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ABSTRACT

Shielding against neutrons produced by medium-energy cyclotron ion beams bombarding elemental tantalum has been studied at the Berkeley 88-inch cyclotron. Beams of 110-MeV alphas, 55-MeV deuterons, and 50-MeV protons were used to bombard a thick tantalum target. The resultant neutrons were attenuated by a stack of precision-cast ordinary concrete blocks into which threshold reaction detectors were placed at 3-in. intervals. The first 12 in. of concrete shielding were replaced with iron and depleted uranium to measure the effect of each of the face materials upon the neutron spectra and upon attenuation lengths of neutrons from the three different ion beams.

The detector materials used were nickel, aluminum, and thallium for the threshold reactions, and gold for thermal and epithermal neutron capture reactions. Properties of the threshold detectors are given in Table I.

The activities produced in each detector were counted with a γ-ray spectrometer. The computer program SAMPO was used to locate the

Table I. Threshold detector properties.

Reaction	Calculated threshold (MeV)[a]	Peak cross section (barns)	Product half-life	Target isotope (%)	γ-Ray energy of product (MeV)
$^{58}Ni(n,p)^{58}Co$	1.1	0.556	71 days	67.8	0.81
$^{27}Al(n,\alpha)^{24}Na$	6.7	0.243	15 hr	100	1.37, 2.74
$^{203}Tl(n,2n)^{202}Tl$	8.5	2.78	12 days	29.5	0.44
$^{58}Ni(n,2n)^{57}Ni$	12.4	0.25	37 hr	67.8	1.36
$^{27}Al(n,\alpha 2n)^{22}Na$	23.4	0.030	2.6 yr	100	0.51, 1.27
$^{203}Tl(n,4n)^{200}Tl$	24.7	≈1.3	27 hr	29.5	1.207

a. The energy at which the cross section value is 2% of the maximum cross section value.

γ-ray peaks, fit them to a Gaussian shape, determine their energy, strip each peak and calculate the area under it. The counts under the peak were corrected for counting geometry and detection efficiencies to obtain absolute counting rates. The activity data from SAMPO were then put into the computer program FLUXPOS along with information regarding irradiation, decay and counting times, half-life, foil and atomic weights, fraction of isotope, atoms per molecule, and the fraction of activity produced by neutrons below 30 MeV (the program's energy cutoff). With this information, the reaction cross section as a function of neutron energy was used to compute the neutron spectra. The relationships between detector activity, cross section, and neutron flux are expressed as

$$A_i' \int_0^\infty \phi(E)\sigma_i(E)d(E),$$

where A' = detector saturation activity or disintegration rate per target nucleus in sec^{-1},

$\phi(E)$ = neutron flux in $cm^{-2}\ sec^{-1}\ MeV^{-1}$,

$\sigma(E)$ = reaction cross section in cm^2,

E = neutron energy in MeV,

and i = identification of the reaction and the residual nucleus.

One equation for each threshold reaction is used to form a set of integral equations that describe the unknown neutron flux. By iteration, the computer produces a set of calculated activities that best fit the set of measured activities. It then calculates the neutron spectrum that would be required to achieve the calculated ratios between the activities and the neutron flux necessary to produce the measured activities. Both programs are run on the CDC-6600 computer. The nine different experimental configurations produced 156 neutron spectra.

The results produce neutron spectra and attenuation data as a function of the measurement depth in the shielding and the material used for the first 12 in. Table II summarizes the attenuation for the nine configurations.

This study is the only known work that experimentally compares three beam ions, their forward neutron spectra, and the attenuation of forward neutrons, for the same geometry.

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Table II. Attenuation length (1/e in g/cm^2).

Energy particle	Shielding configuration: All concrete	12-in. iron faced	12-in. uranium (depleted)
110-MeV alpha	35	29.0	26.8
55-MeV deuteron	36.8	24.4	23.8
50-MeV proton	30.5	24.4	25.0

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