## Title
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# RADIATION MEASUREMENTS AND SHIELDING STUDY OF THE BERKELEY 27-INCH $^3$He CYCLOTRON

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# RADIATION MEASUREMENTS AND SHIELDING STUDY OF THE BERKELEY 27-INCH $^3$He CYCLOTRON

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## Abstract

The 27-inch $^3$He cyclotron was designed and constructed at LRL–Berkeley for use mainly in isotope production and activation analysis. Beam particle energy is 6 MeV/nucleon.

Activation detectors and nuclear emulsions were exposed to secondary radiations produced by an internal beam of $\approx 1\ \mu$A striking a thick copper target. Moderated indium foils, the reactions $^{27}$Al(n, $\alpha$)$^{24}$Na, $^{19}$F(n, 2n)$^{18}$F, and $^{12}$C(n, 2n)$^{11}$C, and emulsions provided the information on neutron yield and spectral shape at this beam intensity from which shielding estimates were made for full beam intensity operation of $\approx 40\ \mu$A.

The radiation levels, detector techniques, and shielding computations are discussed.

## Introduction

Light-element activation-analysis techniques, studied at the Berkeley Heavy-Ion Linear Accelerator with $^3$He particle beams by Markowitz and Mahony,[1] have generated great interest in producing an inexpensive accelerator specifically designed for this work. Such a machine could be used not only for charged-particle activation analysis, but also for production of short-lived positron-emitting isotopes for biomedical research and diagnostic studies. The Berkeley 27-inch cyclotron[2] was designed and constructed toward these ends. It is a fixed-energy accelerator that produces $^3$He ions of 18 MeV energy, an energy high enough to permit penetration of the beam through thin vacuum and protective windows into target materials. Beam currents of 1 to 4 μA are presently attainable; however, with modification of the ion source the beam current could be much larger. Our shielding study assumes a maximum accelerated beam of 40 μA.

## Source Strength and Spectral Distribution Measurements

In order to simplify the measurement problems, a thick copper target was used, to assure that a large fraction of the beam interacted at a known position. Localization of the neutron-production site allowed a simple computation of source intensity from measurements taken at a known distance from this site (a distance of 60 cm from the target at an angle of 90 deg with respect to the beam direction). We assume that neutron production is isotropic, because the beam particle energy is only 6 MeV per nucleon.

Figure 1 shows the differential neutron spectrum derived from the observed proton recoil track distribution in a nuclear emulsion exposed to neutrons from this cyclotron target. The technique for obtaining a neutron spectrum from such an emulsion is described by Lehman.[3] The spectral shape suggests a slight peak at about 6 MeV lying along the upper edge of a more intense broad peak centered near 2 MeV. We attribute the 2-MeV peak to evaporation neutrons from de-excitation of the compound nucleus formed from $^3$He plus either $^{63}$Cu or $^{65}$Cu; the 6-MeV peak is probably from specific simple reactions of $^3$He on these Cu isotopes. Slightly more than half the neutrons have energies between 1 and 3 MeV; for higher energies the intensity decreases rapidly, so that only 10% have energies beyond 7 MeV.

A moderated indium foil[4] was used to measure the source strength over the energy region of interest. Table I shows the results of this measurement along with results from three other detectors -- aluminum,[5] fluorine,[6] and carbon,[7] having activation thresholds at about 6, 12, and 20 MeV, respectively. The use of aluminum and carbon threshold detectors is fairly widespread; the use of fluorine (in the form of Teflon) is relatively new, and was suggested to us by Shaw and Stevenson of the Rutherford High Energy Laboratory. The total source strength is $1.1 \times 10^{10}$ n/sec, normalized to a beam current of 40 μA. The general shape of the emulsion spectrum is confirmed by the threshold detector measurements.

## Considerations in Applying Removal Cross Sections for Neutron Attentuation

The neutrons of interest lie in an energy range from about 0.5 to 15 MeV. Neutrons of lower energy are much more rapidly attenuated in the (concrete) shielding, and there are no neutrons of higher energy. Of the two processes for removal of neutrons from this energy interval -- absorption and scattering -- the latter is by far the more important. Elastically scattered neutrons travel a greater distance in order to penetrate the shield than do uncollided neutrons, and therefore are more likely to undergo additional interactions. Furthermore, if a significant amount of energy is lost in a scattering event, the degraded-energy neutron subsequently loses energy more rapidly than does a higher-energy neutron, because scattering cross sections usually increase with decreasing neutron energy. Thus an elastic collision might be considered to be a reaction that always leads to removal of the neutron. However, if scattering is not isotropic but is peaked in the forward direction, as is clearly the case at very high energies, elastic scattering is not an effective mechanisms for removal. Neutrons that are scattered through small angles with little resultant energy loss cannot be considered to be removed from the beam. In general, elastic scattering can be considered to be isotropic for all nuclei below 100 keV neutron energy (this energy limit is higher for light nuclei); but, because of the effect of potential or shadow scattering, such an assumption (isotropy) cannot be used for fast-neutron shielding studies. This anisotropic scattering is an important consideration, but one for which an attempt at an exact solution may not be justified in view of the complexity of the problem (i.e., the scattering angle is a function of the neutron wavelength and the radius of the struck nucleus, etc.). We also note that nonelastic interactions play an increasingly important role as an energy-loss (removal) mechanism for neutrons, as the neutron energy increases beyond several MeV, and as the mass of the struck nucleus becomes greater.

In a practical situation one must often used rather broad assumptions concerning the ultimate intensity of the radiation source and its spatial distribution, the densities and compositions of shielding materials, etc., so that a high degree of precision in determination of the removal cross sections may not be warranted. This seems a reasonable approach for sources of low to moderate intensity, cases for which a few additional inches of shielding (to cover uncertainties in assumptions and calculations) will not be an important cost factor. However, for high-intensity sources that require an extensive and costly facility incorporating several feet of shielding, a more rigorous evaluation of removal cross-section data would be advisable -- in particular, drawing upon experimentally determined attenuation lengths from similar sources.

In this study we seek an expression which, although accounting for the broad aspects of anisotropic and nonelastic scattering as a function of energy, is not overly complex and burdensome in detail or application. Patterson[8] has shown there is good agreement at high energies between measurements with thick shields under broad beam conditions and a scheme in which the removal cross section $\sigma_r$ is arbitrarily related to the total cross section, $\sigma_t$:

$$\sigma_r = f(E)\sigma_t.$$

The values given f(E) are shown in Table II. Here it can be seen that the removal cross section is set equal to the total cross section at 1 MeV; as E becomes larger f(E) becomes smaller, until at energies above 150 MeV (where elastic scattering is essentially all small-angle forward scattering) the removal cross section is set equal to one-half the total cross section.

The known relative abundance of each constituent of typical Berkeley concrete was used in conjunction with values for the removal cross sections to solve the equation

$$I_t = I_0 \exp\left[-N\sigma_r(E)t\right]$$

for values of t to yield a factor-of-2 attenuation. Patterson's results are shown on Fig. 2. This is the simplification we assume, and now extend its application to the lower-energy region, as exemplified by the radiation field created by the 18-MeV $^3$He cyclotron.

## Estimation of Shielding Thickness

The $^3$He cyclotron ceased operation shortly after completion of the measurements reported here. It was disassembled, moved to the site chosen for permanent location, and is still undergoing reassembly. We have not yet had the opportunity to resume our measurement program and, in particular, cannot now report on evaluation of the shielding that was (in part) designed on the basis of the above measurements. The new shielding is being constructed from "available" materials, and includes assorted shapes and sizes of ordinary concrete blocks, along with some water cans. Thickness of the main section of the concrete shielding wall was selected to be 24 inches; the adequacy of this thickness is now demonstrated from the following simple computations.

The problem is to find the shield thickness required to reduce the neutron flux to a value no greater than 17.5 n/cm$^2$-sec at a location 200 cm from the cyclotron target. This flux intensity is equivalent to a dose rate of 2.5 mrem/hr from the neutron spectral distribution under consideration. Table III shows the basis for such judgment, listing those analytic expressions we use to relate neutron energy to dose equivalent -- the expressions suggested by Thomas.[9] The source strength at full power (from measurement at 1/40 full power) was found to be $1.1\times 10^{10}$ n/sec. We assume the measured spectrum is the energy distribution against which we must shield. We also assume the source is localized at the target position, and ignore buildup. The neutron flux at 200 cm from the target is then computed from the measured spectrum as follows:

$$\phi_{200,\,t} = \sum_{0.5\ \text{MeV}}^{13.5\ \text{MeV}} A(\Delta E)\, I_0 \exp\left[-t/T(\Delta E)\right] ,$$

where $A$ is the fraction of the total flux in each energy interval, $\Delta E$,

$I_0$ is $\dfrac{1.1\times 10^{10}}{4\pi\, r^2}$ and r is 200 cm,

$t$ is concrete thickness in in., for the range 20 to 24 in.,

$T$ is the neutron attenuation length for each energy interval $\Delta E$, derived from Fig. 2.

The measured spectrum was integrated to determine values for A, taking $\Delta E$ intervals each 1 MeV wide. Associated with each energy interval is a corresponding value for T, where T is expressed as

$$T = \frac{\text{half-value thickness}}{0.693} .$$

We have computed the surviving neutron flux through 20 in. of concrete for each of the 13 energy intervals, and have then summed these fluxes over the spectrum. This process was repeated for concrete thicknesses of 22 and 24 in. Results of the three computations are shown on Fig. 3, and indicate that a thickness of about 22.6 in. will reduce the flux to the required 17.5 n/cm$^2$-sec. The corresponding dose rate is 2.5 mrem/hr, there being little contribution from neutrons below 1 MeV or above 10 MeV.

We emphasize the following general points. Given the kind of experimental data presented here -- the source intensity and energy spectrum -- one does not have to proceed "blindly" by assuming the shield must be designed against an arbitrarily assigned flux of neutrons of energy equal to some arbitrarily chosen fraction of the accelerated particle energy. One can proceed in a straightforward and simple fashion, starting from a clearly specified source term, to apply the shielding computation scheme just described. If the computation is followed through the entire range of shield thickness considered, one can observe which is the predominant surviving neutron energy group at any given shield depth. He will then be able to evaluate performance of the next increment of shield thickness.

We lack the experimental data taken outside the shield that would enable us to relate directly the source term, the buildup effects, and the shield attenuation characteristics to the neutron flux and spectrum existing at such an exterior point. The $^3$He cyclotron is expected to be in operation again before the end of 1969. Until such time we are left without experimental verification of the adequacy (or inadequacy) of these estimates. We plan to complete these measurements as soon as possible, to offer them either as an addendum to this UCRL report or as a subsequent report. One measurement in particular, that of placing a string of detectors (indium or gold foils) through the shield wall, is most valuable for determining the actual neutron attenuation length; such a measurement will be included with the other relevant measurements.

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Table I. Detector response and data.

| Detector | Energy (MeV) | Background (cpm) | Response to unit flux within the indicated energy | Source emissivity at 40μA neutron/sec >threshold |
|---|---|---|---|---|
| Moderated In foil $^{115}In(n, \gamma)^{116}In$ | 0.02-20 | 8 | 10 cpm/g (0.5-g foils) | $1.1 \times 10^{10}$ |
| $^{27}Al(n, \alpha)^{24}Na$ | >6 | 73 | 21 cpm (at 14 MeV) | $7.2 \times 10^{7}$ |
| $^{19}F(n, 2n)^{18}F$ | >12 | 50 | 5 cpm | $< 7.2 \times 10^{6}$ |
| $^{12}C(n, 2n)^{11}C$ | >20 | 133 | 88 cpm (85% eff) | not detectable at the 1-μA beam level |

Table II. Tabular values for the expression $\sigma_r = f(E)\sigma_t$.

| Neutron energy (MeV) | f(E) |
|---|---|
| 1 | 1.0 |
| 5 | 0.65 |
| 14 | 0.55 |
| ≥150 | 0.50 |

Table III. Analytic expressions for dose equivalent vs neutron energy.

| Energy range (MeV) | $n\text{-cm}^{-2}\text{-sec}^{-1}$ equivalent to $1\ \text{mrem-h}^{-1}$ |
|---|---|
| $< 10^{-2}$ | 232 |
| $10^{-2} - 10^{0}$ | $7.20\ E^{-3/4}$ |
| $10^{0} - 10^{1}$ | 7.20 |
| $>10^{1}$ | $12.8\ E^{-1/4}$ |