High Energy Neutrons from 500 MeV Protons on Lead

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1. Introduction

The angular distribution of high energy neutrons from a 10.2 cm diameter, 30.5 cm long lead target bombarded by 500 MeV protons was measured by the ^{11}C activation produced in plastic scintillators. The $^{12}C(n,2n)^{11}C$ reaction has an energy threshold of 20 MeV so that essentially only the high energy, direct interaction (cascade) neutron component is seen by these measurements. The number of protons incident in two bombardments, one with a bare target and the second with an 80 cm thick H_2O shield around the target were also measured, enabling the determination of effective, absolute neutron source strengths for 500 MeV protons stopping in a thick lead target.

Section 2 describes the experiment in more detail. Section 3 describes the parameters used to reduce the data to effective source strengths and Section 4 assesses the probable accuracy of the experiment.

2. Experimental Measurements

The angular distribution of secondary neutrons from a stopping thickness lead target bombarded by 500 MeV protons was measured using the $^{12}C(n,2n)^{11}C$ reactions in plastic scintillators. Two separate measurements were made, one with a bare 10.2 cm diameter, 30.5 cm long target and one with the same target surrounded by blanket of H_2O approximately 80 cm thick. In both measurements the 5.1 cm diameter, 5.1 cm high, NE-102 scintillators were mounted outside a 183 cm diameter, 1.3 cm thick wall aluminum tank at the positions indicated on Fig. 1. The target was contained in a 24 cm diameter, 32 cm long air-tight aluminum can and the 10.2 cm diameter proton beam tube extension was evacuated in common with the rest of BL4A at TRIUMF, both shown dotted on Fig. 1.

The ^{11}C activity was assayed by placing the scintiallators on a photomultiplier and counting the pulses above a fixed discrimination level. The absolute detection sensitivity of 79% for the setting chosen was established in two ways. One was to count a scintillator at various discriminator settings and extrapolate the dependence to a zero discriminator setting. The second was by assaying a highly activated scintillator on an independently calibrated, low geometry Ge(Li) spectrometer. The deduced sensitivity factors agreed within ~5%.

The 500 MeV proton beam was delivered to the target for both bombardments at a current of 20 to 30 nA over periods of 20 to 30 min. The instantaneous beam current was determined by measuring the electron current on the foil used to strip the H^- for extraction from the cyclotron. The total number of protons incident on the target was estimated by numerical integration of the beam intensity as a function of time; these estimates for subsequent FERFICON bombardments generally yielded results within 20% of those deduced from $^{27}Al(p,3pn)^{24}Na$ monitor reactions. The recorded time profile of the bombardment was used to estimate the decay correction for the 20.38 min half-life ^{11}C activity to determine the effective, instantaneous integral proton beam current that would have produced the same activation at the end of the bombardment period.

3. Data Reduction and Analysis

The scintillators were recovered from the target assembly tank within 20 min of the end of the bombardment with the 80 cm H_2O blanket and counting was started immediately. The decay curves for the first 80 min after end-of-bombardment (EOB) for this run followed the 20.38 min half-life of the ^{11}C decays to within 0.5%; beyond this period longer lived and background contributions started to become significant. The ^{11}C activity at EOB was deduced by back extrapolation of three assaying points taken on each scintillator during the initial period.

The counting rates for the scintillators used in the bare-target bombardment showed a significant contamination by a 35-40 min activity at the earliest times for which assaying was carried out—in that case between 30 and 80 min after EOB. The contribution from this contaminant amounted to between 5 and 20% of the gross count rate at the earliest assaying times and showed a nearly—within a factor of 2—isotropic angular distribution. Its identity was not established with certainty but ^{38}Cl from thermal neutron activation is suspected. The thermal neutron component was enhanced by the water inadvertently left in the tank at a level 15 cm below the target container during the target bombardment. Longer lived ^{122}Sb and ^{124}Sb components from neutrons capture were positively identified later by half-life and γ-spectroscopy and traced to black masking tape around the sides of the scintillators, used to improve their optical characteristics.

The ^{11}C decay rates for all of scintillators for both the bare target and water blanket bombardment runs are listed in Table 1, along with the estimated effective integral proton beam current, corrected for ^{11}C decay during bombardment. The results are also shown as effective secondary neutron source strengths in the various directions per incident 500 MeV proton reaching the scintillators at the outside of the water tank from the bare target and through the water shield. To obtain the effective source strengths the $^{12}C(n,2n)^{11}C$ reaction probability in the scintillators (110 g of ^{12}C) was estimated for a 1/E spectrum-weighted-average cross section of 10.7 mb in the energy range 20 to 400 MeV. This value is based on the published[1] data

between 20 and 40 MeV and an assumed constant cross section of 10 mb above 40 MeV. Specifically, the number ^{11}C species produced by a total fluence, ϕ cm^{-2}, of such neutrons on a scintillator would be

$$R = \phi \times 0.6023 \times 0.0107 \quad \frac{110}{12}$$

$$= 0.0590\phi$$

and the induced decay rate, D, would be

$$D = R \times \frac{\ln 2}{20.38 \times 60}$$

$$= 5.67 \times 10^{-4}\ R\ s^{-1}$$

$$= 3.34 \times 10^{-5}\ \phi\ s^{-1}\ .$$

For a counting efficiency of 79% the count rate, C, would be

$$C = 0.79\ D$$

$$= 2.64 \times 10^{-5}\ \phi\ s^{-1}$$

Thus

$$\phi = \frac{C}{2.64 \times 10^{-5}} = 3.78 \times 10^{4}\ C\ .$$

Finally to obtain the effective source strength, S per steradian per incident proton the effective fluence ϕ is multiplied by the square of the distance (94 cm) from the centre of the target to the centre of the scintillators and divide by the number of protons incident

$$S = \frac{94^2\ \phi}{P}$$

$$= 3.34 \times 10^{8}\ \frac{C}{P}\ \text{steradian}^{-1}\ .$$

The deduced effective source strengths are listed in Table 1 for the bare and water shielded configurations; they are also plotted in Fig. 2 as a function of the cosine of the angle between the incident proton beam direction and the direction of the scintillator from the target centre.

4. Discussion of Results

The accuracy of the results in Table 1 and Fig. 2 are expected to be limited by the possible error on the measurement of the number of 500 MeV protons incident on the lead target during the bombardments. As cited above the integration of the cyclotron stripper foil current, renormalized by well established loss factors for the electron current, gave general agreement on other occasion with aluminum foil activation measurements within a limit of 20%. Although the sizes of the beam spots on the target were not as good as for subsequent FERFICON runs—fwhm ~ 1 cm as compared to 0.3 cm for most bombardments—the beam transport loss were probably quite small.

The relative accuracy of the angular distribution for each bombardment is expected to be much better, more like 5%, limited by the extraction of the ^{11}C component from the scintillator decay curves. The cause of the apparent discrepancy at high angles through the water blanket is unknown; lacking any reproducibility check, transposition of the data points cannot be ruled out. The sharp drop in intensity in the forward direction for the bare target measurement is probably due to attenuation by the downstream end of the 25 cm long lead target. A smaller reduction in the water shielded case is expected because of the angular resolution broadening that such a blanket would produce.

The angular distribution shown in Fig. 2 presumes that the effective source is at the centre of the Pb target. The source is actually distributed

and the centre of the proton collision distribution is 6.5 cm ahead of the target centre. Thus the angular distribution as seen from large distances would be more anisotropic. In forward directions the intensity would be increased by the approximate factor

$$\left(\frac{94}{94 - 6.5}\right)^2 = 1.14$$

and decreased in the backward direction by the reciprocal, namely $1.14^{-1} = 0.88$.

Reference

1. D.I. Barber and R.R. Kinsey, Neutron Cross Sections, BNL 325, Third Edition, Vol. II, 1976.

Scintillator Placement on Ferticon Water Tank

Tank Diameter = 183 cm; Lead Target 10.2 cm Diameter
30.5 cm Length

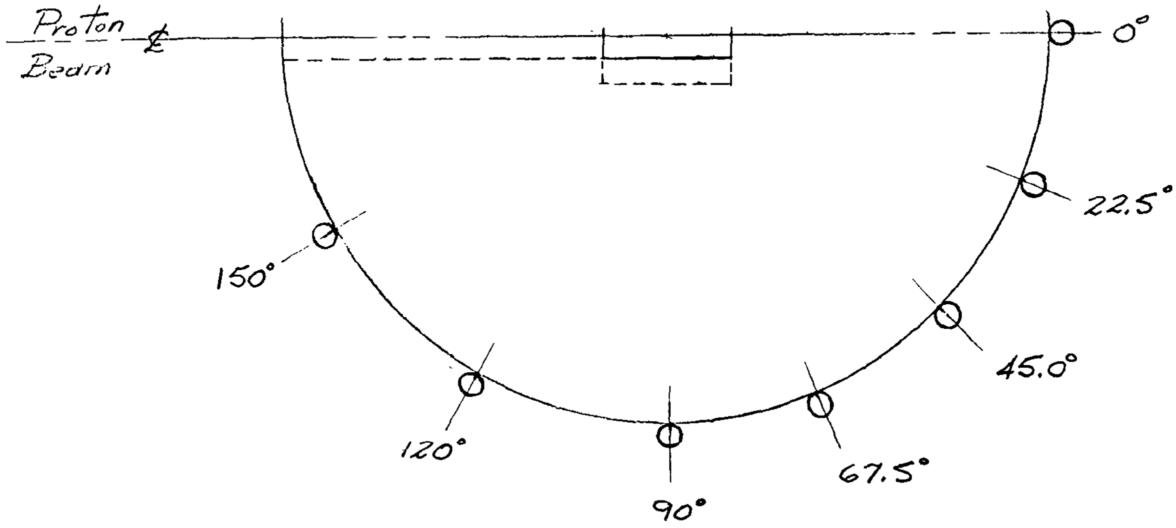

Fig. 1. Schematic plane view of geometry for $^{12}C(n,2n)^{11}C$ activation experiment.

Table 1

^{11}C Activation Results for Bare and Water Shielded Pb Targets Bombarded by 500 MeV Protons

		Bare Target		80 cm H_2O Shield	
Θ	μ	Scint. Decay Rate @ EOB s^{-1}	Effective Source Strength $(p\cdot steradian)^{-1}$	Scint. Decay Rate @ EOB s^{-1}	Effective Source Strength $(p\cdot steradian)^{-1}$
0°	1.000	19000	0.122	18530	0.032
22.5°	0.924	31000	0.200	19670	0.034
45°	0.707	27000	0.173	14370	0.025
67.5°	0.383	18500	0.119	7820	0.0133
90°	0	10000	0.064	3720	0.0064
120°	-0.500	5000	0.032	1570	0.0027
150°	-0.866	3600	0.023	1830	0.0031
Decay Corrected Integral Number of Protons P		0.52×10^{14}		2.0×10^{14}	

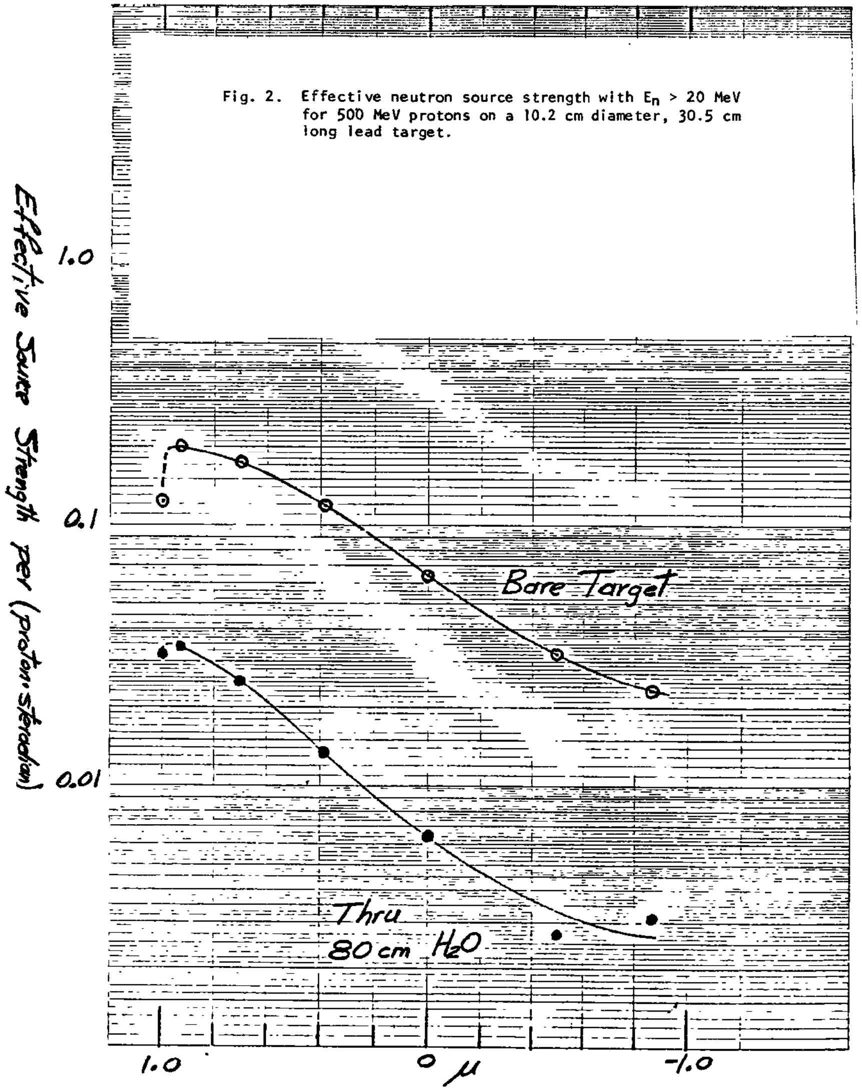

Fig. 2. Effective neutron source strength with $E_n > 20$ MeV for 500 MeV protons on a 10.2 cm diameter, 30.5 cm long lead target.