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"Magic" Energies for Detecting Light Elements with Resonant Alpha Particle Backscattering

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Resonant backscattering is widely used to improve the detection limit of the light elements such as B, C, N and O. One disadvantage, however, is that several incident energies are normally needed if the sample contains a number of the light elements. There are "magic" energies at which several light elements can be detected simultaneously with suitable sensitivities. When these energies are used along with the elastic recoil detection of hydrogen, multiple elements can be detected without changing the beam energy, and the analysis time is greatly reduced. These reactions along with examples will be discussed.

INTRODUCTION

High-energy alpha-particle resonant backscattering has become a standard tool in ion beam analysis (1). There are several resonances that may be selected (2). Unfortunately there are also detrimental effects that accompany the application of resonances to ion beam analysis. Desirable considerations for choosing the ideal resonance energy for analysis are:

- 1) multiple elements can be detected simultaneously,
- 2) the resonances are broad and slowly varying so that depth information can be obtained,
- 3) the resonance cross sections are large compared to the Rutherford cross sections as well as the substrate cross section,
- 4) the energy does not produce prompt radiation from the sample or unduly activate the sample being analyzed,
- 5) there are no unwanted nuclear reactions or resonances from the sample or substrate that complicate the analysis.

The experimenter is lucky if even two of these conditions are met. It is often necessary to change beam energy several times to completely analyze a sample. However, there are several energies where more of the conditions are fulfilled. We refer to these energy regions as "magic." The very first energy region that gained popularity for oxygen detection, 8.6–8.8 MeV, (3)(4)(5) is also useful for carbon and nitrogen. Another example is

near 6.6 MeV where boron, carbon and oxygen have enhanced cross sections. Both cases have the disadvantages of prompt radiation and target activation, and a heavy substrate is necessary because of interfering resonances in light substrates such as silicon

In this paper we explore the (α, α) backscattering cross sections for ^{11}B , C, N and O as well as the elastic recoil cross section (α, p) for H in the energy region from 5 to 6 MeV. The energy region near 5.6 MeV allows the simultaneous backscattering measurement of four elements: B, C, N and O, as well as the elastic recoil detection of H (with a change of scattering geometry.) This energy also allows the use of silicon as a substrate—a very common choice.

EXPERIMENTAL METHOD

Sample Preparation

In practice, a sample to determine backscattering cross sections is made with a light substrate on which a layer of a heavy element is deposited. The element of interest is then deposited on this layer. The heavy element, necessary for the cross section determination, is also used to shift the energy of the substrate signal to lower energies so that the signal from the element of interest can be easily observed. The program RUMP (6)(7) was used to aid in the design of the samples before they were deposited.

Boron & Carbon

The boron and carbon samples were deposited on a 5

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mm thick carbon substrate. The boron in the sample was separated from the substrate by a 4000 Å layer of Mo. This separates, in energy, the boron signal from the carbon substrate signal. The boron layer was a sputter-coated layer of B₄C, 500 Å thick.

For carbon an evaporated 800 Å layer of Au was used followed by a plasma-coated 400 Å layer of carbon.

Oxygen & Nitrogen

The same target was used for both the oxygen and nitrogen measurements. A 2000 Å layer of ZrN₂/ZrO₂ was applied to the carbon substrate. An intermediate layer was not needed because the oxygen and nitrogen signals are naturally separated from the substrate signal.

Hydrogen

A polystyrene layer 8000 Å thick spun onto a silicon substrate was used for the hydrogen elastic recoil cross section measurement.

Backscattering Cross Sections

These measurements were performed in the Ion Beam Materials Laboratory, Center for Materials Science, Los Alamos National Laboratory (8). The He⁺⁺ beam was generated with a National Electrostatics 3MV 9SDH-2 pelletron. Data was collected for B, C, N and O over a range of 5–6 MeV at a scattering angle of 167°.

A standard procedure for measuring backscattering cross sections is the ratio method (2). The ratio method can be derived from the equation for the experimental cross section for a given element:

$$\sigma = \frac{Y}{Q(Nt)\Delta\Omega} \quad (1)$$

σ is the cross section, Y is the integrated yield, Q is the number of incident particles, (Nt) is the atoms/cm² in the target and $\Delta\Omega$ is the solid angle of the detector. While Y can be measured to arbitrarily good statistical uncertainty, the other parameters have higher systematic uncertainties.

In practice, to avoid these uncertainties, a sample is constructed that contains a thin layer of two elements, a light element whose cross section is to be determined, and a heavy element that must be Rutherford at all energies of interest.

The ratio of the yields at an energy where both elements are known to be Rutherford and at the energy of interest allows the cross section ratio to be determined:

$$\left(\frac{\sigma}{\sigma_R}\right)_E \equiv \frac{\left(\frac{Y_x}{Y_m}\right)_E}{\left(\frac{Y_x}{Y_m}\right)_{E_R}} \quad (2)$$

Y_x/Y_m is the ratio of the yields of the element of interest

and the heavy element, E is the energy of interest and E_R is an energy where both elements x and m are Rutherford. The result is an approximation because of the neglect of the mean energy and the screening corrections. These corrections tend to cancel and were not applied in our analysis.

Elastic Recoil Cross Sections

The hydrogen recoil cross sections were measured at scattering angle of 30° with a target tilt of 75°. The cross section in the energy region of interest was obtained by first measuring the yield from the sample at 2.5 MeV, where the cross section is known (9). At both high and low energies the target was thin enough that the yield could be determined by peak integration. This removes the uncertainties associated with stopping cross sections. The yield obtained in the region of 5–6 MeV was then scaled by the 2.5 MeV cross section to determine the cross section.

DATA

The cross section ratios for both backscattering and hydrogen elastic recoil are shown in Fig. 1.

Figure 1. σ/σ_R for alpha resonant backscattering of the elements ¹¹B, C, N and O at a scattering angle of 167° and the elastic recoil cross section of H at a scattering angle of 30°.

The oxygen cross section was not measured below 5.2 MeV because of the interference of the ¹⁴N(α ,p) reaction. The hydrogen cross section was corrected for hydrogen loss and the carbon cross section was corrected for carbon gain

during analysis. The statistical uncertainties in the backscattering ratio measurements are $\pm 4\%$. The uncertainty in the elastic recoil ratios is $\approx 6\%$ (the uncertainty from (9)).

Choosing the analysis energy in this region depends on the elements expected in the sample. If boron is present in a relatively thin film, the best energy is ≈ 5.625 MeV. At this energy silicon has relatively few resonances in the region of the light element signals and can be used as a substrate material. Table 1 lists the cross section ratios and the cross sections for the elements at this energy.

Element	σ/σ_R	σ (mb/str)
Hydrogen	21.1	538
Boron	65.2	209
Carbon	97.6	468
Nitrogen	6.25	44
Oxygen	8.40	81

Table 1. σ/σ_R and σ for resonant alpha backscattering at 5.625 MeV.

APPLICATION

As an example of the application of this "magic" energy a sample of a plasma ion-deposited sample of ≈ 1300 Å of a B/C/N/O/H coating on a silicon substrate. Normally, a Mo substrate would be needed and several higher energies would be necessary for analysis.

The backscattering spectra from the sample and pure silicon are shown in Fig. 2a. The subtracted spectrum is shown in Fig. 2b. The Si signal is approximately Rutherford at energies below 1 MeV. The scattering geometry is as described above with the exception that a target tilt of 45° was used. Charge collected was 30 μC and the solid angle of the detector was 2.5 mstr.

The atomic fractions and the 2σ minimum detection limit of the constituents in the film are given in Table 2.

Element	Atomic Fraction	MDL ($10^{15}/\text{cm}^2$)
Hydrogen	.12	<1.2
Boron	.28	7.2
Carbon	.17	2.5
Nitrogen	.29	20
Oxygen	.13	12

Table 2. Measured atomic fractions and minimum detectable amount for elements in a film on a silicon substrate.

The elastic recoil spectrum is not shown. However, the protons from the $^{14}\text{N}(\alpha, p)$ reaction produce a small

background.

Figure 2. (a)—Spectrum from 1300 Å film of B, C, N, O on Si (solid line) overlaid by the spectrum from pure Si (dashed line). (b)—Difference spectrum showing the B, C, N and O peaks.

For this sample the thickness of the film must be less than 4500 Å at normal incidence for the B and C signals to be separated.

DISCUSSION

For samples containing multiple light elements the 5-6 MeV region has many advantages. In particular, the use of the 5.625 MeV "magic" energy for determining hydrogen, boron, carbon, nitrogen, and oxygen concentrations has many practical applications. Examining the wish list from the introduction:

- 1) four elements, B, C, N and O can be detected simultaneously as well as H (with a change in geometry),
- 2) the resonances are broad, with the exception of B (≈ 50 keV) at 5.625 MeV, and slowly varying so

that depth information can be obtained,

- 3) the resonance cross sections are moderately large compared to their Rutherford cross sections and significantly larger than the Si cross section (there are other useful energies, where the σ/σ_R ratios are larger, that can be used when high sensitivity measurements are needed),
- 4) this energy does not produce prompt radiation from the sample or significantly activate the sample or substrate,
- 5) unwanted nuclear reactions or resonances from the sample or substrate is limited and does not significantly complicate the analysis.

While all of the conditions are not totally met, the use of this "magic" energy results in significant timesavings, safety and convenience for researchers.

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