theory one obtains $\lambda_p=0.08\pm0.09$ for $R=R_p$, and $\lambda_p=0.18\pm0.09$ if 10 percent of the transitions go by an alternative route. The error is almost entirely due to the error in Auger yield. This fact indicates the great need for still more accurate knowledge of the value of a_K as a function of Z. It is clear, however, that if in 30 percent or more of the transitions of some radio-nuclide an L electron were captured ($\lambda_p>0.5$), the method outlined here would make possible a fairly accurate determination of the amount of L capture even with the present uncertainty in the value of a_K. An estimate of the disintegration energy could then be made by use of the results of Rose and Jackson[44] and Marshak[45] as previously indicated.[39]

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[44] M. E. Rose and J. L. Jackson, Phys. Rev. **76**, 1540 (1949).

[45] R. E. Marshak, Phys. Rev. **61**, 446 (1942).

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Neutron Energy Distribution from the Proton Bombardment of Li, Be, and C at 375 Mev*

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High energy neutrons were produced by bombarding lithium, beryllium, and carbon targets with protons having a maximum energy of 375 Mev. The energy spectrum of the neutrons emitted in the forward direction was measured by determining the range spectrum of recoil protons scattered at 45° by a polyethylene scatterer. A telescope of stilbene crystals with copper range-determining absorbers was used as a detector. The neutron beam was monitored by a bismuth fission ionization chamber. For elements studied, the width of the neutron energy distribution broadens and the energy of the peak of the distribution decreases as the atomic number of the target material increases.

I. INTRODUCTION

An investigation[1] was made of the energy spectra of neutrons emitted in the forward direction when several light elements were bombarded by 375-Mev protons. Targets of lithium, beryllium, and carbon were exposed to the internal proton beam of the Columbia University Nevis cyclotron. The energy of the protons was determined from the value of the magnetic field and the radial position of the target. The neutrons produced scattered protons in a polyethylene block. The range in copper of the scattered protons was determined, using a scintillation counter telescope. The energy distribution of the neutrons was then inferred from this proton-range spectrum.

II. DESCRIPTION OF THE EXPERIMENT

A diagram of the experimental arrangement is given in Fig. 1. The targets were placed inside the vacuum tank of the cyclotron in such a position that the neutrons emitted in the forward direction passed through collimating holes in the concrete shielding surrounding the cyclotron. The targets were rectangular slabs held by a clamp. All parts of the clamp were at least 2 in. from the leading edge of the target, so the clamp would not contribute to the neutron flux. The target thicknesses were 2 in. for lithium, $1\frac{3}{4}$ in. for beryllium, and $1\frac{1}{4}$ in. for carbon. The thicknesses of the beryllium and carbon targets were adjusted to give the same multiple scattering of protons, and hence to give roughly the same number of multiple traversals of the proton beam in the two targets. The targets were of sufficient height to intercept a major fraction of the internal beam of the cyclotron.

The neutron beam passed through a $\frac{3}{4}$ in. Plexiglas window and was collimated by a steel tube 4 in. in diameter and 6 in. long, which was imbedded in the lead and concrete shielding of the cyclotron. Two additional blocks of concrete were added to give better shielding to the counters. The neutrons were scattered alternately by carbon and polyethylene scatterers placed in the beam. The scatterers were 4 in. square, and had a thickness of 2.13 g/cm^2 for the carbon, and 2.38 g/cm^2 for the polyethylene. The thicknesses were

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* This research was supported by the joint program of the Office of Naval Research and the Atomic Energy Commission.

[1] A preliminary report of this work was given by Goodell, Loar, and Durbin, Phys. Rev. **83**, 234 (1951).

adjusted to give the same number of carbon atoms in each scatterer. The recoil protons from the hydrogen in the polyethylene were detected by a triple coincidence scintillation counter telescope at an angle of 45° from the incident neutron beam, and the range spectrum of the protons was determined by copper absorbers. Stilbene crystals approximately 2 in. in diameter were viewed by two 1P21 photomultipliers in parallel per crystal. The details of the crystals are given in Table I.

A block diagram of the electronic equipment is shown in Fig. 2. The signals from the counters were fed to bridge-type coincidence circuits similar to those used by Neher[2] at Berkeley with a resolving time of approximately 10^{-7} second. The outputs of the bridges were connected to an Atomic Instrument 501 Coincidence Analyzer after amplification. An additional signal from the third crystal, passed through an amplifier with a rise time of about 0.04 microsecond, was then discriminated in amplitude to allow the recording of only those protons passing through the telescope and losing more than a given amount of energy in the last crystal.

The particles recorded corresponded to protons having a range between R_1 and R_2 before striking the copper absorber. Both R_1 and R_2 were changed by inserting different lengths of absorbers. The absorbers were $2\frac{3}{4}$-in. diameter cylinders of varying lengths and were placed as close as possible to the last crystal to minimize scattering losses in the absorber. By changing the absorbers, a range spectrum of the scattered protons was obtained, from which the energy distribution of the incident neutrons was calculated.

TABLE I. Crystal details.

Crystal	Position	Diameter (in.)	g/cm²
1	back	2.25	1.068
2	middle	2.25	0.932
3	front	1.94	0.957

The beam was monitored by a bismuth fission ionization chamber similar to those used by Wiegand.[3] For beryllium, typical counting rates were 300 monitor counts per minute, 100 coincidence counts per minute from polyethylene, 30 coincidence counts per minute from true recoil protons, and 1600 counts per minute in the third crystal alone.

III. TESTS OF EQUIPMENT

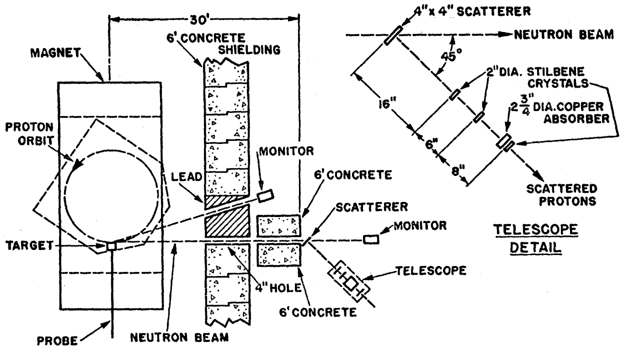

FIG. 1. Experimental arrangement.

The plateaus of the counters were set with the help of a 240-Mev scattered proton beam from the cyclotron. After the initial adjustments, frequent check points were taken to insure that the operating characteristics of the system had not changed. Background runs with no scatterer indicated that the background was about 3 or 4 percent of the true coincidence rate. Crystals were moved out of line to determine the accidental coincidence rate, different thicknesses of scatterers were tried to check the linearity of the system, and the angular resolution of the system was varied by changing the positions of the crystals. No spurious effects were noted in any of these tests. Measurements with a collimated beta-source indicated that the response of the third crystal to a given energy particle was constant to within 15 percent over the face of the crystal. This proportionality was necessary for the differential range type of measurement used.

IV. FACTORS DISTORTING ENERGY DISTRIBUTIONS

Certain factors contributed to the distortion of the neutron energy spectrum observed. The neutrons were absorbed to a slight extent in the target, in the Plexiglas window of the vacuum chamber, and in the polyethylene scatterer. Order of magnitude calculations showed that this absorption was negligible in comparison to other errors in the experiment, and in any case was approximately the same for all the spectra measured.

The major distortions were introduced by the interactions of the scattered protons in the scatterer and the absorbers. The energy loss in the scatterers was calculated using the curves of Aron.[4] Since the scatterers had been adjusted to contain the same number of carbon atoms, the stopping powers were somewhat dif-

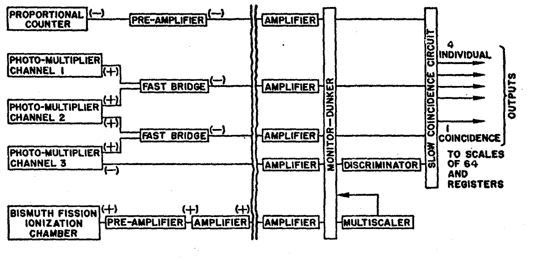

FIG. 2. Electronic equipment block diagram.

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[2] L. F. Wouters, Nucleonics **10**, No. 8, 51 (1952).

[3] C. Wiegand, Rev. Sci. Instr. **19**, 790 (1948).

[4] Aron, Hoffman, and Williams, Atomic Energy Commission Report AECU 663 (UCRL 121) (unpublished).

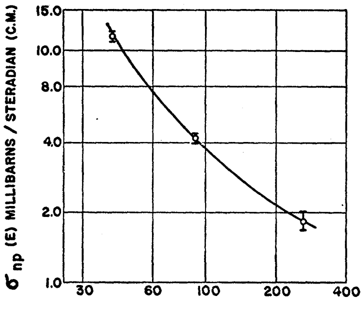

FIG. 3. Neutron-proton cross section at 45° in laboratory system.

ferent, and this introduced a small error in the determination of the number of protons in a given energy range.

The Coulomb scattering in the absorber was estimated by considering the absorber to be made up of a series of short pieces and calculating the mean scattering angle and scattering losses due to each section. Due to the particular geometry used, and the differential range method of measurement, the Coulomb-scattering losses were roughly constant with proton energy, and equal to about 8 percent.

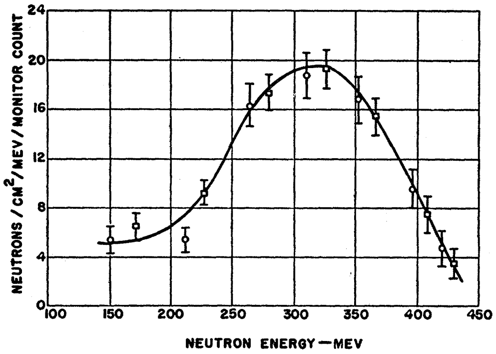

FIG. 4. Neutron energy distribution—lithium.

The nuclear cross section for protons in copper was assumed to be the same as that found by DeJuren[5] for neutrons of the same energy, as no other data were available. Half of this cross section was assumed to be due to elastic nuclear scattering, and half to absorption or inelastic scattering, as was found for protons.[6] Using the cross section and the distribution curves of Bratenahl *et al.*,[6] the percentage of protons missing the last crystal, because of diffraction scattering, was found to be about 3 percent. This varied with the energy of the detected protons, but since the absolute value was small the variation was neglected. The inelastic scattering was treated as an absorption of the protons with a cross section equal to half the total neutron cross section. The mean energy of the protons in each segment of the absorber was determined, and the absorption calculated for each segment. The fraction of protons which did not reach the last crystal because of absorption varied in approximately a linear manner with energy and had a maximum of about 30 percent.

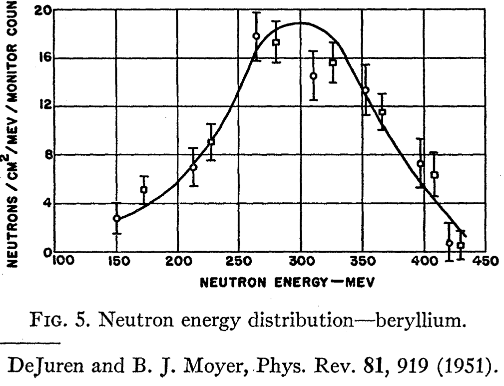

FIG. 5. Neutron energy distribution—beryllium.

These effects were combined to give the over-all distortion. Some of the calculations could be considerably improved, but the angular resolution of the detecting telescope introduced enough distortion by itself to make such improvements of little value.

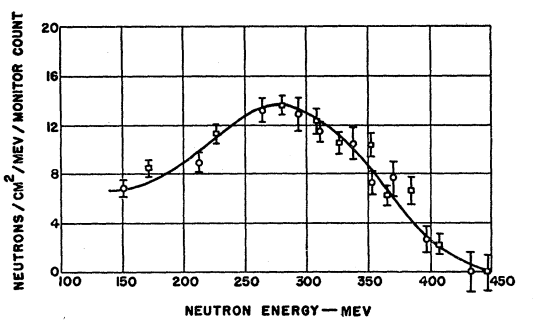

FIG. 6. Neutron energy distribution—carbon.

V. CALCULATIONS

To find the energy distribution of the neutron beam, different thicknesses of absorbers were placed between counters 2 and 3. For each thickness the normalized counting rate of coincidences between 1, 2, and all pulses in 3 greater than a certain size was obtained for the polyethylene and carbon scatterers. As the number of carbon atoms in the two scatterers was the same, a direct subtraction gave the number of counts due to recoil protons from hydrogen, the background counts automatically cancelling. The pulse-height discrimination in the third counter required that the proton counted be within a certain residual range or energy, as the specific ionization had to reach a preset value for the proton to register a coincidence. This in turn required that the energy of the proton before passing though the absorber lie within a certain energy range. Data were taken simultaneously for two different resolution widths to check the consistency and accuracy of the method. These widths correspond roughly to 40 and 60 Mev.

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[5] J. DeJuren and B. J. Moyer, Phys. Rev. **81**, 919 (1951).

[6] Bratenahl, Fernbach, Hildebrand, Leith, and Moyer, Phys. Rev. **77**, 597 (1950).

The number of protons per unit proton energy was obtained by dividing the number measured per energy interval by the energy width of the interval, and correcting for the scattering losses. The mean energy of the interval was calculated from the thickness of the copper absorber, taking into account the energy loss in the scatterer and the crystals. To convert to the neutron energy distribution it was necessary to know the energy variation of the neutron-proton differential cross section at 45°. This was not known accurately above 90-Mev neutron energy. However, data from the Berkeley results[7,8] were plotted as shown in Fig. 3, and a smooth curve drawn through the points. This was combined with the angular resolution of the counter system and relativistic kinematic corrections to obtain the relative flux of neutrons.

The angle of 45° for the telescope was chosen as a compromise between distortions. The larger the angle, the smaller the energy of the scattered protons, and the less severe the scattering corrections in the absorbers—especially the nuclear absorption. As the cross section for this absorption is not too well known, the final result should depend as little as possible upon it. The neutron-proton cross section is also the flattest around 45°. However, the larger the angle, the greater the smearing of the angular resolution of the telescope.

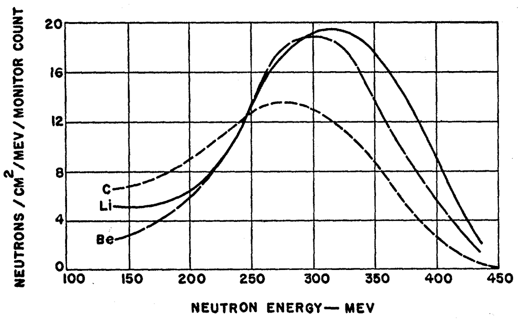

FIG. 7. Neutron energy distributions—comparison.

VI. RESULTS

The results of the experimental runs for lithium, beryllium, and carbon are shown in Figs. 4, 5, 6, and 7, and the comparative results for beryllium at several energies are shown in Fig. 8. These include the spectra taken at Harvard,[9] Harwell,[10] Rochester,[11] Berkeley,[12] and the present work.

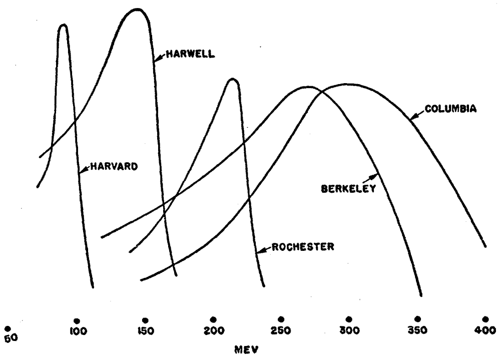

FIG. 8. Beryllium energy distributions for various proton energies.

These curves have been compared with symmetrical bell-shaped curves modified by the effects of the various resolution widths and distortions, and the parameters for best fit are given in Table II. The carbon curve is quite definitely a broader and lower energy curve than the others.

An order of magnitude comparison of the intensity of neutrons from the various targets was made, although no careful measurements were made of beam current. Multiple traversals of the proton beam were taken into account by calculating the mean scattering angle in the target, and assuming that the number of traversals was such that the same scattering angle was attained in each target.[13] With these assumptions, the number of neutrons emitted per nucleon of the target was roughly constant.

TABLE II. Parameters for best fit of observed energy spectra to $1/(p^2x^2)$ curve.

Parameter	Lithium	Beryllium	Carbon
Energy at peak	317 Mev	305 Mev	280 Mev
Full width at half-amplitude	160 Mev	150 Mev	200 Mev
Area under peak per nucleon	1.4	1.6	1.7

The general shapes of the spectra are seen to be in agreement with the data taken at lower energies.

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[7] Hadley, Kelley, Leith, Segrè, Wiegand, and York, Phys. Rev. **75**, 351 (1949).

[8] Kelly, Leith, Segrè, and Wiegand, Phys. Rev. **79**, 96 (1950).

[9] D. Bodansky and N. F. Ramsey, Phys. Rev. **82**, 831 (1951).

[10] Cassels, Randle, Pickavance, and Taylor, Phil. Mag. **42**, 215 (1951).

[11] Nelson, Guernsey, and Mott, Phys. Rev. **88**, 1 (1952).

[12] Cladis, Hadley, and Hess, Phys. Rev. **86**, 110 (1952).

[13] W. J. Knox, Phys. Rev. **81**, 687 (1951).