IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

NEUTRON PRODUCTION BY Ne AND Si IONS ON A THICK Cu TARGET AT 670 MeV · A WITH APPLICATION TO RADIATION PROTECTION

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Summary

Beams of neon and silicon at 670 MeV·A from the Bevalac were stopped in a copper target. Neutron yields and angular distributions were measured with activation detectors. Attenuation of neutrons through a concrete shield was measured at 7°, 54° and 72° to the beam direction. Dose equivalent estimates were made in adjoining areas by using moderated BF_3 proportional counters and carbon and aluminum activation detectors. Data are presented and radiation protection aspects discussed.

Experimental Arrangement

The purpose of these measurements is to determine source parameters which will be useful in shielding calculations for a proposed medical accelerator [1, 2]. Beams of Ne and Si at 670 MeV·A at an intensity of about 2.5×10^8 ions/sec were brought from the Bevalac into Cave I (Fig. 1). The beam monitor was a calibrated secondary emission monitor. The targets used were 76.5 or 38.4 g cm^{-2} of Cu, somewhat thicker than the range of the primary ions, Ne and Si, respectively, and were placed as shown on Fig. 1. Neutron detectors [3] were placed at several locations both within and outside of the cave (Table 1).

Table 1. Neutron Detectors Used.

Type of detector	Reaction	Energy Range
Indium	n capture	Thermal
BF_3 (moderated)	$^{10}B(n, \alpha)^7Li$	0 - 15 MeV
Aluminum:	$^{27}Al \rightarrow {}^{24}Na$	> 6.5 MeV
	$^{27}Al \rightarrow {}^{22}Na$	> 25 MeV
	$^{27}Al \rightarrow {}^{18}F$	> 50 MeV
Teflon	$^{19}F \rightarrow {}^{18}F$	> 10 MeV
Polyethylene $(CH_2)_n$	$^{12}C \rightarrow {}^{11}C$	> 20 MeV

Attenuation Measurements

Secondary particles from primary beam interactions which have sufficient energy (>150 MeV) initiate hadronic cascades. Lower energy neutrons reach equilibrium with the highest energy component after 2 to 3 mean free paths and the subsequent ratio of low to high energy neutron intensity remains approximately constant. This makes it possible to measure the attenuation of the energy integrated fluence using low energy neutron detectors. In particular, advantage may be taken of the high activation cross sections of indium for thermal neutrons. Indium foils were placed in narrow spaces (to prevent neutron streaming) between concrete shielding blocks at known angles to the beam direction. Figure 2 shows measurements at angles of 7°, 54° and 72°, for Ne and Si beams.

Values of the effective attenuation length observed at 7°, λ_{conc} = 114 and 109 g cm^{-2}, for Ne and Si, respectively, are consistent with those at high energy proton accelerators and represent the maximum value. This is a consequence of the constancy of the inelastic cross sections at energies above about 150 MeV [4].

For the range of concrete shielding thickness used, the effective attenuation length decreases with increasing angle. Values obtained from Fig. 2 are 64 and 56 g cm^{-2}, for secondaries from Ne at 54° and 72°, respectively, and 61 g cm^{-2} for

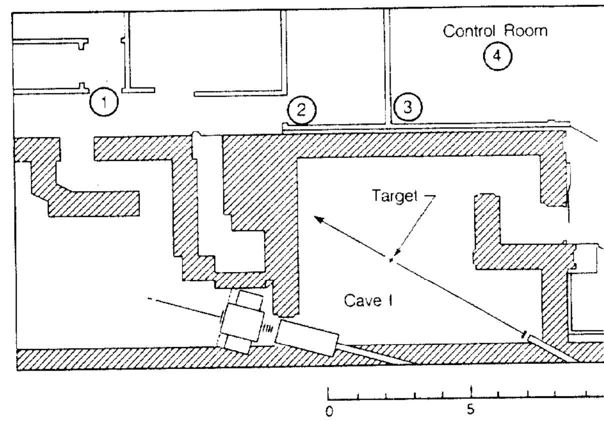

Fig. 1 Experimental arrangement around Cave I. Dose equivalent measurements were made with moderated BF_3 counter at locations 1 - 4.

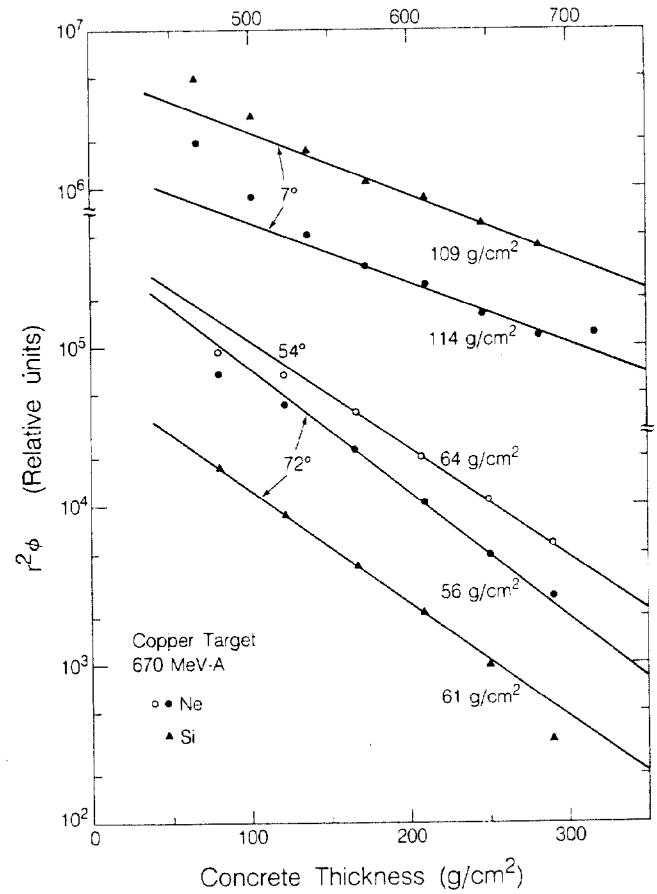

Fig. 2 Attenuation curves in concrete for secondaries from a Cu target struck by 670 MeV·A Ne or Si ions. Detectors are indium foils. Data at 7° begin at 466 g cm^{-2} (upper scale). Units are relative.

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Si at 72°. For a beam of Ne ions on Cu, $\lambda_{conc}(\theta)$ may be represented by the equations:

For $\theta < 75°$: $\lambda_{conc}(\theta) = 115\ e^{-0.01\,\theta}\ g\ cm^{-2}$, (1a)

for $\theta > 75°$: $\lambda_{conc}(\theta) = 55\ g\ cm^{-2}$, (1b)

where the angle θ is in degrees. The second of these expressions (1b) is a conservative assumption and is used because of inadequate data at larger angles.

Even at large angles some secondary nucleons are produced which have sufficient energy to initiate hadronic cascades in target and shielding materials. In situations where the beam intensity is high, and thick shields are therefore required, it is these high energy particles, having an attenuation length of 115 g cm^{-2} which determine the shield thickness; the softer components of the secondary radiation emitted from the target are removed by the inner layers of the shield (see below).

Multiplying by the ratio of inelastic cross sections, we can infer that the attenuation in steel is given by

$$\lambda_{Fe}(\theta) = 0.436\lambda_{conc}(\theta). \quad (2)$$

This gives the observed value of $\lambda_{Fe}(0°) = 160$ g cm^{-2}.

Angular Distribution and Yield Measurements

The angular distribution of secondary particles was studied using Al, $(CH_2)_n$ and teflon detectors, arranged around the Cu target on an arc of 1 m radius (Fig. 1). Results are shown in Figs. 3 and 4. The slope corresponding to exp[-2.3 θ (radians)], indicated by the line segment represents the angular distribution derived for high energy proton interactions [5, 6]. The upward tail at large angles on several of the observed distributions can be attributed to spurious particles accompanying the beam at large radii. An alternative explanation is that charged secondaries have less target material to penetrate in the backward direction, and enhance the count rate relative to sideward directions.

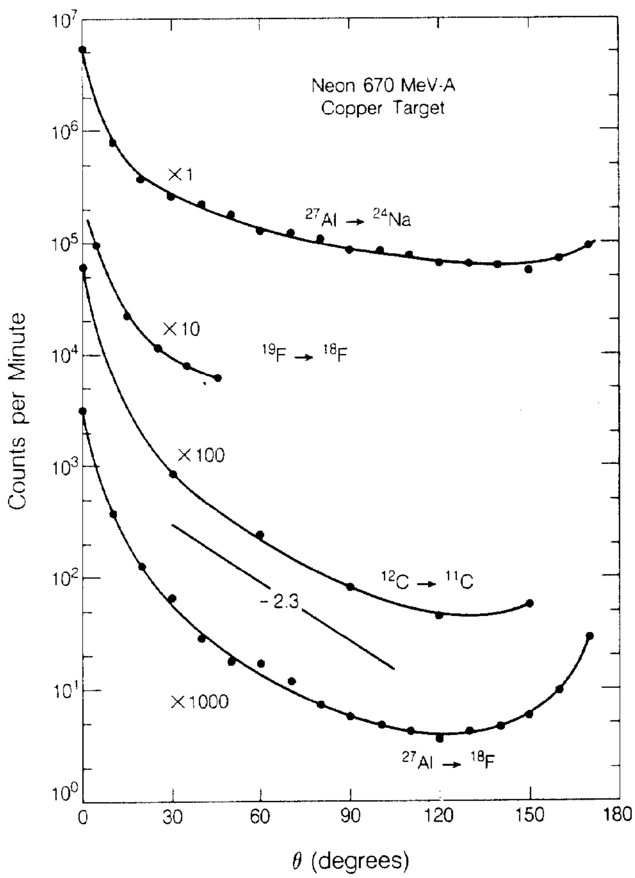

Fig. 3 Angular distributions as determined at 1 m by four types of activation detectors having thresholds in the range 6.5 - 50 MeV. Beam was 2.5×10^{8} Ne ions sec^{-1} on to a thick Cu target. Normalization is arbitrary.

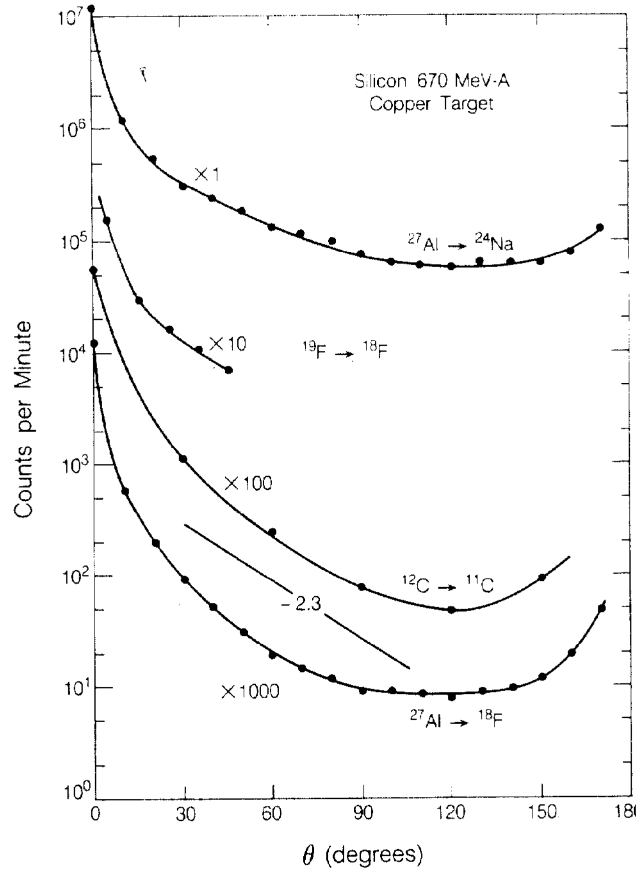

Fig. 4 As for Fig. 3 but using beam of Si ions.

An analytical fit to the $^{27}Al \rightarrow {}^{24}Na$ distribution, useful for computational purposes for the range $2° < \theta < 180°$ is:

$$\phi(\theta) = 3.72\times10^{2}\ \theta^{-1}\ \text{neutrons m}^{-2}\ /\ \text{ion}. \quad (3)$$

at 1 m for incident Ne ions (θ is in degrees).

Empirical Model for Thin Shields

The measurements described above suggest an empirical model used to calculate the dose equivalent, $H(\theta)$, outside shields within the range of thicknesses studied. On the basis of the measured attenuation lengths and angular distributions shown in Figs. 3 and 4, an empirical model was devised to fit measured dose equivalents at the locations shown in Fig. 1:

$$H(\theta) = N\ C_1\ C_2\ \phi(\theta)\ r^{-2}\ e^{-\ell(\theta)/\lambda(\theta)}, \quad (4)$$

where H is in Sv and θ is in degrees, and

- N — is the number of Ne ions stopped in a copper target.
- C_1 — accounts for that fraction of the dose equivalent due to neutrons of energy greater than 20 MeV. This factor ranges from 2 in heavily shielded areas to about 5 where the shielding is less thick [7, 8].
- C_2 — converts fluence to dose equivalent. The value 2.33×10^{-14} m^{2} Sv neutron^{-1} was used [9].
- $\phi(\theta)$ — is the neutron fluence 1 m from the target [neutrons m^{-2}; equation (3)].
- $r(\theta)$ — is the distance from the target to the detector (m).
- $\ell(\theta)$ — is the shield thickness in the direction θ (g cm^{-2}).

$\lambda(\theta)$ is the attenuation length [g cm^{-2}; equation (1)].

Combining the above factors, we obtain:

$$H(\theta) = 8.67\times10^{-12}\ N\ C_1\ \theta^{-1} r^{-2}\ e^{-\ell(\theta)/\lambda(\theta)}. \quad (5)$$

Table 2 compares the dose equivalent rates measured at the numbered locations on Fig. 1, to values calculated as just described. The model is accurate to within a factor of two for these conditions.

Table 2. Comparison with Measurements at 2.5×10^8 Ne/sec.

Location	θ (deg)	Distance (m)	Shielding Thickness (g/cm^2)	C_1	Dose Equivalent Rate Measured (μSv/hr)	Dose Equivalent Rate Calculated (μSv/hr)
1.	2	12.2	953	2	26	11
2.	30	6.1	251	5	2000	1840
3.	65	5.3	222	3	200	320
4.	80	8.8	237	2.2	50	37

This model is adequate to relate observed dose equivalent levels outside the shield to beam loss in Cave I and provides a rough guide for the proposed medical accelerator shielding. However, it is not necessarily applicable to geometries which substantially differ in lateral shielding thickness.

Dose Equivalent Estimates for Thick Shields

For the estimation of dose equivalent outside thick shields where particle equilibrium is achieved, equations (1) are inappropriate. Under such conditions we have

$$\lambda_{conc} = 115\ \text{g cm}^{-2}. \quad (1c)$$

Additionally, in order to account for the nucleons emitted with sufficient energy to initiate hadronic cascades we base the source term, $\phi(\theta)$, on the fluence as measured by the reaction $^{12}C \rightarrow {}^{11}C$. For incident Ne ions, we use parameterizations for the fluence at 1 m which are analogous to equation (3). For $0° < \theta < 20°$:

$$\phi(\theta) = 248\ e^{-0.20\ \theta}\ \text{neutrons m}^{-2} / \text{ion}, \quad (6a)$$

and for $20° < \theta < 120°$,

$$\phi(\theta) = 10\ e^{-0.038\ \theta}\ \text{neutrons m}^{-2} / \text{ion}, \quad (6b)$$

where θ is in degrees. Substituting these source terms, together with the value $C_1 = 2$, in equation (4), we have for $0° < \theta < 20°$:

$$H(\theta) = 12\times10^{-12}\ N\ e^{-0.20\ \theta}\ r^{-2}\ e^{-\ell(\theta)/115} \quad (7a)$$

and for $20° < \theta < 120°$,

$$H(\theta) = 0.48\times10^{-12}\ N\ e^{-0.038\ \theta}\ r^{-2}\ e^{-\ell(\theta)/115} \quad (7b)$$

where H is in Sv, r is in meters and ℓ is in g cm^{-2}.

These approximations are expected to be conservative for the forward hemisphere because they use a source term based on yields measured by the $^{12}C \rightarrow {}^{11}C$ reaction (20 MeV threshold); this source term will be larger than that ideally needed (neutrons > 150 MeV). However, for angles larger than about 120°, the source term might be underestimated if the backward rise seen in Fig. 3 is significant.

The models of equations (5) and (7) have been used in the design of shielding for a proposed Heavy Ion Medical Accelerator which can accelerate a variety of ions from H to Ar, at energies up to 800 MeV·A and at intensities of 10^7 to 10^9 ions sec^{-1} [2].

Conclusions and Future Efforts

The uncertainties in the data presented here demonstrate the need for more detailed measurements. Neutron yields and angular distributions as functions of ion energy, ion species and target material are required. The attenuation of secondary neutrons in concrete at depths up to 6 m in the forward direction and 3 m in the transverse direction are needed.

Acknowledgements

The authors wish to express their gratitude to Jose R. Alonso, William T. Chu, Richard A. Gough and Tim R. Renner of the LBL Accelerator Division for their assistance and to Jensen Young, Head of the Environmental Health and Safety Department, and W. D. Hartsough, Head of Facilities Management, for support and encouragement. This work was supported by the U. S. Department of Energy under Contract No. DE-AC03-76SF00098 with the University of California.

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