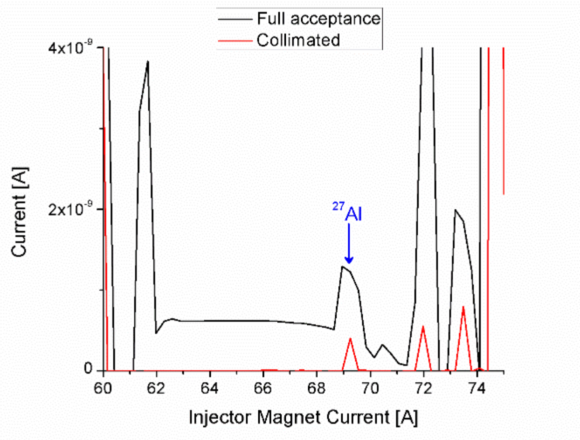


Figure 5. Beam current integration before injecting into the tandem accelerator by scanning the magnetic field in the low energy magnet. The black line corresponds to full acceptance and the red line to the case where only central trajectories are allowed.

If we restrict the beam before the injecting magnet allowing only central trajectories, we get the mass distribution shown in Figure 5 (red line). The ^{27}Al current is much smaller, but the background around mass 27 disappears, the tuning is more certain and we can guarantee that each and every count in the shaded area is ^{26}Al as shown before in Figure 4 (b).

All deuteron-induced nuclear reactions occur at the surface of our Al/Si mixture target. At our energies, beams are stopped within the first 30 μm. Figure 6 shows ΔAl for cathodes irradiated at different beam energies as a function of time for the first 5 minutes. ΔAl exhibits the same behavior for all but one irradiated cathode. The contrast with a control non-irradiated cathode serves to demonstrate that an excess ^{26}Al was indeed produced during deuteron irradiations.

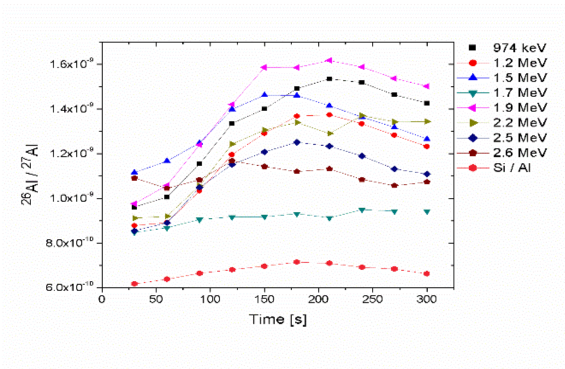


Figure 6. Shows ^{26}Al/^{27}Al ratio of cathodes irradiated and compared with a non-irradiated cathode. (Non-standard data)

The Sputtering Negative Ion Cesium Source (SNICS) at *LEMA* will sputter ions from the very center of the cathode. If, as was the case of the irradiation at 1.7 MeV, the beam-target alignment is off by a few hundred microns, the reactions of interest will happen near the edge of the Copper holder and the *SNICS* will not sputter those atoms.

Knowing we were facing systematic problems in our data, we decided to continue with the data processing to calculate a "yield" (thick target integrated cross section), which is one step closer to the desired excitation function.

The number of ^{26}Al is derived from ΔAl in *LEMA* and the number of incident deuterons is determined by SIMNRA. With that information we can calculated the Yield function, *Y(E)*.

$$Y(E) = \frac{number\ of\ Aluminium\ 26\ produced}{number\ of\ incident\ particle}$$

Figure 7 shows this function as calculated with data from each of the two monitor detectors used during deuteron irradiation.

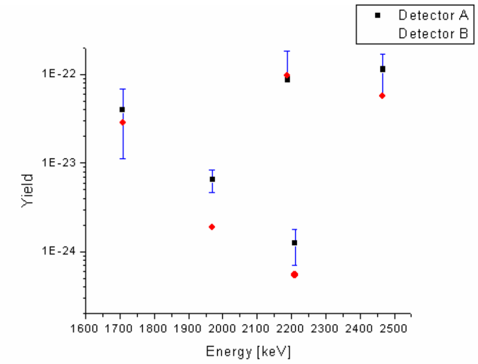


Figure 7. Shows Yield function as a function of energy.

The behavior in Yield function reflects the problems already mentioned in the derivation of both the number of ^{26}Al produced during irradiation, as well as the number of incident deuterons.

4. Summary and conclusions

This is a progress report of an ongoing effort to measure the ^{28}Si(d,α)^{26}Al excitation function at energies below the Coulomb barrier. Here we describe a number of sources of systematic errors encountered along our work. Some are related to the quantification of the number of incident beam particles on target during deuteron irradiation and others to the determination of the number of ^{26}Al produced.

We learn how to fine-tune our beam-target alignment during deuteron irradiations at the CN-Van de Graaff accelerator facility. We prove that the simple mixture Al/Si works fine for the ^{26}Al counting at our AMS facility, provided extra care is taken to reduce background from mass 28. No need for any additional chemical treatment of the irradiated substance. Having identified the main sources or systematic errors in our experimental setups, we are ready to collect new data and generate a yield function from which we could extract the desired excitation function and extend it to lower energies until we reach the practical limit of this technique, we estimate it to be near 10 nb.

It is worth to pursue this effort to produce needed data in this region, which has implications for stellar evolution models.

Acknowledgments

Special thanks to M. Veytia, R. Gleason and H. Vargas for help with design and construction at IFUNAM's mechanical shop. This work was possible thanks to financial support from CONACYT through grants numbers: 51600, 82692,123655 and DGAPAUNAM: IN-118310, IN-112609, IN-105510, IN-115213, TA-100213, IN-103312, IA-101616.

References

[1] Firestone R B, Shirley V S, and Baglin C M 1996 *Table of isotopes* Wiley Interscience
[2] Samworth E A, Warburton E K, and Engelbertink G A P 1972 *Phys. Rev. C* **5** 138
[3] Çalık A E, Gerçeklioğlu M, and Salamov D I 2009 *Zeitschrift für Naturforsch. A* **64** 865
[4] Tuniz C 2001 *Radiat. Phys. Chem.* **61** 317
[5] Suades M, Hernanz M, and De Séréville N 2010 *Highlights of Spanish Astrophysics V* Springer
[6] Lee T, Papanastassiou D A, and Wasserburg G J 1976 *Geophys. Res. Lett.* **3** 41
[7] Mahoney W A, Ling J C, Jacobson A S, and Lingenfelter R E 1982 *Astrophys. J.* **262** 742
[8] Straniero O, Imbriani G, Strieder F, Bemmerer D, Broggini C, Caciolli A, Corvisiero P, Costantini H, Cristallo S, DiLeva A, Formicola A, Elekes Z, Fülöp Z, Gervino G, Guglielmetti A, Gustavino C, Gyürky G, Junker M, Lemut A, Limata B, Marta M, Mazzocchi C, Menegazzo R, Piersanti L, Prati P, Roca V, Rolfs C, Rossi Alvarez C, Somorjai E, Terrasi F, and Trautvetter H P 2013 *Astrophys. J.* **763** 100
[9] Formicola A, Best A, Imbriani G, Junker M, Bemmerer D, Bonetti R, Broggini C, Caciolli A, Confortola F, Corvisiero P, Costantini H, Elekes Z, Fulop Z, Gervino G, Guglielmetti A, Gyürky G, Gustavino C, Lemut A, Limata B, Marta M, Mazzocchi C, Menegazzo R, Prati P, Roca V, Rolfs C, Alvarez C R, Somorjai E, Straniero O, Strieder F, Terrasi F, and Trautvetter H P 2008 *J. Phys. G: Nucl. Part. Phys.* **35** 014013
[10] Arazi A, Faestermann T, Niello J O F, Knie K, Korschinek G, Poutivtsev M, Richter E, Rugel G, and Wallner A 2006 *Phys. Rev. C* **74** 025802
[11] Strieder F, Limata B, Formicola A, and Imbriani G 2012 *Phys. Lett B* **707** 60
[12] Fitoussi C, Duprat J, and Tatischeff V 2008 *Phys. Rev. C* **78** 044613
[13] Niello J O F, Arazi A, Faestermann T, Knie K, Korschinek G, Richter E, Rugel G, and Wallner A 2003 *Brazilian J. Phys.* **33** 218
[14] Araujo-Escalona V, Andrade E, Barrón-Palos L, Canto C, Favela F, Huerta A, De Lucio O, Ortiz M E, Solís C, and Chávez E 2015 *AIP Conf. Proc* **1671** 030003
[15] Nuclear C 1993 "Alpha PIPS detectors -properties and applications," *Appl. Note*
[16] Egorov O B, Addleman R S, O'hara M J, Marks T, and Grate J W 2005 *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.* **537** 600
[17] Mayer M 1997 SIMNRA User's Guide, Tech. Report IPP, 9/113 *Rep. IPP*, p. 9/113
[18] Araujo-Escalona V, Acosta L, Andrade E, Cantó C, Favela F, Huerta A, De Lucio O, Solís C, and Chávez E 2016 *Nucl. Instruments Methods Phys. Res. Sect. B Beam Interact. with Mater. Atoms*, under review