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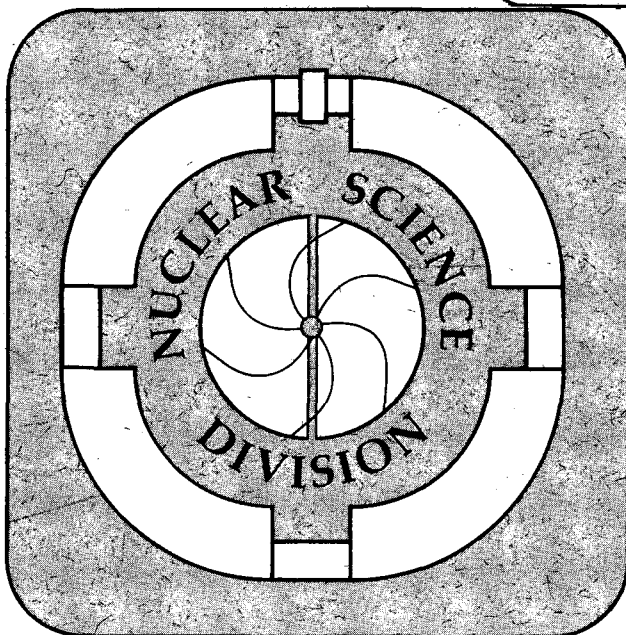Methods in Physics Research B

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Abstract: The level of purity of a target foil is very important in low cross section nuclear reactions. Carbon foils prepared by two different techniques were analyzed for their surface and bulk content of light impurities such as nitrogen, oxygen, and sodium. These data indicate that the technique used to manufacture a foil is the largest source of contamination. Foils prepared by vacuum evaporation showed sizable levels of nitrogen, oxygen, and sodium, whereas foils prepared by chemical vapor deposition were substantially purer.

1. Introduction

In the experimental study of nuclear reactions, the experimentalist needs to have control over reaction conditions, especially target-projectile pairing, for the target and projectile that react will determine what products are produced. For the low energy nuclear reaction experiment that is briefly introduced below, a target with low atomic number (Z) is needed; carbon (Z=6) seems the best candidate. Carbon is available in solid form in high purity, is inexpensive, non-toxic, and easily handled. Important for this experiment, carbon is light enough to have a relatively low fusion barrier, and its low mass ensures that the product compound nucleus will have a relatively small angular momentum.

The emission of complex fragments (Z≥3) from very hot nuclear systems is the subject of much current interest.[1-4] At very high bombarding energies, multifragment emission has been observed, but the process is not well characterized. At low bombarding energies, asymmetric fission of the compound nucleus is the dominant mechanism producing complex fragments. The probability of emission of a particular complex fragment is controlled by the height of the conditional barrier for that asymmetric division. These emission barriers can be calculated with the liquid drop model,[5] but experimental data exist for only a few systems.[6-9]

We have embarked on a program to measure the asymmetric conditional barriers for a large range of compound nuclear systems. These barriers will give us a better understanding of complex fragment emission processes, and more specifically, allow us to compare nuclear models with experiments, and to determine some fundamental nuclear model constants more accurately, such as the surface energy (a_s) and surface asymmetry (k_s) constants. To determine conditional barriers, one must measure excitation functions associated with each complex fragment for the compound nucleus of interest. To determine the barrier height accurately, the excitation functions must extend down to energies near the conditional barrier. At these low bombarding energies, the asymmetric fission cross sections are extremely small.

By employing reverse kinematics (the use of the heavier nucleus as the projectile and the lighter nucleus as the target) in our experiments, two advantages are gained: first, the fission fragments are forward focused in the laboratory frame, increasing their

detection rate, and second, the fragments receive a "kinematic boost" from the projectile, ensuring that they are well above the detector thresholds. By detecting both fission fragments in coincidence, we can measure the atomic number of the parent compound nucleus. For the choice of the low-Z target nucleus, carbon (Z=6) seems the best candidate.

The carbon foil used in these experiments needs to be virtually free of any heavier element impurities because the yield of complex fragments from heavier impurities can be very large. Furthermore, the yield from the carbon target falls off much more rapidly with decreasing beam energy than does the yield from heavier impurities. A calculation of the relative yields from carbon and several heavier impurities has been performed with the statistical code GEMINI,[10] and is displayed in Figure 1. At higher energies, the yield for the reaction with a sodium impurity is two orders of magnitude greater than that for carbon; at the lowest energy, this yield differential is increased to approximately *four-and-a-half orders of magnitude*. Yields from nitrogen and oxygen impurities, while not as large as those from sodium, could also be significant sources of background reactions as well. It is for these reasons that a very pure carbon target is required for this experiment.

2. Experiment

In an initial experiment, a carbon target (1.0 mg/cm^2 thickness, from two adjacent 0.5 mg/cm^2 foils) was bombarded with a beam of ^{86}Kr ions, and the resultant asymmetric fission of the compound nucleus was measured. Figure 2 shows a plot of the number of coincident events versus the sum of the measured atomic number (Z) of the two fragments. At the higher bombarding energy, a single peak centered at Z≈42 (all Z measurements carry an error of ±1) is observed, corresponding to the fusion of krypton (Z=36) and carbon (Z=6); however, at the lower energy there are two peaks, a smaller one at Z≈42 and a larger one at Z≈47. The smaller peak corresponds to the reaction of interest, while the larger, broader peak is due to reactions with a heavier impurity, with sodium being the likely culprit. As the energy of the beam is decreased, the yield of fission fragments from the carbon target decreases precipitously, relative to the yield of fragments from the heavier impurities. Thus, at lower energy, the observed yield is from reactions on the impurities in the carbon target, not on carbon itself.

3. Results and Discussion

To measure the yield at the lowest energies, it is necessary to use a purer carbon foil. Furthermore, because beam-time at the cyclotron is expensive, we would like to have an assay of the impurities in a new foil before using it in an experiment. Numerous articles have been written concerning carbon foil purity and purification techniques;[11-18] however, most of the techniques discussed for purging carbon foils of their impurities do not achieve the requisite level of purity required for our experiments. Because almost all carbon foil manufacturers begin with spectrographically pure graphite, it appears that the manufacturing technique is the main source of impurities in the foils. For this reason, we have studied some of the manufacturing techniques to gain insight into which technique will produce the purest carbon foil.

The carbon foil used in the initial experiment was produced by vacuum evaporation, which is a widely used foil preparation technique. In this procedure, a source of spectrographically pure carbon, in the form of graphite, is heated in vacuum, causing evaporation of the carbon onto a glass slide coated with a parting agent. The parting agent is used to facilitate the removal of the foil from the glass plate, typically accomplished by floating the foil onto a water surface. Thus, the majority of parting agents are soaps, because soap is highly water soluble. Even though the parting agent is washed from the surface of the foil after it is floated off, our experience indicates that some of the parting agent remains adsorbed onto the foil surface. An attempt to rinse the foil several times with concentrated hydrofluoric acid followed by deionized water proved ineffective; the foil surface adsorbed water, substantially increasing the level of oxygen impurity. Other methods for improving foil purity, such as ultrasonic bath treatment,[18] did not demonstrate the ability to reduce contaminants to the level required by our experiments.

The foil we used in our original experiment, Foil A, was a standard carbon foil typically used as an electron stripper foil for accelerator beams. It was prepared using vacuum evaporation, and the manufacturer quoted impurities of 0.1% and 1.0% (atomic) for sodium and oxygen, respectively. The parting agent for Foil A is proprietary, but is most likely a soap or soap derivative; the manufacturer reports that the parting agent does contain sodium.[19]

A promising alternative technique that does not involve a parting agent is chemical vapor deposition. In this technique, a hydrocarbon gas is "cracked" at a high temperature in an inert gas environment, and carbon is deposited onto a bed of molten metal. When the molten metal cools, the carbon foil curls off the metal surface. This technique is more expensive than vacuum evaporation, but because it avoids the parting agent and because the foil does not need to be floated on water, the surface of the foil is relatively free of contaminants. The second foil, Foil B, was prepared by this technique, and the manufacturer[20] quoted the sodium impurity as $\leq 1 \times 10^{-6}$% (atomic).

Before exposing the second foil to beam, we wished to check both manufacturers' claims of purity. Measurements of the surface and bulk impurities were made using two different analytical techniques offered by the Surface Science Division at Lawrence Berkeley Laboratory. Rutherford Backscattering Spectrometry (RBS) was used to gauge the surface purity of the two foils. This technique measures the energy of a light projectile when it is backscattered by nuclei on the surface of a sample; the scattering energy is related to the atomic number of the scattering nucleus, thus identifying components on the surface of the sample. A comparison of the spectra of the two foils (Figure 3; notice the very large carbon edge at approximately 500 keV, and the marked nitrogen and oxygen edges on the magnified scale) shows that Foil A has a greater degree of surface contamination, with 1.7% (atomic) nitrogen, 2.1% oxygen, and 0.12% sodium. The contamination level in Foil B is below the sensitivity of the technique, indicating ≤ 1.0% (atomic) nitrogen, ≤ 0.8% oxygen, and ≤ 0.10% sodium (see Table 1).

Since the graphite used to manufacture the foils is very pure, it is instructive to determine if the majority of the contamination is on the surface or in the bulk of the foil. Secondary Ionization Mass Spectrometry (SIMS) is an analytical technique in which a surface is bombarded with a charged particle beam, and the secondary ions which are

ejected from the surface are collected and analyzed for their masses. For both Foil A and Foil B, SIMS was used to compare the relative levels of impurities on their surfaces, and by etching away a portion of the foil surface, in their bulk. The SIMS data (not shown) indicate that the contamination for both foils is primarily on the surface; Foil A has significantly more surface contamination than Foil B, which is consistent with the manner in which each is manufactured. Foil B has a purer surface than Foil A because it never comes in contact with a parting agent.

Because the level of impurity of the foil prepared by chemical vapor deposition was below the limit of detection by RBS, only limits on the impurity were determined. However, it seemed sufficiently purer than the foil prepared by vacuum evaporation to warrant using it in a low cross section experiment. An identical bombardment was done using an ^{86}Kr beam on Foil B of the same thickness as Foil A. The analysis of the two coincident fragments (lower portion of Figure 4) shows a single peak at $Z \approx 42$, and the absence of any additional contamination peaks. For comparison, the spectrum from Foil A at the same energy is shown in the upper portion of the figure. Using the statistical simulation cross section data of Figure 1, these data indicate that the level of sodium impurity in Foil B is $\leq 0.02\%$ (atomic), consistent with RBS measurement, and is sufficiently low to measure a complete excitation function.

4. Conclusion

In summary, we have determined that carbon foils prepared by chemical vapor deposition are purer than those prepared by vacuum evaporation onto a coated glass slide. A significant impurity in foils prepared by the latter technique is sodium. Since spectrographically pure carbon is used in both procedures, a small amount of sodium is likely introduced by the parting agent used to coat the glass slide. The foils produced by chemical vapor deposition are of sufficient purity to measure excitation functions at very low cross sections and extract asymmetric conditional barriers.

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Foil	Thickness (mg/cm^2)	N	O	Na
A	0.5	1.7%	2.1%	0.12%
B	1.0	≤1.0%	≤0.8%	≤0.1%

Table 1

Surface impurities for carbon foils as determined by Rutherford Backscattering Spectrometry; impurity levels given as atomic percent.

Figure 1

Yield of complex fragments (14<Z<26) from the reaction of ^{86}Kr with various suspected target impurities versus bombarding energy. At the lowest bombarding energy, the yield from reaction with sodium is four-and-one-half orders of magnitude greater than the reaction with carbon.

Figure 2

Number of coincidence events versus the sum of the measured atomic number for each fragment for Foil A, at bombarding energies of 12.21 (upper) and 7.99 (lower) MeV/A. At the lower energy, the target impurity (Z≈47) peak eclipses the peak of interest (Z≈42).

Figure 3

Rutherford Backscattering Spectrometry spectra of Foil A (upper) and Foil B (lower). Foil A shows impurity peaks for nitrogen, oxygen, and sodium, whereas Foil B shows no impurity above the limits of detection. Note scale change; position of edge due to backscattering indicated.

Figure 4

Number of coincident events versus the sum of the measured atomic number for each fragment for Foil A (upper) and Foil B (lower) at the same bombarding energy.
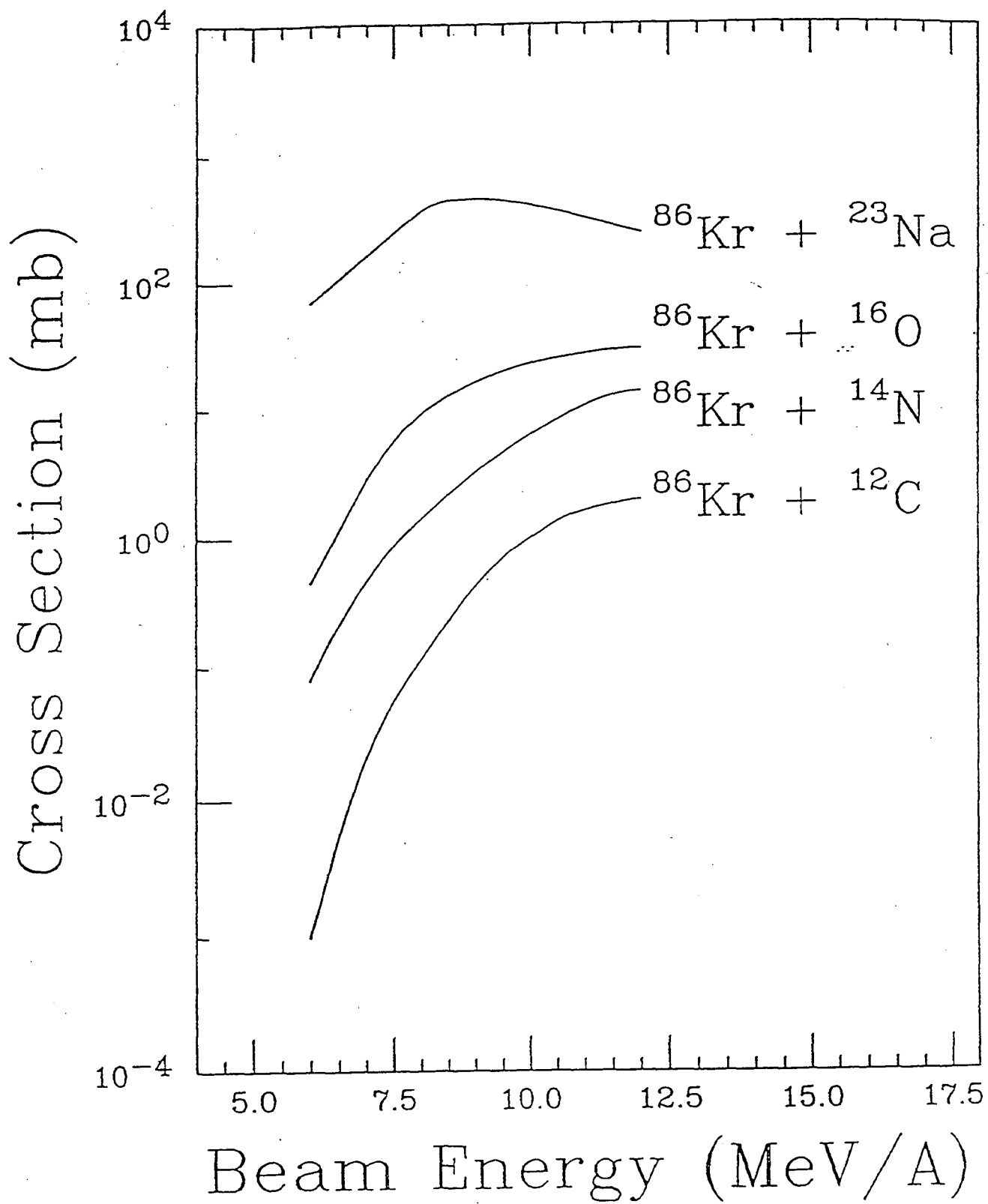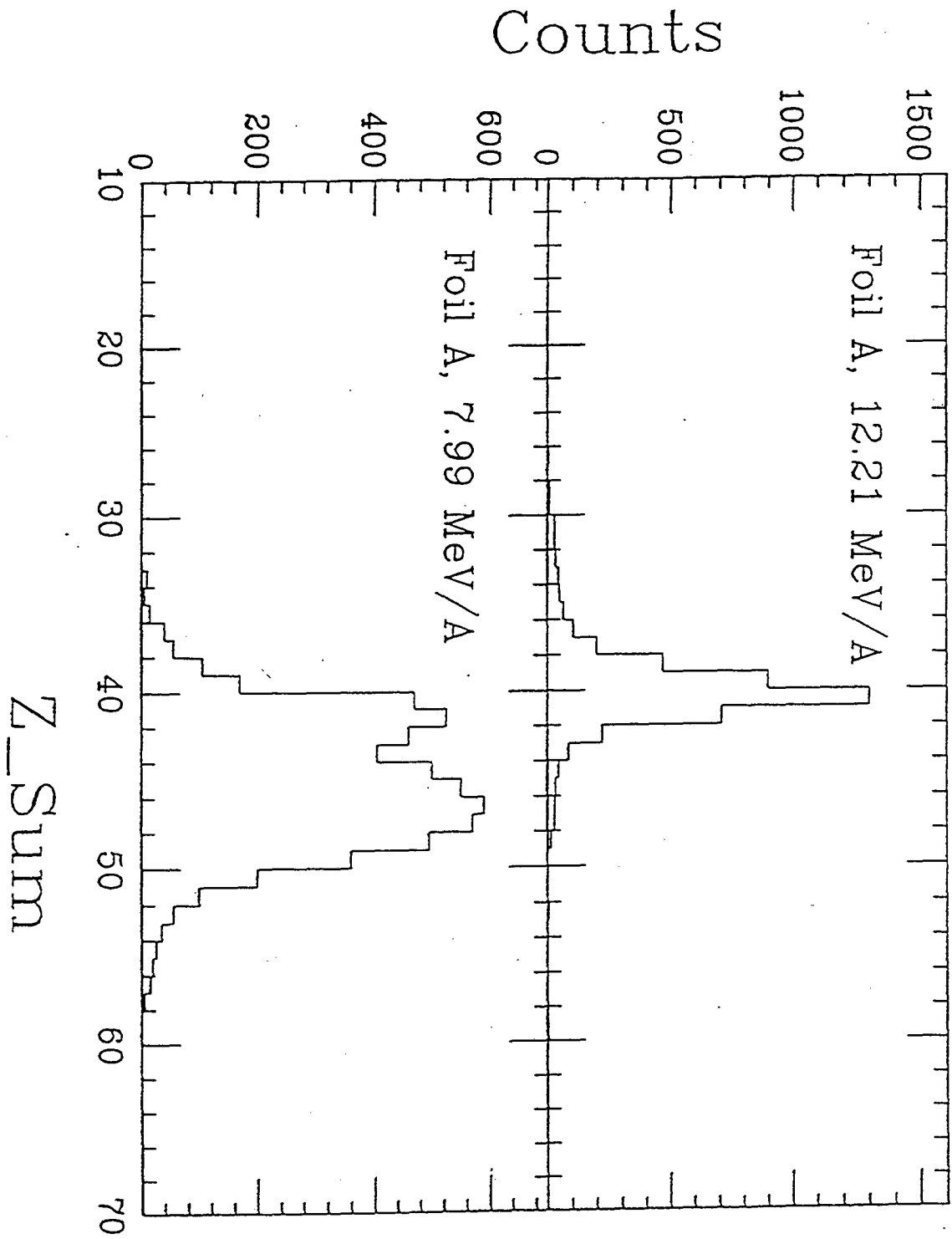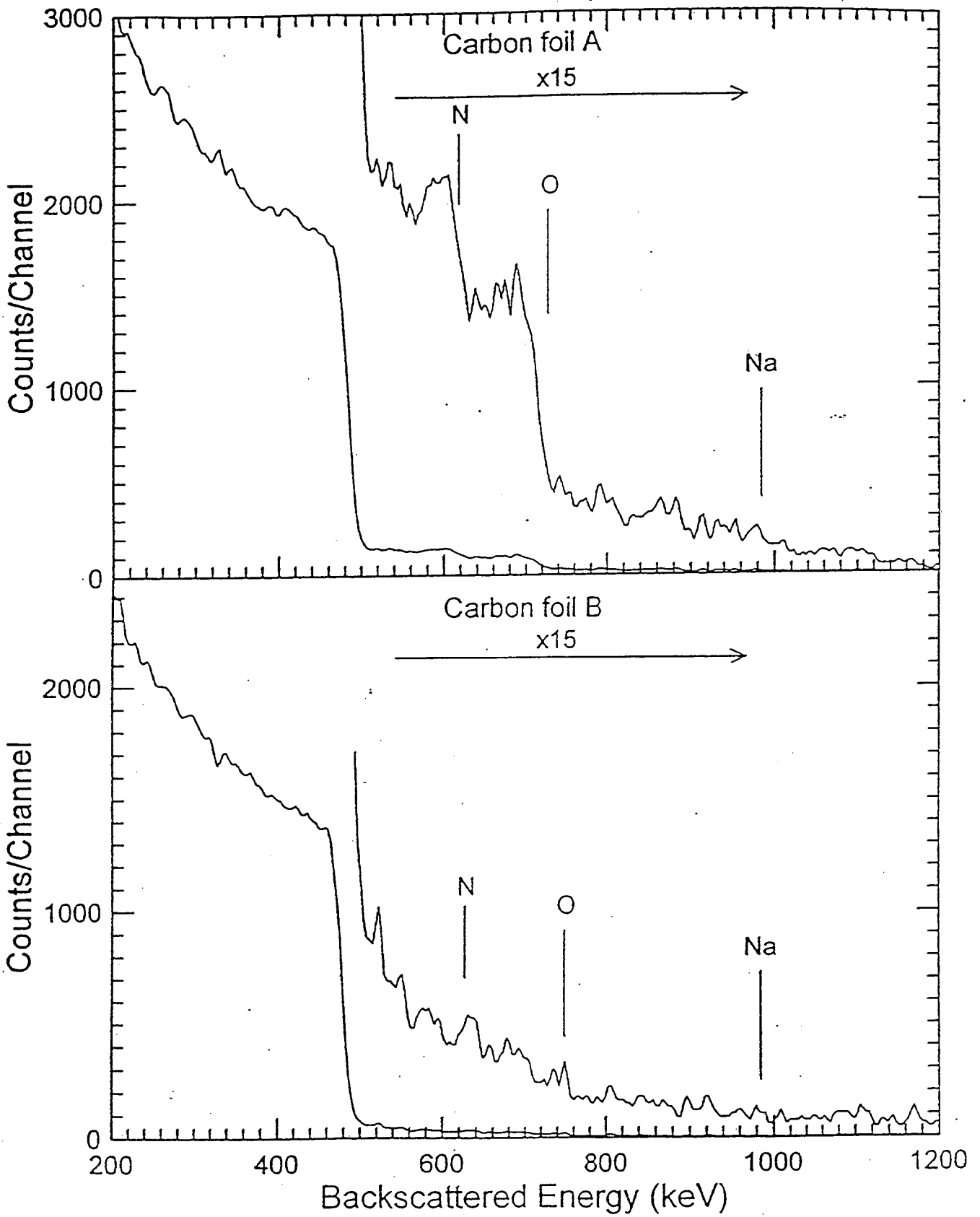
Figure 1

Figure 2

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Figure 3

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Figure 4

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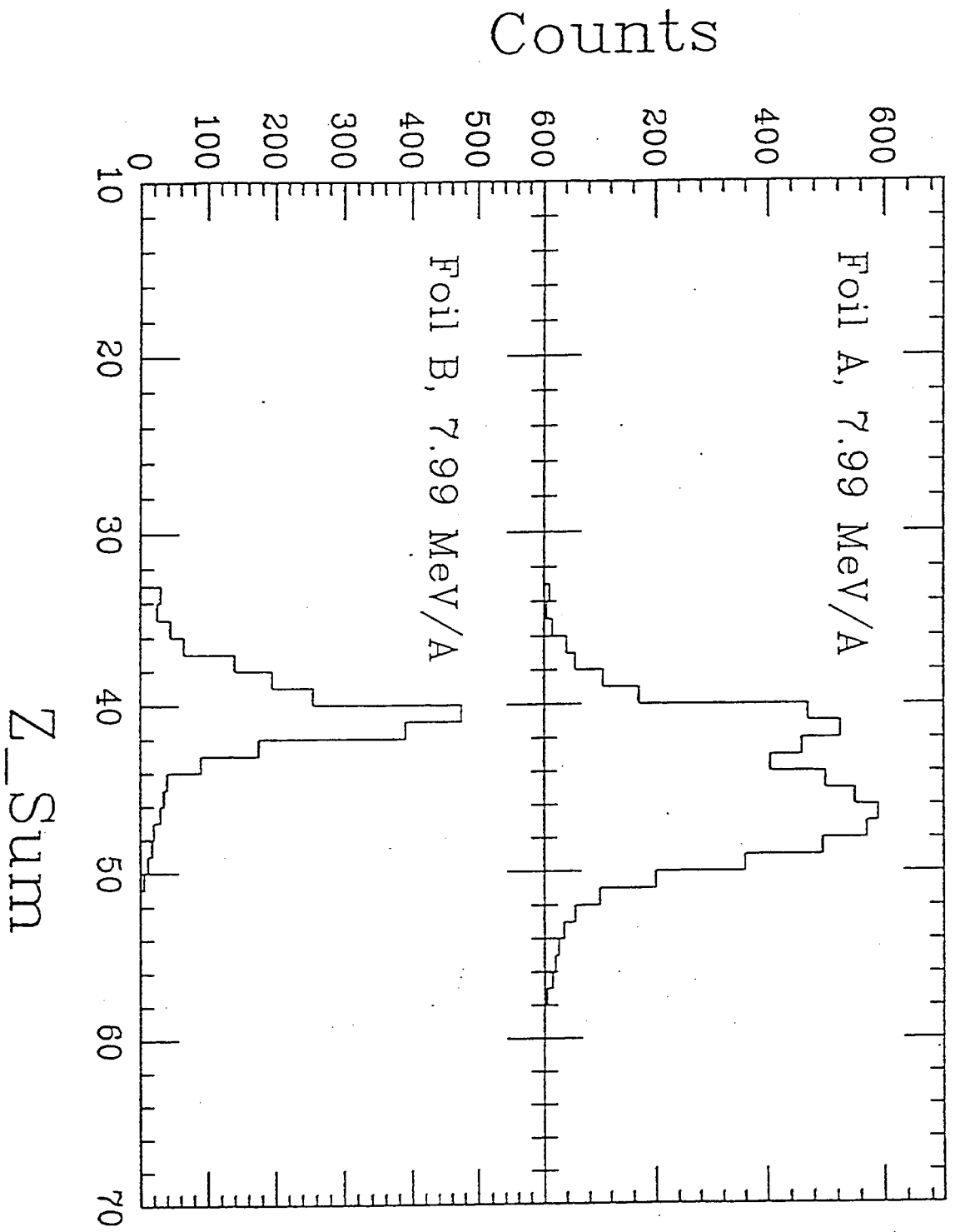
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