Lab 4: Nuclear Reactions and Nucleosynthesis

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March 26, 2017

Abstract

A 2 MeV proton beam is used to annihilate lithium and flourine atoms from a LiF foil. Alpha particle detection is used to verify the nuclear reactions involved. The probabilty cross-sections are computed for the nuclear reactions ^{19}F(p,α)^{16}O and ^{7}Li(p,α)^{4}He.

1 Introduction: Lithium and Fluorine

The nuclear properties of lithium are of interest, especially the reaction differential cross-section for ^{7}Li(p,α)^{4}He. Studies of the Sun's photosphere show the abundance of lithium relative to hydrogen and helium less nearly an order of magnitude. A large cross-section for ^{7}Li(p,α)^{4}He is believed responsible; it predicts that ionized hydrogen will readily collide with lithium, transforming the lithium to helium, and emitting an alpha particle. This is one transition that takes place in stellar nucleosynthesis, and is maintained as fresh lithium is carried toward a star's core by convective currents, but even with this process and reaction in mind, modern astrophysicists have yet to completely explain the lack of abundant lithium in our sun's photosphere. Studies of the nuclear properties of lithium could elucidate a better stellar structure model, but this is outside the scope of our study. [2]

Fluorine can be rearranged in a similar fashion. It is one of the rarest elements observed by astronomers, and thought to be for the same reasons: it is readily rearranged by a proton to produce oxygen and an alpha particle. Figure 1 shows relative abundances of many elements. To judge whether the high-probability explanation is plausible, we will determine the reaction differential cross-sections of the fluorine-proton reaction ^{19}F(p,α)^{16}O and the lithium-proton reaction ^{7}Li(p,α)^{4}He. In this study, we performed a prompt radiation analysis by observing the alpha particle products of each reaction, and from the kinetic energy spectrum of these products, the differential cross-sections can be computed.

2 Proton Beam and Detector

The Tandem Van de Graff Accelerator Lab provided a 1.95 ± 0.05 MeV proton beam incident on a LiF foil. Under these conditions, we expected the nuclear reactions described in Section 3 to occur, and Rutherford scattering. We used a circular normal-faced surface barrier detector to observe the alpha particle products of ^{19}F(p,α)^{16}O and ^{7}Li(p,α)^{4}He and the protons from Rutherford scattering. [1] The detector was positioned at $149.95^\circ \pm 0.05^\circ$ from the proton beam, which we define as the lab frame of reference; see Figure 2.

The end goal is to create an alpha particle spectrum, and toward this the detector is used to count alpha particles and measure their kinetic energy. An alpha particle incident on the detector

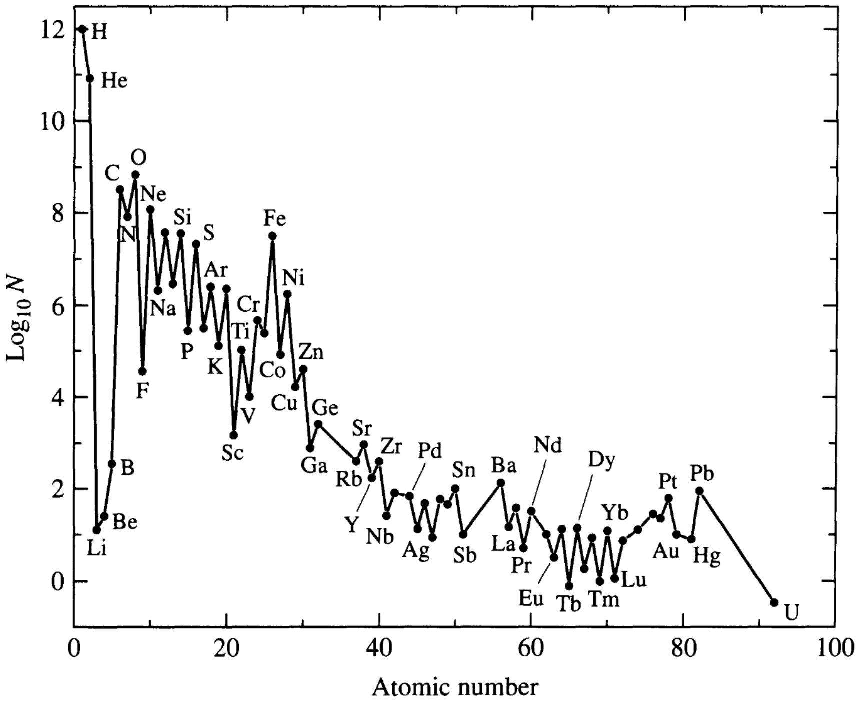

Figure 1: Relative elemental abundances in the sun's photosphere. Lithium and fluorine are much less abundant than their neighbor elements. It is thought this is due to large reaction differential cross-sections for a proton collision with these nuclei. [2]

Figure 2: The detector was positioned at 149.95° ± 0.05° relative to the direction of the proton beam. This angle was maintained through both experiments.

M1,E1:	Incident Particle
M2,E2:	Target Nucleus
M3,E3:	Emitted Particle
M4,E4:	Residual Nucleus

Table 1: These variables represent the mass and kinetic energies of the particles involved in the collision described in Figure 3.

Species	Mass
^{7}Li	^{1}9F
Cu	Si
p	α

Table 2: Masses of particles and nuclei involved in our expected nuclear reactions and Rutherford scattering. The lithium and fluoride species are seen in the LiF foil and are expected to undergo nuclear reactions. Cu and Si are the nuclei involved in Rutherford scattering. p and α refer to a proton and an alpha particle, respectively.

creates a current pulse which is converted to a voltage pulse with a high-impendence conductor. The voltage signal is then sent by way of a pre-amplifier to the receiving amplifier in the control room. A multi-channel analyzer receives voltage signals from the second amplifier, binning counts as a function of voltage. The amplifier is adjustable, allowing the voltage range to fit properly within the MCA's detection domain, and the voltage received at the MCA is directly proportional to the kinetic energy of the alpha particle. [1] In Section 3.1, a kinetic energy scale is calibrated to the voltage scale, thus providing the alpha particle spectrum.

3 Nuclear Reactions and Detection Plan

The nuclear reactions ^{19}F(p,α)^{16}O and ^{7}Li(p,α)^{4}He can be analyzed in terms of the kinematic diagram in Figure 3. In this diagram, each M#,E# pair refers to the mass and kinetic energy of a particle involved in the collision, with associations defined in Table 1. In the case where the incident particle does not have sufficient kinetic energy to overcome the electric potential barrier of the target nucleus, Rutherford scattering will occur. When it does overcome the potential barrier, a nuclear reaction may occur. We ignore tunneling in this analysis, which is a potential source of error.

The particle masses used to predict the nuclear reactions and scattering are tabulated in Table **??**. Lithium and fluorine are provided by a LiF foil that is placed across the detector, so the available Lithium is ^{7}Li and fluorine ^{19}F.

3.1 Calibration with Rutherford Scattering

The maximum expected kinetic energy resulting in Rutherford scattering can be computed, and by observing this value, the energy scale of the detector can be calibrated. Rutherford scattering can be analyzed in terms of Figure 3, where M1 = M3, and M2 = M4. The scattering angle $\theta = 149.95° \pm 0.05°$. If the collision is elastic, the kinetic energy of the scattered Proton $E3 \propto E1$. We define a kinetic factor K as the constant of proportionality. This factor can be computed as [1]

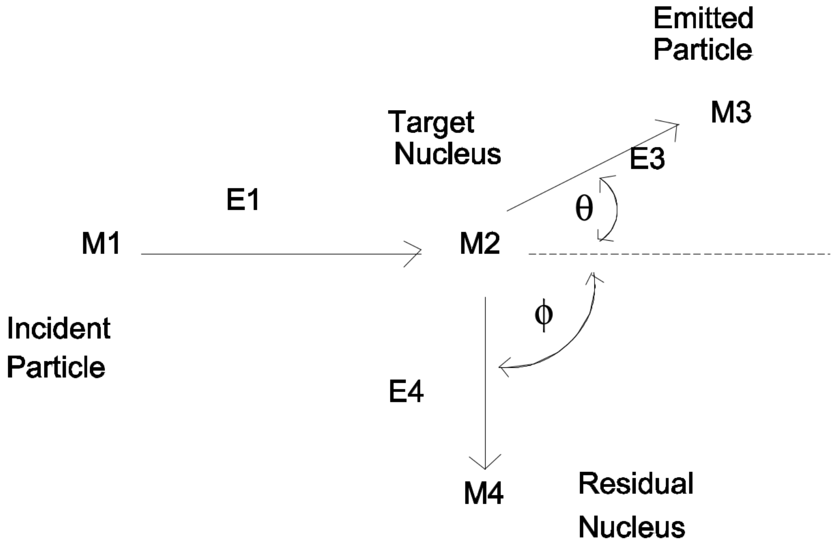

Figure 3: In general, an incident particle collides with a target nucleus, resulting in an emitted particle and a residual nucleus. The backscattering experiments in this study have $\theta = 149.95° \pm 0.05°$ [1].

$$K = \left(\frac{M1cos(\theta) + \left(M2^2 - M1^2 sin^2(\theta)\right)^{1/2}}{M1 + M2} \right)^2 . \tag{1}$$

4 Results

5 Conclusion

References

[1] Clement Burns and Asghar Kayani. *Nuclear Reactions*. Lab Guide. Western Michigan University, 2017.

[2] Bradley W. Carroll and Dale A. Ostlie. *An Introduction to Modern Astrophysics*. 2nd ed. pp. 542. 1301 Sansome St., San Fransisco, CA 94111: Pearson Education, Inc., publishing as Addison-Wesley, 2007. ISBN: 0-321-44284-9.