various runs. Least-squares fits of the observed counting rates in the delayed-time channels lead to the following results:

Pile up (three runs totaling 10 000 seconds): 2.55±0.15 delayed counts/min.
Pile down (three runs totaling 6000 seconds): 2.14±0.13 delayed counts/min.
Difference due to the pile: 0.41±0.20 delayed count/min.

This difference is to be compared with the predicted ~$\frac{1}{5}$ count/min due to neutrinos, using an effective cross section of ~6×10^{-20} barn for the process. It is to be remarked that a small channel overlap in the time-delay analyzer would be reflected in an amplified percentage decrease (<0.12 count/min) in the pile difference number. Measurements of the number of fast neutrons leaking from the pile face made with nuclear emulsion plates, and consideration of thed etector shielding employed, rules out neutron-proton recoils as causing this difference.

A more detailed report is in preparation. It is difficult to acknowledge properly the many contributions to all phases of this experiment. We wish to thank our colleagues: E. C. Anderson, L. J. Brown, D. Carter, F. B. Harrison, F. N. Hayes, C. W. Johnstone, Lt. P. R. Powell (USN), R. L. Schuch, Capt. W. A. Walker (USA), M. P. Warren, T. J. White, and J. G. Winston for their devotion to the task. Dr. R. Sard of Washington University was most helpful in discussions relative to cosmic rays. The staff of the Hanford Engineering Works has been wonderfully cooperative during the Hanford phase of the work.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] F. Reines and C. L. Cowan, Jr., Phys. Rev. **90**, 492 (1953); Cowan, Reines, Harrison, Anderson, and Hayes, Phys. Rev. **90**, 493 (1953). Important changes from the detector described in this reference include the use of Dumont K1177 photomultiplier tubes and a sodium silicate-titanium dioxide reflecting surface.
[2] E. Konopinski and H. Primakoff (private communications).
[3] We find it convenient to label the neutrino accompanying β^- emission as ν_-, and that accompanying β^+ emission as ν_+.
[4] E. J. Konopinski and L. M. Langer, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, California, 1953), Vol. 2, p. 261.
[5] L. W. Alvarez, University of California Radiation Laboratory Report UCRL-328, 1949 (unpublished); K. Way and E. P. Wigner, Phys. Rev. **73**, 1318 (1948). Work in progress at this laboratory tends to indicate that these predictions are high.

Nuclear Scattering of High-Energy Neutrons

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THE so-called "optical model" of the nucleus has been re-examined in the light of recent measurements[1-3] of the total neutron cross sections of various nuclei for neutron energies ranging from 30 Mev to 400 Mev. Using the nuclear model and method of calculation described by Fernbach, Serber, and Taylor,[4] an attempt was mace to fit the measured cross sections by adjusting the values of R, the nuclear radii K, the inverse mean free path for absorption of neutrons in nuclear matter, and V, the average potential encountered by a neutron inside the nucleus. Both K and V were allowed to depend upon the neutron energy, but were assumed to be the same for all nuclei. Calculations were made only for neutron energies greater than 50 Mev because of the feeling that below this energy the approximations which were used in solving the scattering problem would not be valid.

The ratio $\sigma_{\text{total}}/\pi R^2$ may conveniently be expressed as a function of k_1R, with k_1/K as a parameter, where k_1 is the increase in the magnitude of the propagation vector of a neutron upon entering the nucleus. It was observed that $\sigma_{\text{total}}/\pi R^2$ is a maximum for k_1R equal to 2.0, for all values of k_1/K. Hence k_1R_{lead} was taken to be equal to 2.0 at 85 Mev, the neutron energy at which the maximum in the experimental lead cross section occurs. It was then possible, by using the measured cross sections of Pb, Cd, Cu, Al, and C at 85 Mev, to find a value of k_1 and a set of nuclear radii which would correspond to any chosen value of k_1/K. A search was then made for values of K and k_1 as a function of energy, for several assumed values of k_1/K at 85 Mev, which would give good agreement between all the experimental and

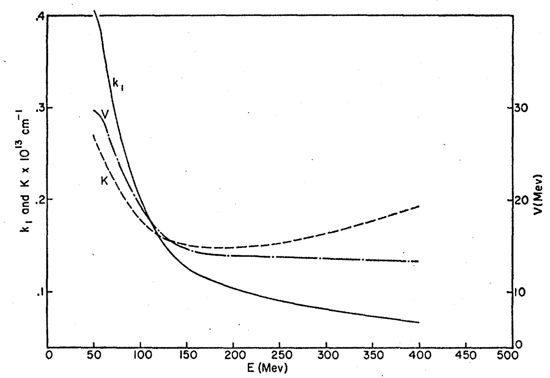

FIG. 1. Energy dependence of k_1, K, and V.

calculated cross section between 50 and 150 Mev, as well as at 400 Mev. By assuming a value of k_1/K of 1.25 at 85 Mev, it was possible to choose the energy dependence of K and k_1 in such a way that the calculated cross sections for all the nuclei considered agreed within quoted experimental errors with the observed cross sections in the neutron energy range of 65 to 400 Mev. The resulting curves of K and k_1 as a function of energy are shown in Fig. 1, together with the values of V corresponding to k_1. The nuclear radii which were obtained are given in Table I, and the calculated and observed cross sections are compared in Fig. 2.

TABLE I. Nuclear radii of C, Al, Cu, Cd, and Pb as determined from the best fit of their total neutron cross sections.

Nucleus	$R\times10^{13}$ (cm)	$R\times10^{13}/A^{\frac{1}{3}}$
C	3.52	1.54
Al	4.49	1.50
Cu	5.80	1.45
Cd	6.86	1.42
Pb	8.12	1.37

The value of K at 85 Mev may be changed by ±50 percent without causing serious disagreement between calculated and observed cross sections. Corresponding to this spread in K, however, there is possible a spread of only ±10 percent in k_1 and ±3 percent in the radius of any of the nuclei considered. There appears to be a definite minimum in K as a function of energy somewhere be-

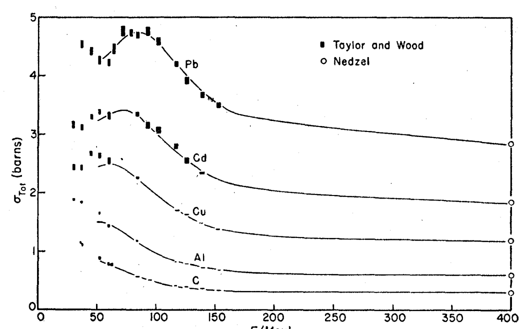

FIG. 2. Observed and calculated total neutron cross sections of Pb, Cd, Cu, Al, and C as functions of neutron energy.

tween 150 and 400 Mev, for all choices of K at 85 Mev. Since, according to this model, the neutron absorption cross section is independent of k_1, measured neutron absorption cross sections (cross sections for all inelastic processes) would provide a much better basis for determining K than an analysis of the total cross sections alone.

It is interesting that V decreases from the conventional 30 Mev at low energy to about 14 Mev above 180 Mev. The drop occurs moderately rapidly near the energy at which the repulsive core in p-p scattering becomes important. It is not necessary to let V go to zero or negative values.

A detailed account of this work will be published later. The author wishes to express his thanks to Professor H. A. Bethe for his continued interest in this work and for many helpful discussions.

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π^+-p Scattering Near 260 Mev*

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Elastic scattering of positive pions of 260-Mev average kinetic energy has been observed in a hydrogen-filled diffusion cloud chamber. The pions which were emitted from a carbon target at 32° to the 2.2-Bev proton beam in the Cosmotron were selected from particles of different momenta or negative sign by an analyzing magnet, and separated from protons of the same momentum by a 2.5-inch carbon absorber. They then entered the cloud chamber which has a sensitive length of 6 feet and width of 11 inches. A hydrogen pressure of 19 atmospheres was maintained. We are here reporting on data obtained from 1300 photographs. The pictures were scanned for scattering and $\pi-\mu$ decay events occurring in the gas, using a projected image which was distorted so that the 6 foot length was compressed to a length of 1.5 feet while the 11 inch width was retained. In this manner, a considerable amount of scanning time is saved and confusion due to background radiation occurring in random directions is reduced. Furthermore, since small angles are magnified 4 to 5 times in the distorted images, actual deflections somewhat smaller than 1° can easily be detected.

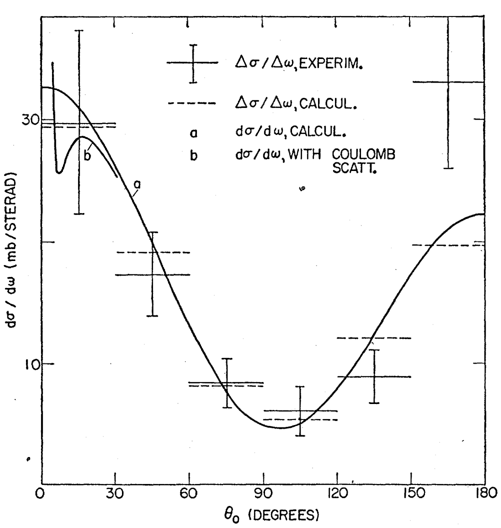

Fig. 1. Differential scattering distribution $\Delta\sigma/\Delta\omega$ for 260-Mev π^+-p scattering in center-of-mass system. Curve (a) was calculated making use of s- and p-wave phase shifts found by Fermi and Metropolis at 213 Mev. Curve (b) indicates the effect of Coulomb scattering.

292 $\pi-\mu$ decays were found, 281 of which showed deflections of less than 7.0°. From this cut-off angle one infers that over 90 percent of the pions had energies above 210 Mev. If all pions had 210-Mev energy, the angular distribution of $\pi-\mu$ deflections should be constant between 0 and 7.0°. The actual distribution begins to drop at 5°, indicating that some pions with energies as high as 330 Mev were present. From the shape of the $\pi-\mu$ distribution, one can infer that the average energy of the pions was 260 Mev. Adding a 15 percent correction to the number of $\pi-\mu$ decays observed for cases with deflections $<1°$, which were not counted, one finds by the previously described method[1] that 1280 ± 70 g/cm^2 of hydrogen were scanned. A direct measurement of the track length in a sample of pictures gave a path length consistent with that inferred from the $\pi-\mu$ count.

116π^+-p elastic scattering events with scattering angles $>5°$ were found, resulting in a cross section of 150 ± 18 millibarns.[2] Their differential angular distribution in the center-of-mass system, shown in Fig. 1, appears to be nonisotropic and somewhat asymmetrical. Assuming charge independence, Fermi and Metropolis[3] have deduced s- and p-wave phase shift angles from π^--p scattering up to 213 Mev. From their phase shifts of $\alpha_3=-63.6°$, $\alpha_{33}=42.9°$, and $\alpha_{31}=36.5°$, one would expect a cross section of 170 mb for π^+ at 213 Mev. It thus appears that the cross section remains high at our average energy, although a slight drop is indicated. Making use of the same phase shifts but normalizing to the cross section found here, curve (a) in Fig. 1 has been drawn and also averages have been indicated for the same intervals as used for the experimental data. Most experimental points agree within our statistical errors. The high experimental value above 150°, if substantiated by further experiments now in progress, may indicate a d-wave scattering component.

Curve (b) shows the result expected from interference with the Coulomb scattering[4] taking place mostly at angles $<30°$. Because of the large magnitude of the α_3, α_{33}, and α_{31} chosen here, the effect of Coulomb scattering is small at all angles of interest to us. Its effect on an admixture of d-wave scattering, however, could be great for angles $<30°$.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
† Now at Yale University, New Haven, Connecticut.
‡ Now at Wesleyan University, Middletown, Connecticut.
[1] Fowler, Fowler, Shutt, Thorndike, and Whittemore, Phys. Rev. **91**, 135 (1953).
[2] Two additional scattering events were found which were probably inelastic.
[3] E. Fermi and N. Metropolis, Los Alamos Report LA-1492, 1952 (unpublished).
[4] L. Van Hove, Phys. Rev. **88**, 1358 (1952).

Time-Dependent Quadrupole Interaction in Angular Correlation of Nuclear Radiation. I. Cd^{111}*

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Several interactions of nuclear moments with extranuclear fields may be responsible for the attenuation of directional correlations of successive nuclear radiation:

(a) interaction of the magnetic moment μ of the intermediate nuclear state with a static magnetic field H;

(b) interaction of the electric quadrupole moment Q of the nucleus with a static electric field gradient $\partial^2V/\partial z^2$;

(c) interaction of μ with a randomly fluctuating field H (magnetic "relaxation" process);

(d) interaction of Q with a randomly fluctuating electric field gradient $\partial^2V/\partial z'^2$ (quadrupole "relaxation" mechanism).