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Calibration of direct nuclear activation diagnostics for measuring intense proton, lithium, and fluorine beams

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ABSTRACT

In the light-ion-beam fusion program at Sandia National Laboratories an intense lithium beam is being developed to drive inertial confinement fusion targets. Since beam purity is an important issue, direct nuclear activation diagnostics based on the thick target yields of the reactions $^{7}Li(p,n)^{7}Be$, $^{10}B(p,\alpha)^{7}Be$, $^{19}F(^{7}Li,d)^{24}Na$, and $^{11}B(^{19}F,2p)^{28}Mg$ have been developed to measure the proton, lithium, and fluorine content of the beam. The specific target materials chosen for this work are LiF and BN. To calibrate these diagnostics, a Van de Graaff accelerator was used to measure the thick target yields as a function of ion energy for each of the ion and target material combinations. Each target material was also irradiated by carbon ions to assess the importance of any possible competing reactions. The results of these calibration studies will be presented in this paper.

I. INTRODUCTION

Intense lithium beams are being developed at Sandia National Laboratories (SNL) on the Particle Beam Fusion Accelerator II (PBFA II). These beams are being developed as a driver for light-ion, inertial-confinement-fusion experiments. One important development issue is the purity of the lithium beam. It has been conjectured that impurities in the beam result in a "parasitic load" that significantly degrades the diode performance. The most likely sources of beam impurities are hydrocarbons in the form of anode surface contamination and residual gases in the diode. Thus, any contamination of the beam will probably be dominated by hydrogen and carbon. Often LiF anodes are used so fluorine ions could also be a contaminant.

To minimize beam contamination, the PBFA II vacuum system has been recently improved and cleaning by heating and RF discharge has been introduced into the diode.[1] A series of experiments were conducted to investigate the effectiveness of these measures. As part of these experiments, a new set of diagnostics based on direct nuclear activation has been developed to measure the amount of hydrogen, lithium, carbon, and fluorine in the beam. In this paper we discuss the basic principles of these diagnostics; the experimental method used to calibrate them; and the calibration results. A companion paper[2] in this journal discusses the results

obtained with these diagnostics on the barrel diode configuration of PBFA II.

II. DIAGNOSTIC APPROACH

Energetic ions can induce nuclear reactions in materials. By measuring the amount and kind of radioactivity induced in the material, information about the ion beam can be inferred. Nuclear activation diagnostics[3-5] have been used previously for measuring ion beam fluences and voltages generated by pulsed power devices. In this work we are interested in measuring the presence of hydrogen, lithium, carbon, and fluorine in the beam and the fraction of the total beam energy carried by each.

To measure the energy fluence of a particular ion species, an appropriate sample material is exposed to the ion beam and then the absolute activity induced in the sample is measured. Since this induced activity is proportional to the energy fluence, the energy fluence can be inferred from the measured induced activity and a knowledge of the reaction thick target yield and the diode voltage and current time histories. The "calibration" of these diagnostics consists of experimentally measuring the thick target yields for each ion and material combination of interest or by calculating them from cross section data. In this work we experimentally measured the thick target

yields.

A successful direct nuclear activation diagnostic must meet the following requirements. Each ion of interest must drive a reaction that produces a radionuclide that is uniquely associated with that particular ion. Each reaction must take place at the ion kinetic energies typically encountered in the diode with a sufficiently high yield that a statistically significant measurement can be made. The activation product must be able to be unambiguously identified. The half life of the induced activity must be long enough that the samples can be recovered and counted before the activity decays away. Finally, the target nuclide must be available in solid form. On PBFA II, the kinetic energy range of interest is approximately 2 to 30 MeV, although the energies of immediate interest are below 12 MeV. In the barrel diode geometry the sample recovery time is 3 to 24 hours, which eliminates many interesting reactions from consideration.

Direct-nuclear-activation diagnostics were developed for measuring hydrogen and lithium in the PBFA II beam that essentially meet all of the above requirements. The diagnostics for measuring carbon and fluorine ions also meet all of the requirements except that they are only sensitive to ions having kinetic energies exceeding about 12 MeV. As a result, they were of limited use on the barrel diode

experiments[1] where most ion kinetic energies were less than 12 MeV. The carbon and fluorine diagnostics should be of more value on the extractor diode experiments for which the voltage should exceed 15 MV.

The suitable reactions that we identified are listed in Table I. These reactions meet our requirements of producing readily detectable radionuclides that have sufficiently long half lives. Suitable target materials in the form of LiF and BN are available and are particularly attractive because, between them, all of the potential ion species of interest could be measured. In calibrating these reactions we observed many products that had half lives too short for application on PBFA II. We will report these results elsewhere.

III. EXPERIMENTAL APPROACH

Calibration of these diagnostics consists of measuring the thick target yields of each reaction as a function of incident ion kinetic energy. These calibrations were conducted on the tandem Van de Graaff accelerator at the Ion Beam Facility at Los Alamos National Laboratory. In these experiments we irradiated samples of LiF and BN with known fluences of proton, lithium, carbon, and fluorine ion beams. The activities induced in the samples were then measured with a calibrated high purity germanium detector.

Because LiF and BN are insulators we could not measure the ion current on target directly. Instead we estimated the current by measuring the current into a Faraday cup just prior to each irradiation and then irradiating the sample for a known time interval. Assuming that the current remains constant over the time of irradiation, the total ion fluence incident on the sample can be estimated. Measurements of current into the faraday cup before and after irradiations indicated that the current was constant to within 10% for most irradiations. Average currents were typically 10 to 100 na. Irradiation times ranged from 0.5 to 20 minutes, with most being 3 minutes or less.

After irradiation, each sample was counted with a calibrated, high-purity, germanium detector. Samples were counted at least three different times and at different distances to provide a consistency check. The distances were standardized at "0" (on the face of the detector), 5, 10, 15, 20, and 25 cm. The counting position was selected by determining, prior to each count, the closest position for which the dead time, as indicated by the ORTEC Maestro II data acquisition system, was less than 5%.

In this work we irradiated both target materials, BN and LiF, with all four ion species, protons, lithium, carbon, and fluorine. For the primary reactions of interest we calculated thick target yield curves from the measured

activities and incident ion fluences. By irradiating all materials with all ions we were able to assess the importance of any interfering reactions. In this work we investigated proton reactions over the energy range of 1.5 to 20 MeV; lithium and carbon reactions over the energy range of 5 to 35 MeV; and fluorine reactions over the energy range of 12.5 to 45 MeV.

IV. RESULTS AND DISCUSSION

Figure 1 shows the ^{7}Be thick target yield curves for protons on LiF and BN. Figure 2 shows the ^{24}Na thick target yield curves produced by lithium, carbon, and fluorine incident on LiF. Figure 3 shows the ^{24}Na thick target yield curves produced by carbon and fluorine incident on BN. Figure 3 also shows the ^{28}Mg thick target yield curve for fluorine incident on BN. Note that in some cases there may be multiple pathways that lead to the same product radionuclide. For example, ^{28}Mg could be produced by fluorine on BN via the reaction $^{10}B(^{19}F,n2p)^{28}Mg$ and/or the reaction $^{14}N(^{19}F,^{5}Be)^{28}Mg$. We did not attempt to resolve such cases because, having calibrated the actual materials to be used in our diagnostics, we need only know the product yield per incident ion. The specific pathways only become important if the target material changes.

Of all the reactions investigated, the proton reactions are

most ideal for our applications. The thresholds are low: 1.3 and 1.9 MeV for the proton on B and Li reactions, respectively. The yields are nearly flat for proton energies above about 4 MeV. As a result, these diagnostics are relatively insensitive to voltage for PBFA II parameters. Of the other ion species that we investigated none of them produced ^{7}Be to interfere with the proton measurement. Both diagnostics are viable, but the lithium reaction, although it has a slightly higher threshold, has a considerably higher yield overall which makes it the more desirable of the two.

The lithium reaction with fluorine to yield ^{24}Na is also suitable for our applications. Although there is no threshold for this reaction, the coulombic barrier limits the useful sensitivity of this diagnostic to lithium ions having kinetic energies of about 5 MeV or more. This range is acceptable because most lithium ions on PBFA II will be in the range of 7 to 12 MeV for which the combination of reaction yield and beam fluence results in readily measurable activities. The yield curve does increase dramatically between 5 and 10 MeV. As a result, better knowledge of the diode voltage and current time histories is required than in the proton case. Since the average ion energy is all that is really needed to reduce the data, however, absolute, detailed knowledge of the voltage and current time histories is still not required to obtain a

reasonable estimate of the lithium energy incident on the sample.

We also observed that carbon and fluorine incident on LiF produce ^{24}Na and therefore, directly interfere with the lithium measurement. Fortunately, the coulombic barriers for these reactions are high and yields per ion at a given ion energy are always significantly less than for lithium. There has also been no evidence of carbon or fluorine ions on PBFA II having energies as great as 15 MeV which is the lowest energy that these reactions were measurably observed in our calibration experiments. Although these interferences could be a problem, they do not appear to be an issue on the current set of PBFA II experiments.

The carbon and fluorine reactions suffer from high coulombic barriers and as a result are only sensitive to ions having kinetic energies exceeding about 12 MeV. For our immediate applications these diagnostics are at best marginally effective because most ion kinetic energies are expected to be less than 12 MeV. In higher voltage experiments, however, they could work quite well. There is a fluorine reaction that produces the same product, ^{24}Na, as the primary carbon diagnostic. As a result, it is an interfering reaction, but, as above, the yield per ion at a given ion energy is much less than the primary reaction so it is unlikely that it would be a problem. Fluorine also produces

^{23}Mg, which carbon does not, so this reaction can be used to determine the amount of fluorine in the beam and whether it is of a magnitude to significantly interfere with the carbon measurement. Of course in many situations there would be no source of fluorine ions to give rise to an interference.

Unfortunately we observed another, unexpected interference with the primary carbon measurement which was the result of lithium reacting with an impurity in the BN samples. This result was unexpected because we had specified 99.999% pure samples from the manufacturer. The only impurity we were able to identify with certainty was calcium[6], but lithium ions reacting with another, unidentified impurity yielded ^{24}Na. The yield of this reaction is of the same order as the carbon reaction. Thus, in the case of PBFA II for which lithium is expected to be the dominant ion, this interfering reaction will obscure any carbon interactions unless much purer BN samples can be obtained. Of course, for diode experiments that are not designed to produce lithium beams, this interference would not be an issue.

V. CONCLUSIONS

We have measured the thick target yields as a function of incident ion energy for proton, lithium, carbon, and fluorine ions on BN and LiF. These yields serve as

calibrations for direct nuclear activation diagnostics for measuring protons, lithium, carbon, and fluorine ion beams. The hydrogen diagnostic is viable for proton energies above about 2 MeV, the lithium diagnostic for lithium energies above about 5 MeV and the carbon and fluorine diagnostics for ion energies above about 12 MeV. For the BN samples we investigated, an impurity in the sample material resulted in a lithium reaction that directly interferes with the carbon diagnostic measurement. This interference makes the carbon diagnostic problematical for mixed lithium and carbon beams unless purer samples of BN can be obtained.

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6. Protons incident on the calcium in the BN samples produced ^{43}Sc, ^{44}Sc, and ^{48}Sc via (p,n) reactions. These results suggest that a well characterized material containing calcium could be an excellent proton diagnostic because the yields of these reactions are high and because the range of different thresholds offered by the single calcium target would yield some information about the proton spectrum.

Table I

Nuclear Reactions Used For Direct Nuclear Activation Diagnostics on PBFA II

Reaction	Signature Gamma Ray	Half-life	Threshold	Coulombic Barrier
$^{7}Li(p,n)^{7}Be$	478 keV	53.3 days	1.9 MeV	1.2 MeV
$^{11}B(p,\alpha)^{7}Be$	478 keV	53.3 days	1.3 MeV	1.9 MeV
$^{19}F(^{7}Li,2n)^{24}Na$	1368 kev	15 hrs	+Q	7.0 MeV
$^{14}N(^{12}C,2p)^{24}Na$	1368 keV	15 hrs	+Q	10.7 MeV
$^{11}B(^{19}F,2p)^{28}Mg$	1778 keV	21 hrs	+Q	11.0 MeV

FIGURE CAPTIONS

Figure 1. Thick target yield curves for protons on LiF and BN yielding ^{7}Be.

Figure 2. Thick target yield curves for lithium(diamonds), carbon(circles), and fluorine(squares) incident on LiF yielding ^{24}Na.

Figure 3. Thick target yield curves for carbon(circles) and fluorine(squares) on BN yielding ^{24}Na and the thick target yield curve for fluorine on BN yielding ^{23}Mg(triangles). Also shown are the data points for lithium reacting with an impurity in the BN yielding ^{24}Na(diamonds).

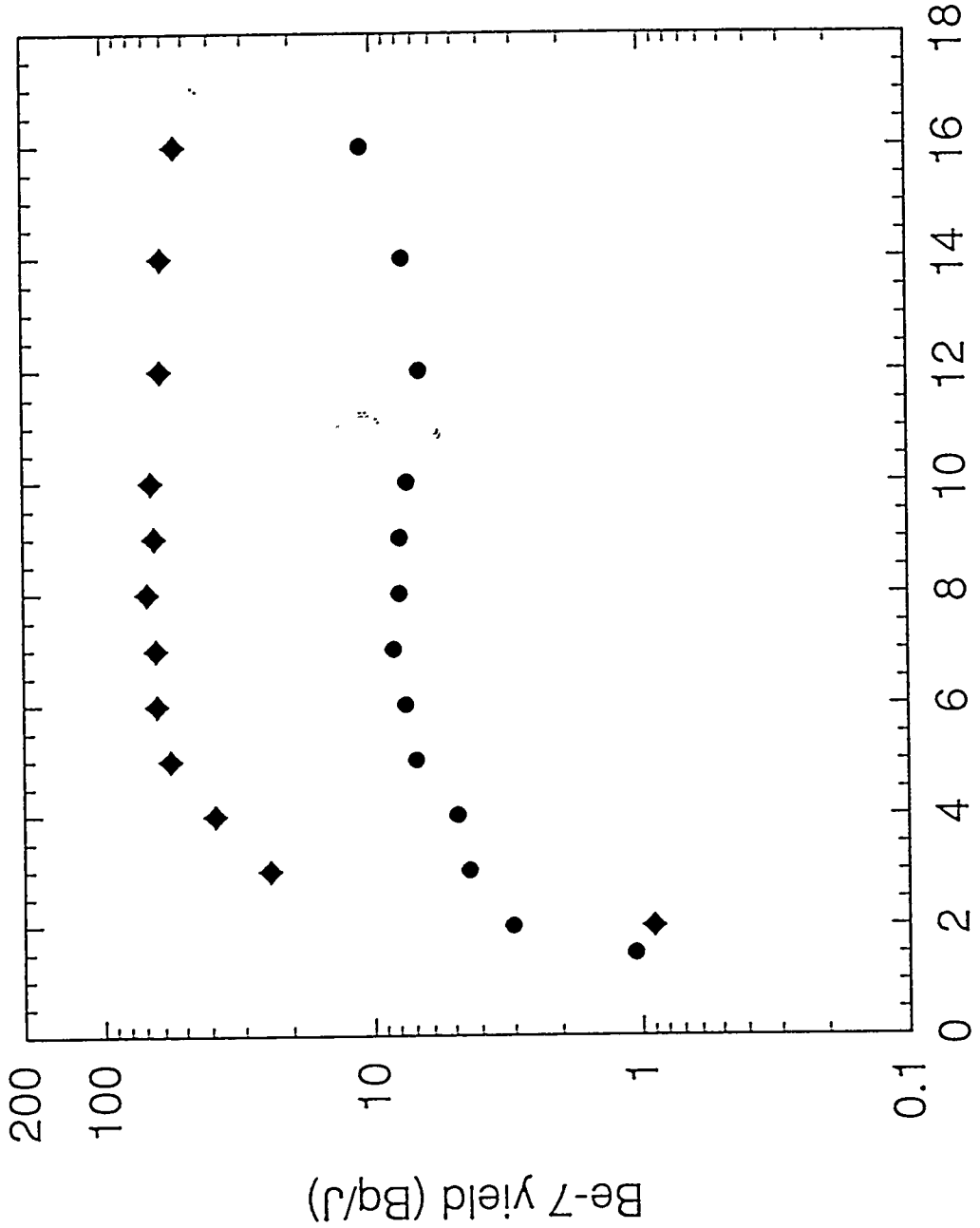
Be-7 yield (Bq/J)
200
100
10
1
0.1
0
2
4
6
8
10
12
14
16
18
proton kinetic energy (MeV)

Figure 1

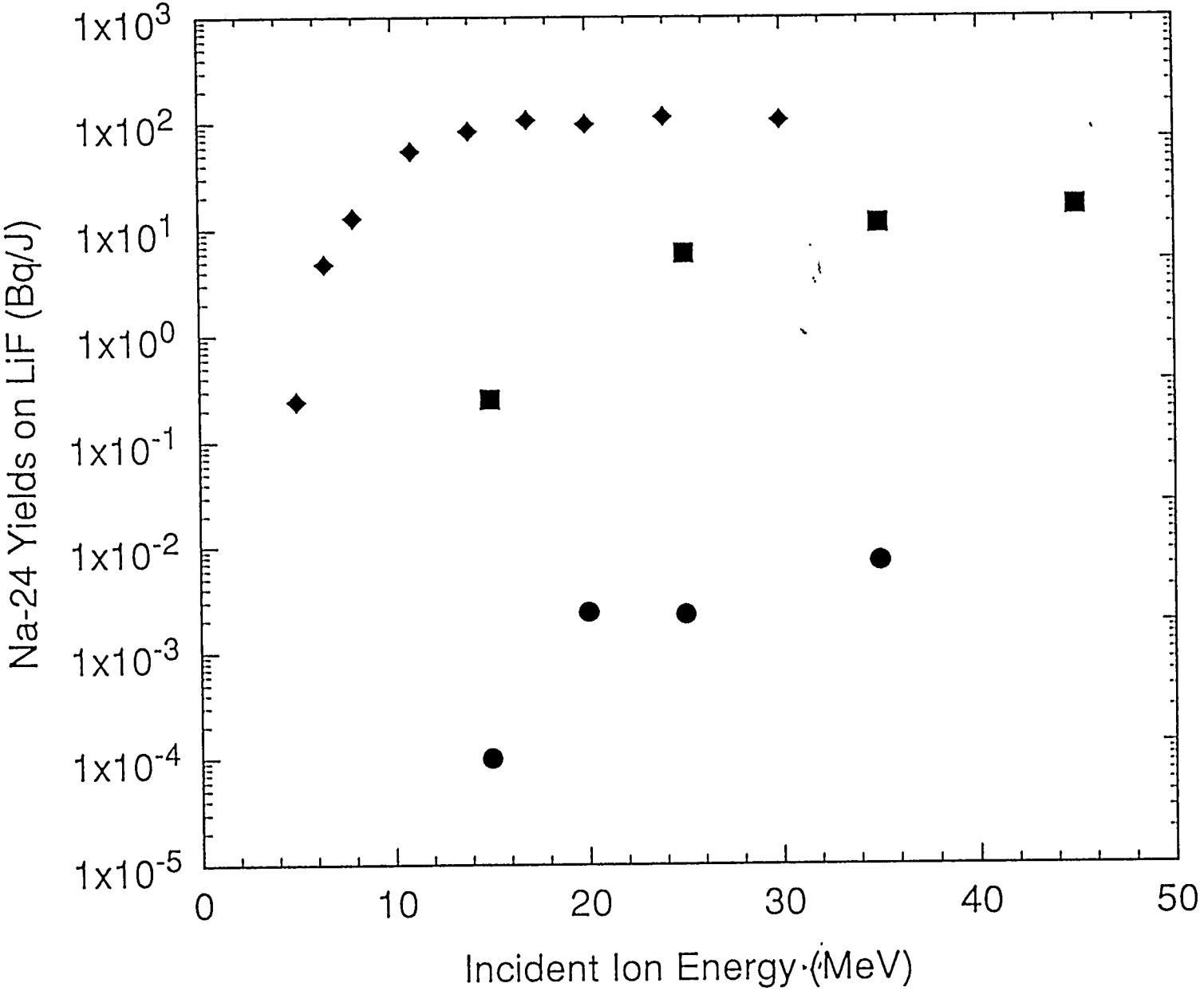
1x10^3
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
1x10^-5
Na-24 Yields on LiF (Bq/J)
0
10
20
30
40
50
Incident Ion Energy (MeV)

Figure 2

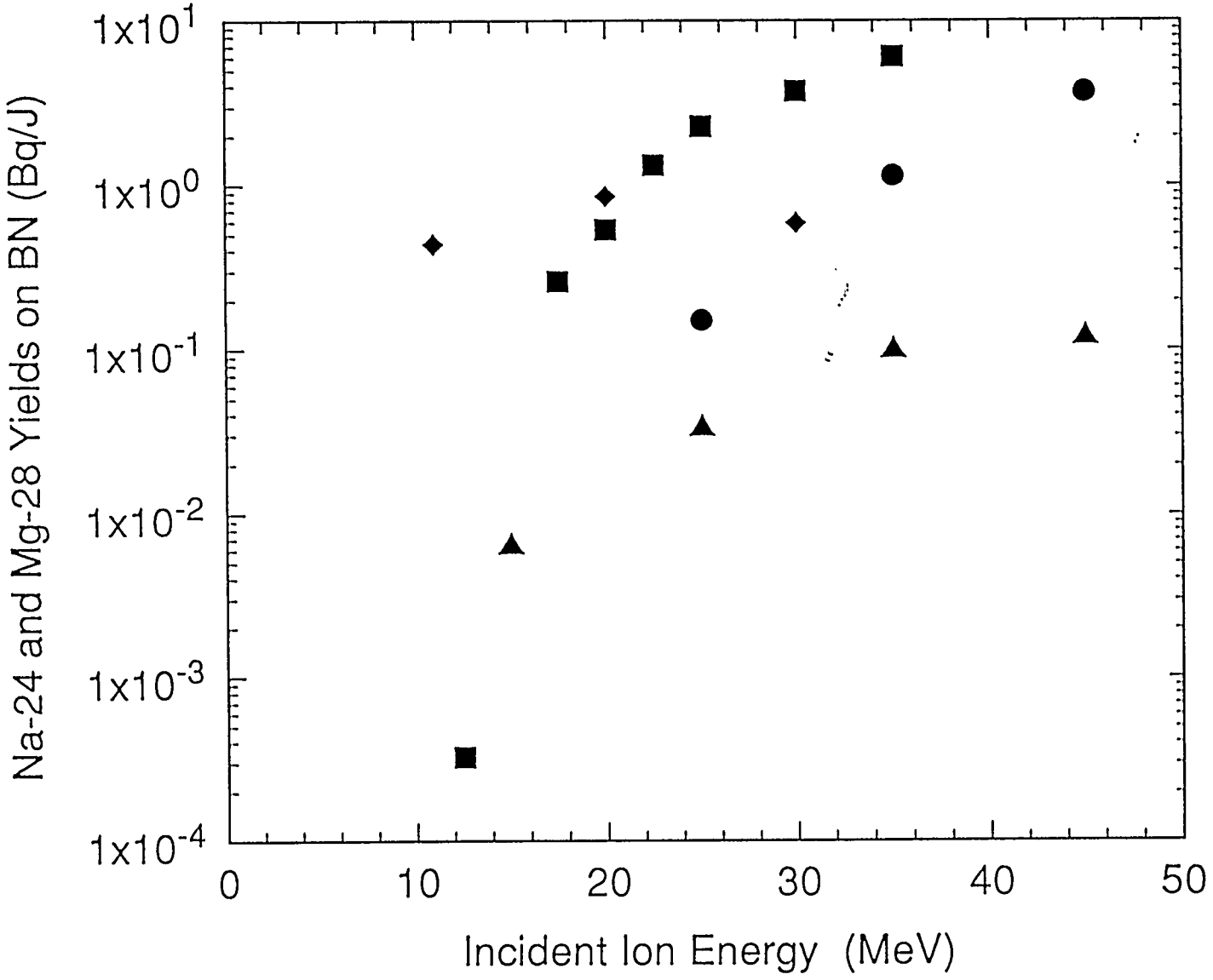
Na-24 and Mg-28 Yields on BN (Bq/J)
1x10^1
1x10^0
1x10^-1
1x10^-2
1x10^-3
1x10^-4
0
10
20
30
40
50
Incident Ion Energy (MeV)

Figure 3

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