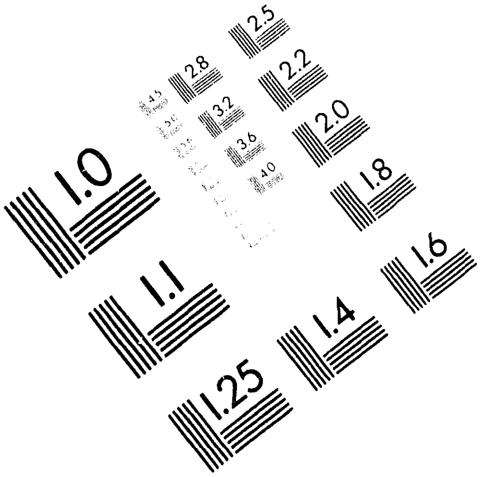

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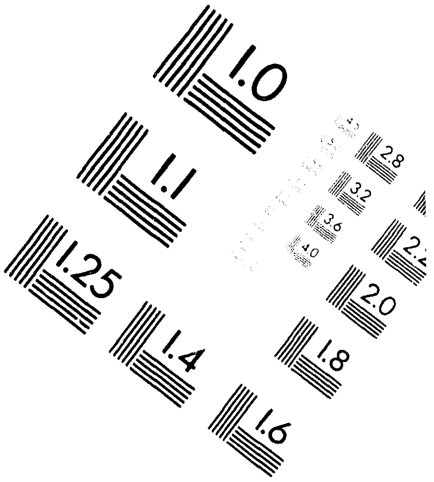

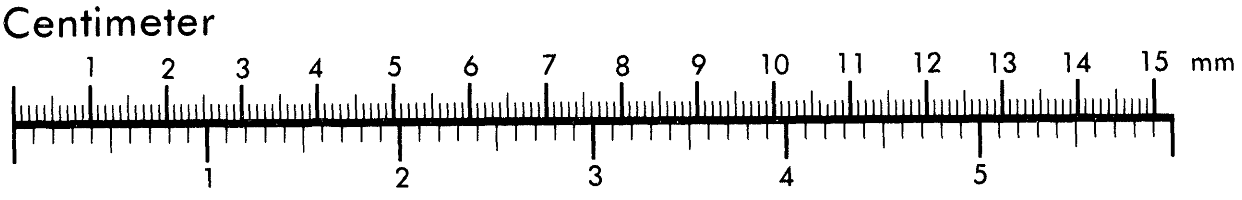

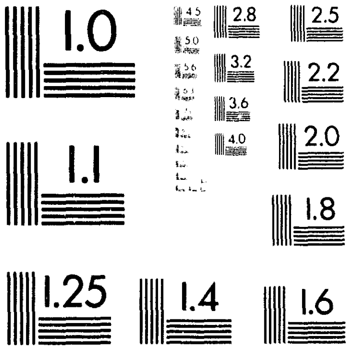

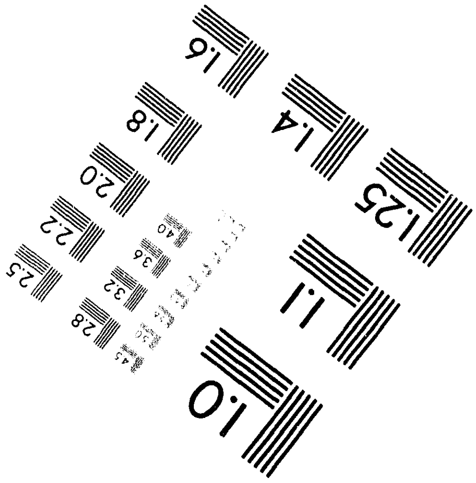

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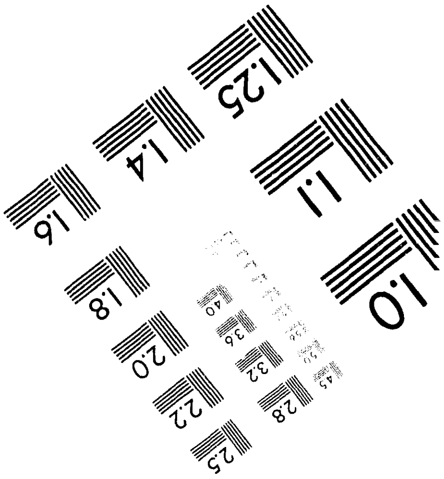

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An Intense Proton Beam Diagnostic using the $^{7}Li(p,\gamma)^{8}Be \Rightarrow {}^{141}Pr(\gamma,n)^{140}Pr(\beta^{+})$ Nuclear Reaction Sequence.

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Abstract

An indirect nuclear activation diagnostic was developed to measure the proton fluence onto a thick target of lithium metal located in the diode region of pulsed power accelerators. This diagnostic uses the nuclear reaction sequence $^{7}Li(p,\gamma)^{8}Be \Rightarrow {}^{141}Pr(\gamma,n)^{140}Pr(\beta^{+})$ to relate the proton fluence to induced ^{140}Pr activity. This diagnostic was calibrated using a Van de Graaff accelerator. Energetic protons were focused onto a thick lithium target driving the $^{7}Li(p,\gamma)^{8}Be$ reaction. The resulting prompt gamma rays activated a secondary ^{141}Pr target via the reaction $^{141}Pr(\gamma,n)^{140}Pr(\beta^{+})$. A NaI gamma-gamma coincidence detector system was used to measure the induced ^{140}Pr activity as a function of proton energy and proton fluence. These data yielded a calibration curve for proton energies ranging from 2 to 12 MeV. Since deuterium impurities can interfere with this diagnostic by driving the reaction sequence $^{7}Li(d,n)^{8}Be \Rightarrow {}^{141}Pr(n,2n)^{140}Pr$, a similar calibration experiment was conducted using deuterium ions. These data yielded a correction factor that can be used to determine the deuterium contribution to the ^{140}Pr activity providing that the deuterium beam fraction is known.

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*now with the Westinghouse Hanford Company

Introduction

Intense ion beams are being investigated as a driver technology for inertial confinement fusion (ICF) experiments at Sandia National Laboratories (SNL) [1]. Recent experiments on the Particle Beam Fusion Accelerator II (PBFA II) have focused lithium ion beams to power densities equivalent to 1.5 TW/cm^2 averaged over a surface area of a 6 mm diameter spherical target in a 12-15 ns (FWHM) pulse at a peak voltage of 10 MeV. As part of the diode development process, intense proton beams having peak voltages of 7 to 15 MeV are occasionally employed. A major challenge is to accurately measure these intense beam currents. This is problematic because the beams will be nearly 100% space-charge and current neutralized which will preclude many electrical measurements invoking charge collection or the measurement of self-magnetic fields. Additionally, there are intense pulses of electromagnetic and bremsstrahlung background radiations which interfere with measurements.

A straightforward method of measuring the time-integrated current is to use beam induced nuclear activation. Direct activation, however, is complicated by intense beam ablation of the activation sample. Unless the ablated sample material can be fully recovered, the measurement underestimates the integrated current. Our approach for overcoming the ablation problem is to use indirect activation.

Indirect activation diagnostics have been developed for measuring both Li [2] and proton [3] beams on PBFA II. The proton diagnostic is based on the ^{7}Li(p,γ)^{8}Be reaction. This reaction emits high-energy gamma rays (14 to 18 MeV) when a proton beam strikes a thick lithium target. These gamma rays, in turn, induce ^{63}Cu(γ,n)^{62}Cu(β+) reactions in a remotely located copper sample. The amount of 9.74 minute half-life, ^{62}Cu activity formed can be accurately measured using gamma-gamma coincidence techniques to detect the annihilation gamma rays associated with the positron decay of ^{62}Cu. The measured induced activity in the copper can then be related to the number of protons that struck the lithium target. Even though the intense proton beam will heat and cause the lithium target to expand, the amount of expansion in the short, 20 to 50 nsec pulse is small and the lithium will always present a thick target to the beam.

This proton diagnostic has given excellent results for moderate proton energies (1 to 3 MeV). As the operating voltage increases beyond this range, however, both the number of possible (p,n) reactions induced in machine hardware materials and the rates at which these reactions occur increase dramatically. The resulting large, low-energy neutron population leads to neutron capture reactions in the copper sample which can limit the usefulness of the diagnostic. In particular, the ^{63}Cu(n,γ)^{64}Cu reaction occurs producing the positron emitting ^{64}Cu which directly interferes with the gamma-gamma coincidence measurement of ^{62}Cu. ^{64}Cu is also produced at lower voltages (primarily via the ^{65}Cu(γ,n)^{64}Cu reaction), but the amount of the 12.7 hour half-life ^{64}Cu can be easily separated from ^{62}Cu on the basis of the difference in their half-lives. At higher voltages, however, enough additional ^{64}Cu can be produced via neutron capture reactions that it becomes difficult or impossible to extract the short-lived, ^{62}Cu activity. In addition, the production of both ^{64}Cu and ^{66}Cu (a 6.5 minute half-life, beta minus emitter) can create significant dead-time in the counting electronics.

To eliminate these problems and allow the continued use of this diagnostic at the routinely higher operating voltages of PBFA II, we have identified a different secondary target material, praseodymium, which has several advantages over copper. The activation product, ^{140}Pr, of the analogous ^{141}Pr(γ,n)^{140}Pr(β+) reaction, like ^{62}Cu, is a positron emitter and has an acceptable half-life of 3.38 minutes. The (γ,n) reaction cross section of Pr for gamma ray energies of interest is actually higher than that of ^{63}Cu and thus, more sensitive. The principal advantage over copper, however, is that natural praseodymium consists entirely of the isotope ^{141}Pr and the ^{141} Pr(n,γ)^{142}Pr reaction leads to a beta minus emitter. Thus, there is no direct interference with the gamma-gamma coincidence measurement of ^{140}Pr by the decay of ^{142}Pr. The relatively long, 19.2 hour half-life of ^{142}Pr also results in a much smaller effect on the system dead time.

Whether Cu or Pr secondary targets are used, the accurate interpretation of results requires that the presence of naturally abundant deuterium in the beam be accounted for. The ^{7}Li(γ,n)^{8}Be reactions produces neutrons having enough energy to drive ^{141}Pr(n,2n)^{140}Pr reactions. More importantly, the thick target yield of the ^{7}Li(d,n)^{8}Be reaction is approximately 1000 times greater than that of the ^{7}Li(p,γ)^{8}Be reaction. As a result, even the natural abundance of deuterium in the beam (~0.15%) will induce an activity of ^{140}Pr comparable with that induced by the proton reactions. Thus, this diagnostic must be calibrated for both proton and deuterium beams. These calibrations are the major emphasis of this paper. The calibration experiments were performed on the tandem Van de Graaff at the LANL Ion Beam Facility. A more complete discussion of this work can be found in Ref. [4].

Experiment

The experimental procedures and configurations for the proton and deuterium beam calibrations were essentially identical. Figure 1 shows a schematic of the experimental arrangement used to calibrate this diagnostic. The geometry and detector system are essentially the same as that employed when this diagnostic is fielded on PBFA II. A steady current, 1.8 to 12 MeV proton or deuterium beam impinged onto a thick lithium target (the range of 12 MeV protons in lithium is 0.4 cm and the target thicknesses were typically > 1 cm). The lithium targets were placed inside a Faraday cage biased to -300V to suppress secondary electron production. The beam currents were in the range of 100 to 400 namp. The beam spot was typically 4 mm^2. Beam irradiation times were typically 10 and 4 minutes for protons and deuterons, respectively. The prompt gamma rays and neutrons produced, impinged upon praseodymium samples located 7.62 cm from the lithium target and oriented 90^o with respect to the beam. All praseodymium samples were 1.25 cm thick and either 2.5 or 7.62 cm in diameter. The thresholds for the (γ,n) and (n,2n) reactions in praseodymium are 9.4 and 9.46 MeV, respectively.

After irradiating for the designated beam on target time, the Pr disk was removed, placed in the standard γ-γ coincidence counting system, and the induced ^{140}Pr activity, counted for three consecutive, four minute intervals. In this apparatus, the two 0.511-MeV annihilation gamma rays were detected with two NaI(Tl) scintillation detectors, 12.7 cm diameter by 7.6 cm thick. The annihilation gamma rays had a 50% probability of escaping the Pr target. The detectors were shielded from background by a 2.5 cm thick lead shield that completely surrounded both detectors. The typical background coincidence count rate was 6 counts/minute. The detectors were absolutely calibrated with a 1.05μCi Na-22 positron source.

Analysis

For the condition of steady irradiation of the target, the relationship that describes the experiment is given by [3]:

$$C - B = I_i\,(1/\lambda)\,(1 - e^{-\lambda t_0})\,(e^{-\lambda t_1} - e^{-\lambda t_2})\,F(E_i)$$

where I_i is the number of protons or deuterons per second, $1/\lambda$ is the mean lifetime of $^{140}Pr = 0.0034$ sec, t_0 is the irradiation time, t_1 is the start time of the count measured from the end of irradiation, t_2 is the stop time of the count measured from the end of irradiation, C-B is the counts minus background per gram of Pr sample, and $F(E_i)$ is the calibration factor. For a mixed proton and deuterium beam the fraction of counts due to protons is given by a correction factor [3]:

$$CF(E_i) = Y_p(E_i)\left\{Y_p(E_i) + \frac{\xi(d)Y_d(E_i)}{\sqrt{2}}\right\}^{-1}$$

where $Y_p(E_i)$ is the thick target yield of the $^7Li(p,\gamma)^8Be$ reaction at a proton bombarding energy E_i, $Y_d(E_i)$ is the thick target yield of the $^7Li(d,n)^8Be$ reaction at the deuteron energy E_i, and $\xi(D)$ is the fraction of deuterium in the beam. Using the calibration and correction factors, the time integrated current on a pulsed accelerator such as PBFA II in which the current and voltage are functions of time can be unfolded using techniques described in Ref [3].

Calibration Results

The results of the calibration experiments are shown in Fig. 2 and 3. The absolute efficiency of the detector is a constant in this work and has not been unfolded. Plotted in Fig. 2 is the calibration factor for protons as a function of incident proton energy. The data had statistical errors of ±20%. Figure 3 shows the analogous calibration factor for deuterium. The statistical errors of these data were ±10%. For protons the most useful energy range is 3 to 9 MeV over which the calibration factor only changes a factor of 4. Above 9 MeV incident energy, the calibration factor begins to change very rapidly as a function of incident proton energy. In this range the voltage must be well known to accurately unfold an integrated current. The deuterium calibration curve exhibits a nearly constant, moderate variation over the entire 1.8 to 12 MeV range.

Figure 4 shows the deuterium correction factor as a function of incident ion energy assuming natural abundance (0.15%) deuterium in the beam. Fortunately, this correction is nearly constant as a function of energy. It is a sensitive function of the deuterium fraction, however, with even natural abundance deuterium accounting for 30 to 50% of the induced Pr activity. Changing the deuterium fraction by a factor of 2 will change the correction factor by 20 to 50%, depending on the ion energy.

PBFA-II Results

The goal of our program at SNL is to produce a Li beam suitable for ICF experiments. Hence, most diode experiments employ Li beams. These Li beams do not produce the large, low-energy neutron backgrounds associated with proton shots which has allowed us to continue to use Cu as a secondary target on Li shots. There have been a few proton shot series, however, on which we have successfully fielded Pr as the secondary target. On all of these shots, as expected, the use of Pr eliminated the interference problems associated with the use of Cu targets. On one of these shots the experimental geometry allowed a direct comparison of integrated current (converted to total beam energy) as measured by the activation and ion pinhole camera [5] diagnostics. The values obtained for total beam energy on this shot were 31 KJ by activation and 27 KJ by the ion pinhole camera. Since the overall uncertainties in the measurements are ±20%, we consider the results to be in excellent agreement. On the remaining shots, experimental constraints prevented the activation diagnostic from being fielded in the calibration geometry. As a result, only relative comparisons could be made with the ion pinhole camera but these comparisons were in excellent qualitative agreement.

Conclusions

A diagnostic to measure integrated beam current on PBFA II using the reaction sequence ^{7}Li(p,γ)^{8}Be $\rightarrow$^{141}Pr(γ,n)^{140}Pr(β+) has been developed. This diagnostic has been calibrated for both protons and deuterium over the energy range of 1.8 to 12 MeV. This diagnostic has yielded measurements of total beam energy that are consistent with the results obtained with other diagnostics on PBFA II.

Acknowledgments

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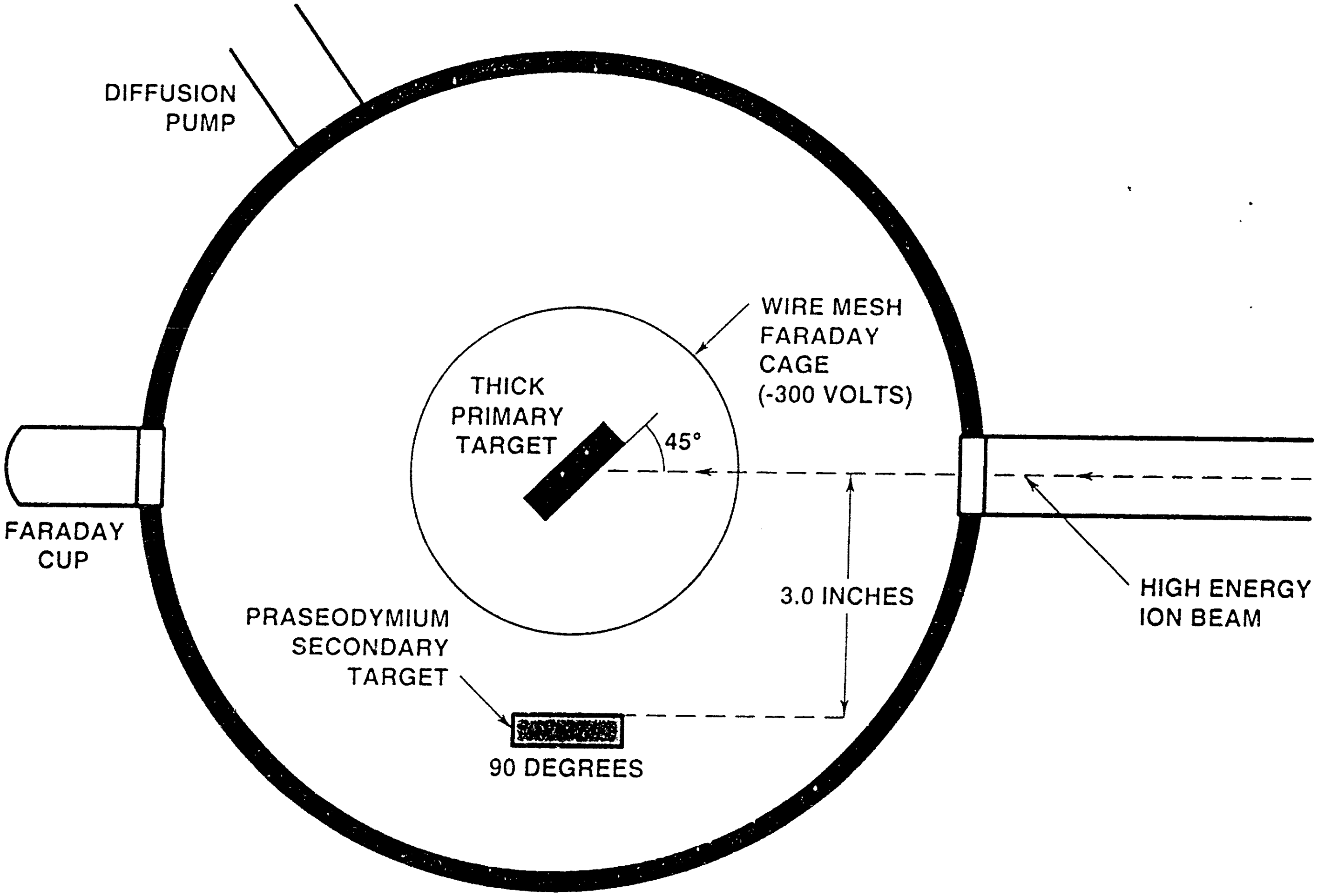
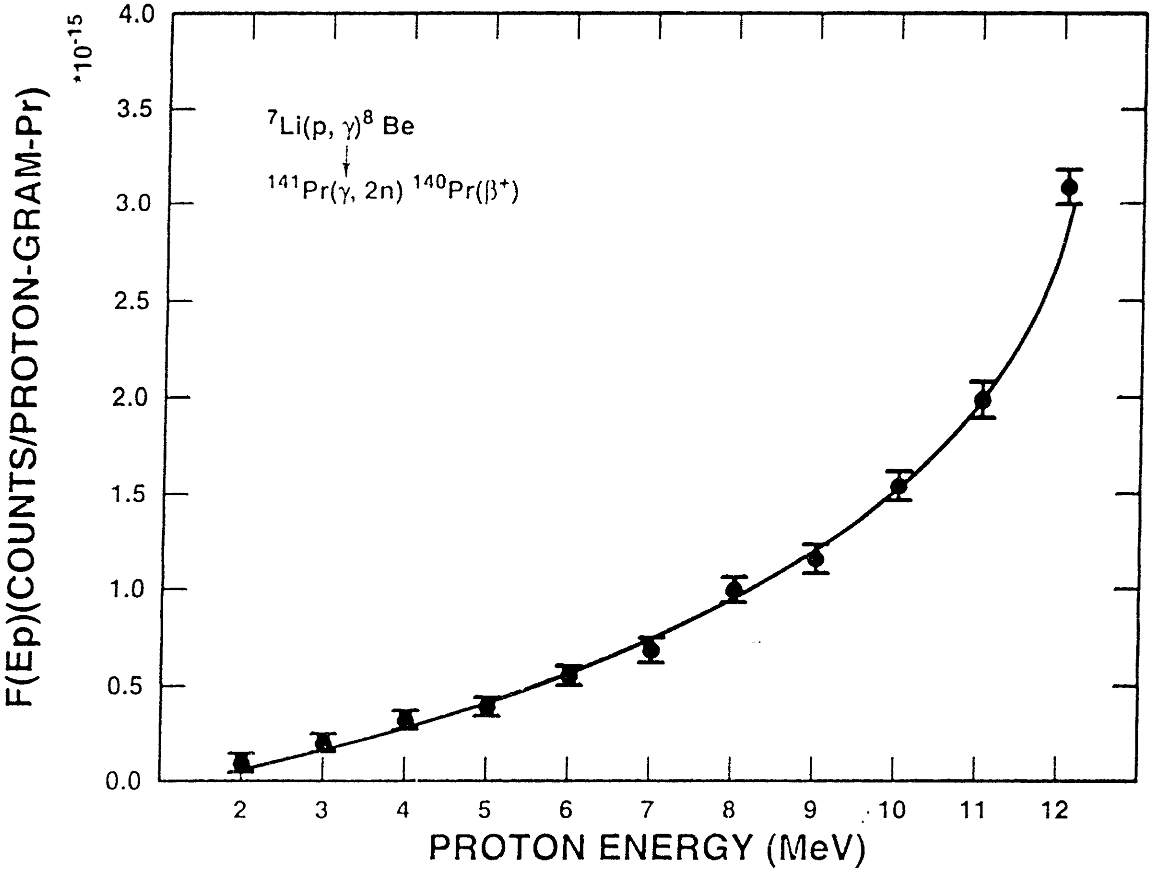
CAPTIONS

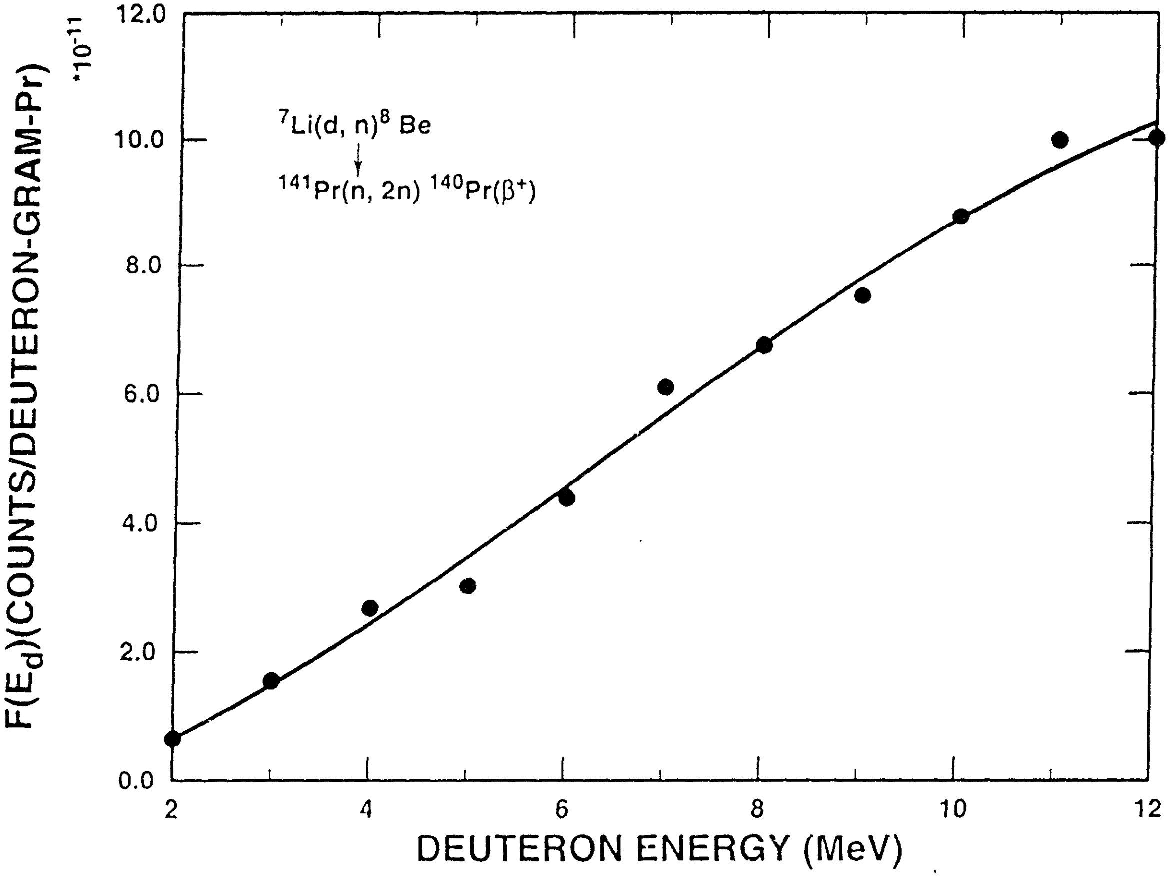
1. Calibration Experiment Geometry
2. Proton calibration factor versus incident proton energy
3. Deuterium calibration factor versus incident deuterium energy
4. Deuterium correction factor for natural abundance (0.15%) deuterium


DIFFUSION PUMP
WIRE MESH FARADAY CAGE (-300 VOLTS)
THICK PRIMARY TARGET
45°
FARADAY CUP
3.0 INCHES
HIGH ENERGY ION BEAM
PRASEODYMIUM SECONDARY TARGET
90 DEGREES

CALIBRATION FACTOR, F, VERSUS PROTON INCIDENT ENERGY



CALIBRATION FACTOR, F, VERSUS DEUTERON INCIDENT ENERGY



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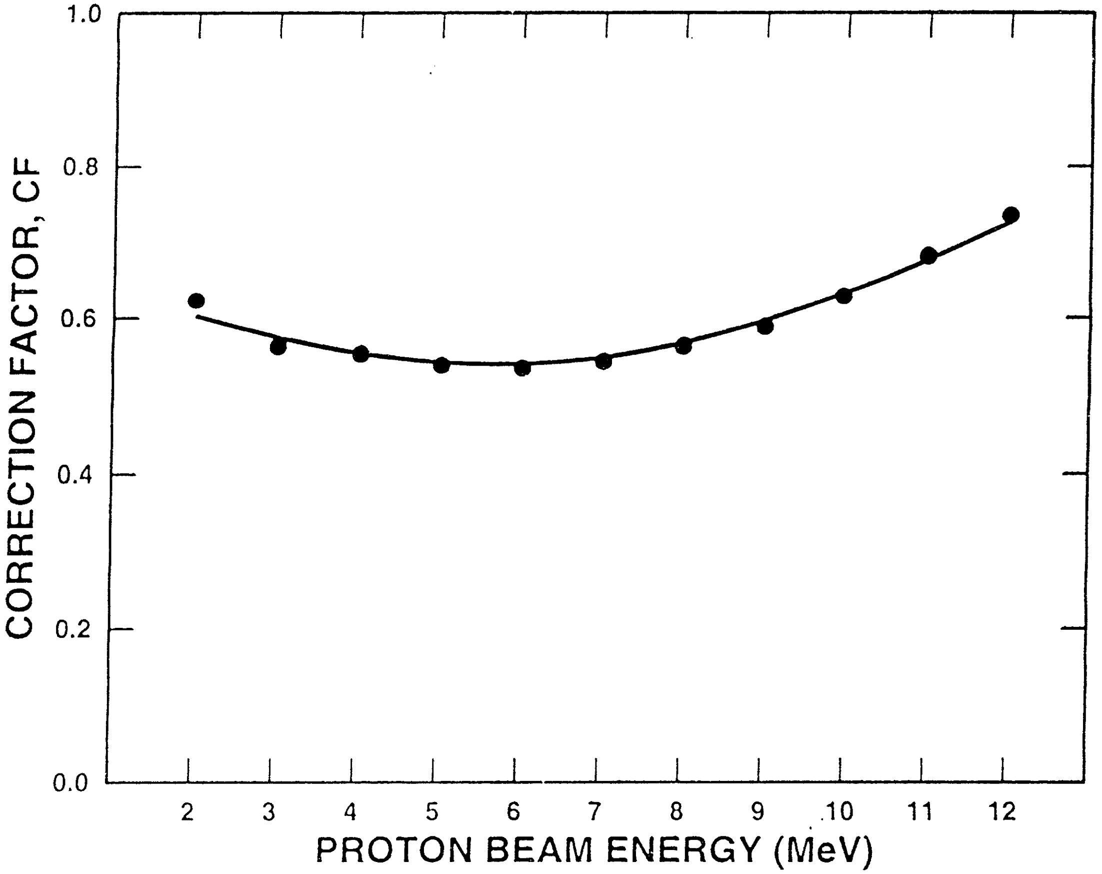
CORRECTION FACTOR, CF, Pr IRRADIATION FROM LITHIUM TARGET



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