Neutron Energy Distribution in Proton Bombardment of Beryllium*

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A MEASUREMENT has been made of the energy distribution of the neutrons emitted in the forward direction from a one-eighth-in. thick beryllium target bombarded by the 110-Mev internal proton beam of the Harvard cyclotron. The results are shown in Fig. 1.

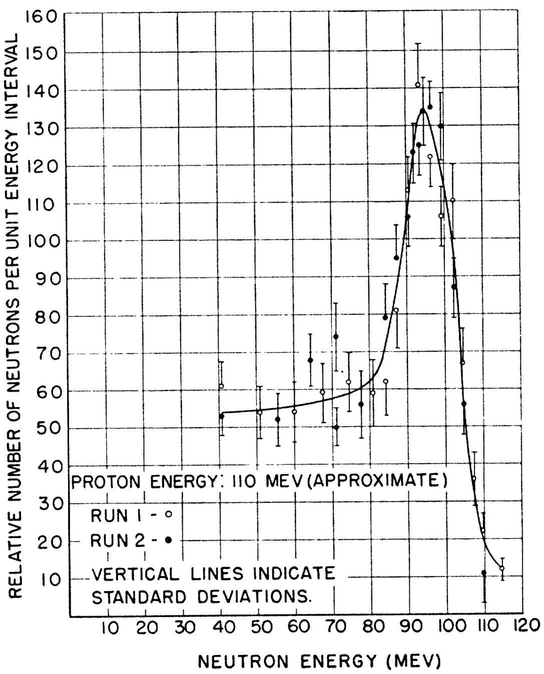

FIG. 1. Neutron energy distribution with beryllium target.

The neutrons from the target passed through a collimating hole in the concrete shielding surrounding the cyclotron and fell upon two one-fourth-in.-thick polyethylene scatterers. The recoil protons from the scatterers were counted by anthracene scintillation counters used in triple coincidence telescopes. One telescope system was used as a monitor. The second telescope system consisted of four individual scintillation counters directed at the second scatterer at an angle of 15 degrees with the neutron beam.

In the second system the difference in the triple coincidence rates of counters 1, 2, and 3 and counters 1, 2, and 4 (numbered away from the scatterer) was due to the stopping power of the anthracene crystal of counter 3. By interposing different thicknesses of aluminum absorber between counters 1 and 2, data were obtained for a differential proton range distribution. The measurement was repeated with a carbon scatterer of appropriate thickness and a polyethylene-carbon subtraction performed to give the number of protons arising from neutron-proton scattering.

The recoil proton energy was calculated from the range in the aluminum absorbers and the anthracene crystals. The corresponding incident neutron energy was found from the relativistic two-body collision equation. In calculating the number of neutrons per unit energy interval, the recoil proton counts observed with a given aluminum absorber were multiplied by a correction factor. The numerator of this factor uses Berkeley data[2] at 40 and 90 Mev to account for the energy dependence of neutron-proton scattering. To interpolate and extrapolate over the experimental energy range the differential cross section for neutron-proton scattering was assumed to vary as $1/(A+E_n)^2$ where E_n is the energy in the laboratory system of the incident neutrons.[3] At a given angle A should be constant, and was evaluated to fit the Berkeley data for recoil protons at 15 degrees. The denominator of the correction factor accounts for the energy dependence of the width of the interval in initial energies of the recoil protons which stop in the crystal of counter 3. The correction factor used was $(127+E_n)^2/(dE/dx)E_p$, where E_p is the energy of the recoil protons.

The measured neutron energy distribution from a beryllium target was peaked at 95 Mev and showed no other marked peaks in the energy interval 40 to 110 Mev. The stable orbit energy of the incident protons in the cyclotron was calculated from the magnetic field and target radius to be 114 Mev. Effects arising from oscillations of the proton beam and multiple traversals of the target may cause a significant spread and reduction in the energy of the protons actually striking the target. Hence, the observed peak in the neutron energy distribution may be at a lower energy and may be wider than the peak which would be obtained with a 114-Mev monoenergetic proton beam.

Preliminary results of a similar measurement with a carbon target do not show the marked high energy peak obtained with the beryllium target.

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[1] The experimental arrangement was strongly influenced by the experiment of Hadley, *et al.*, Phys. Rev. **75**, 351 (1949).
[2] Hadley, *et al.*, reference 1.
[3] This form of the dependence was suggested by Dr. M. L. Goldberger.

Scattering and Polarization of Neutrons in an Iron Single Crystal*

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IN 1947 Halpern,[1] stimulated by work of Shull and Wollan[2] that indicated excessive incoherent neutron scattering, suggested the use of iron single crystals to reveal the source of the incoherent scattering. When slow neutrons are transmitted through a single crystal (oriented so that no Bragg scattering occurs), only incoherent scattering is observed. Halpern pointed out that of the three main sources of incoherent scattering, isotope disorder, spin-dependent scattering, and inelastic lattice scattering, only the last would be affected by a magnetic field and hence capable of producing neutron polarization. By measuring the neutron polarization as well as the transmission with an iron crystal, it would then be possible to isolate the inelastic scattering. Although most of the diffuse scattering observed by Shull and Wollan later proved to be instrumental[3] (multiple scattering in the samples), it was important to investigate the iron single crystal because of the large polarization effects which had been observed in polycrystals[4,5] compared to theoretical estimates.[6] Halpern, Hamermesh, and Johnson[6] had subtracted 2.5 barns of isotope disorder scattering from the cross section of iron in their calculation of neutron polarization and it seemed likely that the isotope effect was actually much smaller.

A single crystal of iron, 2×2×3 cm, containing 10 percent (by weight) of silicon was obtained from Professor Kaufmann of M.I.T. The total cross section of the single crystal, measured with monoenergetic neutrons obtained with the Argonne "chopper," is shown in Fig. 1, together with earlier results for a polycrystalline

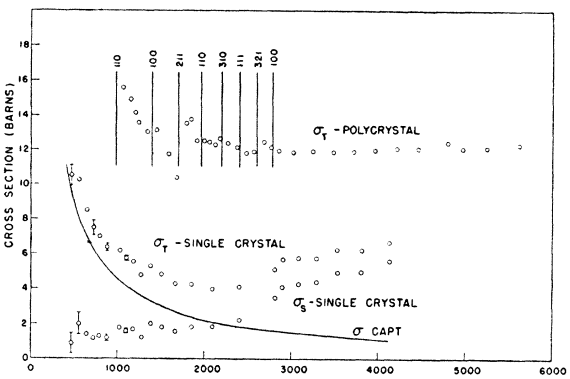

FIG. 1. Measured total cross sections of an iron polycrystal and a single crystal of iron-silicon. The scattering cross section of the single crystal, σ_S, obtained by subtraction of capture, is also shown. The vertical lines are the limiting velocities for reflection by lattice planes, marked with the appropriate Miller indices.

sample. The single crystal cross section is much smaller than that of the polycrystal, especially in the region just above the "cut-off" velocity (980 meters per sec., below which velocity the polycrystal exhibits no coherent scattering). The points marked σ_S are those for the single crystal after subtraction of the capture cross section, taken as 1/v and equal to 2.45 b at 2200 m/s for iron. (The single crystal cross sections of Fig. 1 all refer to the "average atom" in the crystal, containing 18 percent silicon atoms.) After an additional 0.40 b is subtracted from the single crystal points, to take account of the incoherent scattering caused by the assumed random location of the silicon atoms, the remaining scattering, shown in Fig. 2, represents the incoherent scattering of the

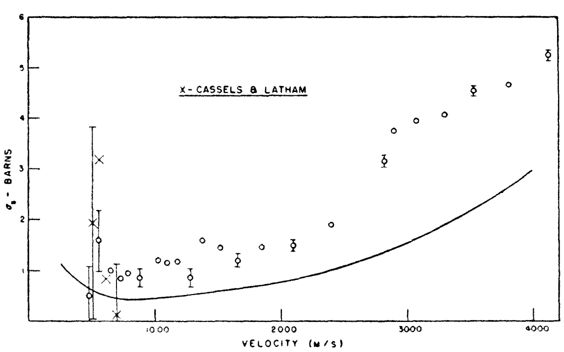

FIG. 2. The incoherent scattering of the iron-silicon single crystal after subtraction of the calculated scattering resulting from the assumed random location of the silicon atoms. Results of Cassels and Latham and the calculated inelastic scattering (Weinstock) are shown for comparison.

crystal. Some points obtained by Cassels and Latham[7] are also shown (we have re-analyzed their data, using 2.45 b for capture instead of their 2.2 b), as well as the inelastic scattering calculated by Cassels and Latham from the theory developed by Weinstock.[8] The variation of the incoherent scattering with velocity suggests that the scattering is mainly inelastic and about twice the calculated value. Both spin-dependent and isotope disorder scattering, in contrast to the inelastic scattering, would show no change with neutron velocity.

The polarization, which would result from inelastic scattering but not from other incoherent scattering, was next sought and found by magnetizing the crystal in a field of 11,000 oersteds and measuring the single[1,6] transmission effect, E_s. E_s is the fractional increase in transmitted neutron intensity resulting from magnetization to saturation. The measured points for an iron thickness of 2.97 cm are compared in Fig. 3 with the effect calculated from

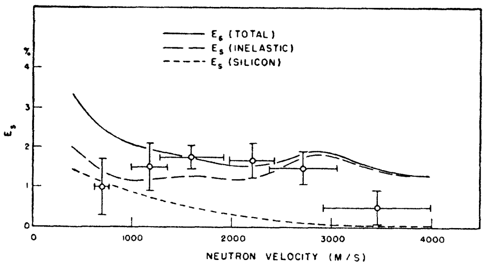

FIG. 3. Observed single transmission effect, E_s, in a 2.97-cm single crystal of iron-silicon compared with the calculated value.

the observed incoherent scattering assuming it to be entirely inelastic and isotropic. The form factor for the magnetic scattering used in the calculation is that given by Steinberger and Wick.[9] The silicon atoms constitute irregularities in the magnetic scattering of the magnetized single crystal, and there will be corresponding production of neutron polarization from the resulting incoherence, in addition to that arising from inelastic scattering. The calculation of the polarization caused by silicon atoms is complicated by the unknown amount of order in the silicon location. The silicon effect shown in Fig. 3 is based on the assumption of random location; if order were present the silicon effect would be smaller but the inelastic effect larger by a comparable amount, leaving the total almost unchanged.

Considering the results mainly above 1200 m/s where the silicon effect is small, it is seen that the observed E_s is consistent with the assumption that the incoherent scattering in iron is largely inelastic. In fact, as the calculated E_s varies with the square of the inelastic scattering cross section, the presence of only 0.25 b of spin-dependent or isotope disorder scattering would change E_s by about 50 percent at 1500 m/s and destroy the agreement exhibited by Fig. 3. The present results support the recent calculation of polarization in polycrystalline iron by Steinberger and Wick[9] in which it was assumed that most of the total scattering (coherent plus incoherent) produces polarization. We wish to express our gratitude to Dr. M. Hamermesh for his generous help in the analysis of these measurements.

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[8] R. Weinstock, Phys. Rev. 65, 1 (1944).
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A 3×10^{-9} Sec. Isomeric State in $_{63}Eu^{153}$

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An excited state in Eu^{153} with a half-life $(3.0\pm0.3)\times10^{-9}$ sec. has been observed with a delayed coincidence scintillation spectrometer. The position of the metastable state in the disintegration scheme has been determined.

The delayed coincidence scintillation spectrometer employing anthracene with Type 5819 multiplier tubes as detectors is similar to that described in a previous letter.[1] The video amplifier sections have been replaced with Hewlett Packard 460A wide-band amplifiers. With this apparatus the existence of the short-lived isomeric state[2] of Yb^{170} $(1.6\times10^{-9}$ sec.) was confirmed.

Sm^{153} (47 hr.) is known to decay by a 0.78-Mev beta-ray branch leading to an excited state of Eu^{153}. This state is de-excited by γ-ray transitions in cascade[3] corresponding to 69 and 103 kev