Angular Distribution of n–p Scattering with 90-Mev Neutrons

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ONE of the important experiments that became feasible as soon as the 184-inch cyclotron started to operate was the measurement of the angular dependence of n-p scattering. As is well known, experiments of this type acquire particular significance when the de Broglie wave-length of the neutron is comparable with the range of nuclear forces.

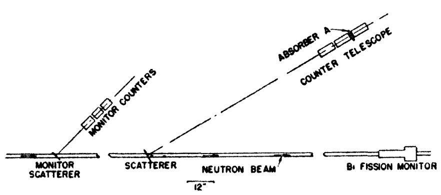

FIG. 1.

The neutron beam[1] of the cyclotron has an angular distribution well described by Serber's[2] stripping theory. We assume that the energy distribution of the neutrons is also that predicted by this theory, i.e., has a maximum at 90 Mev; the corresponding wave-length in the center of mass system is $\lambda\!\!\!^{-} = 0.95 \times 10^{-13}$ cm.

We have used these neutrons to measure the n-p cross section as a function of the angle of scattering θ, in the CM system, between 70° and 170°. Figure 1 shows a schematic layout of the apparatus. The neutron beam produced by stripping 180-Mev deuterons on a Be target was collimated to about 2.5-cm diameter and scattered by paraffin or polyethylene targets which were larger in diameter than the neutron beam. The recoil protons used for the measurement were detected by a telescope of three proportional counters in coincidence pointing towards the scatterer. The primary neutron beam was monitored either by the protons scattered by an auxiliary hydrogenous target or by a bismuth fission chamber.

The telescope was made insensitive to protons below a certain energy by the Al absorber A. The thickness of the absorber was adjusted so that protons of energy less than $66 \cos^2[(\pi-\theta)/2]$ Mev could not enter the third counter. Thus we made sure that if the recoil protons detected originated from elastic collisions of neutrons on hydrogen, the impinging neutron had an energy greater than 66 Mev. (We have neglected some small relativity correction.) By taking background measurements with a carbon scatterer and with no scatterer we distinguished the protons due to n-p scattering and those due to (n-p) reactions on C and air.

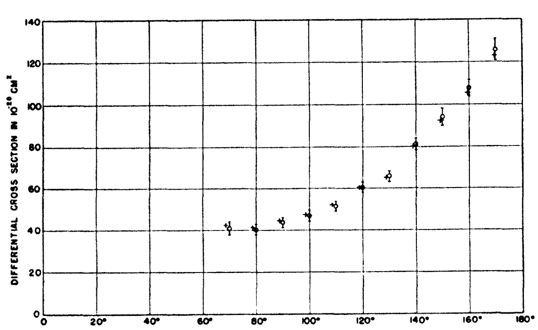

FIG. 2. Plan view of experimental arrangement.

Table I gives the cross section as a function of θ. Smaller and larger angles are being investigated but the results will not be available for some time.

From what we have said above it is apparent that our measurements give only a number proportional to $(d\sigma/d\omega)\Delta\omega$ where ω is the solid angle; however, we have normalized our figures by the following method: we have *hypothetically assumed* that $d\sigma/d\omega$ is the same for θ and $\pi-\theta$ and we have made the total scattering cross section 0.083×10^{-24} cm^2 as reported by Cook, McMillan, Peterson, and Sewell.[3] Our assumption on the behavior of the cross section for $\theta < 90°$ is not in disagreement with some preliminary observations at $\theta < 90°$ by us and with some cloud-chamber data communicated to us by Dr. W. Powell, *but is by no means established.* The data are also plotted in Fig. 2 with the relativistic corrections.

In order to avoid some sources of systematic error in these experiments, we have checked the following:

1. Plateau of the coincidence counting rate of the counter telescope *versus* voltage in the counters, bias voltage of the discriminators, duration of the opening of the coincidence gate of the counters.
2. Proportionality of the number of coincidence counts in the telescope to the intensity of the primary beam and to the thickness of the scattering target for a given primary neutron beam.
3. The influence of Rutherford scattering of the absorber A on the efficiency of the coincidence telescope.
4. Scattering by the air column traversed by the neutron beam.
5. The error introduced by the finite dimensions of the scattering target.
6. Whether the coincidence system counted only protons coming from the scatterer and all those with energy $>66 \cos^2\theta$.

This list is not final and there are some important controls that should still be performed, but we feel confident enough of our results to give this preliminary account.

TABLE I. Differential cross section in 10^{-28} cm^2 (normalization hypothetical). The errors listed are based only on statistical standard deviations.

Scattering angle θ[a]	(b)	(c)	(d)	(e)
70	43.7±4.0	35.3± 2.8	39.0±3.7	40.8±3.1
80	42.6±3.5	32.5± 4.9	40.4±3.7	40.2±2.5
90	42.0±2.4	44.0± 4.2	45.1±4.9	43.5±2.4
100	47.0±3.0	42.4± 6.1	48.0±3.7	46.7±2.7
110	50.2±3.4	51.8± 6.1	53.0±3.5	51.4±2.5
120	59.0±2.7	59.7± 6.3	63.2±4.5	60.4±2.4
130	66.8±3.1	70.0± 7.0	61.5±3.8	65.6±2.7
140	79.5±3.1	78.5± 7.8	84.7±5.6	81.2±2.8
150	92.5±4.4	99.0± 7.0	94.0±5.4	94.1±4.1
160	105.5±3.8	127.0±10.6	107.5±7.9	107.7±3.8
170	126.0±5.8	127.5±14.0	123.2±9.4	125.7±5.0

[a] θ is the neutron scattering angle in the center of mass system.
[b] Composite of runs on apparatus 1.
[c] Run on apparatus 2, scatterer 150 mg/cm^2 $(CH_2)_n$.
[d] Run on apparatus 2, scatterer 283 mg/cm^2 $(CH_2)_n$.
[e] Weighted average of all runs with estimated error.

It must be added that these experiments were performed independently with two separate sets of equipment which were similar in principle but differed in many details. This procedure helped considerably in making us aware of unsuspected caused of trouble.

The peak of protons in the forward direction is a clear indication of the existence of exchange forces between neutron and proton. A more detailed analysis that takes into account the total scattering cross section and the angular distribution indicates that there might be comparable amounts of ordinary forces.

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[1] A. C. Helmholz, E. M. McMillan, and D. Sewell, Phys. Rev. 72, 1003 (1947).
[2] R. Serber, Phys. Rev. 72, 1007 (1947).
[3] L. F. Cook, E. M. McMillan, J. M. Peterson, and D. C. Sewell, Phys. Rev. 72, 1003 (1947).

The Spectrum of Locally Isotropic Turbulence

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RECENT theories* employ a physical picture of the fully developed turbulence at high Reynolds numbers as an "eddy-cascade" where the kinetic energy of the larger scale eddies is transferred to the smaller ones by the Reynolds stresses of the small scale motion.

Assuming similarity in this turbulent energy transport mechanism and neglecting viscosity, several authors** have succeeded in deriving a spectrum for the medium frequency range, which is a "five-thirds-power law."

It follows from Kolmogoroff's first similarity hypothesis that the spectrum of locally isotropic turbulence expressed in a non-dimensional form must be a unique function. This leaves us with only two parameters (characteristic frequency and characteristic intensity), and these can be expressed in terms of ϵ_0, the total energy dissipation per unit mass and unit time, and ν, the kinematic viscosity of the fluid. The two parameters are not independent, but may be combined into a Reynolds number which is a universal constant. We define the spectrum function $F(n)$:

$$\overline{u^2}=\int_0^\infty F(n)dn, \quad (1)$$

u = velocity fluctuation in the turbulence, n = wave number.

We make two assumptions: *first*, $S(n)$, the kinetic energy per unit mass and unit time that passes through frequency n, depends only on the values $F(n)$ and n.*** The energy transport must have dimensions of u^3l^{-1}; the only possible form is

$$S(n)=k_1F^{3/2}n^{5/2}, \quad (2)$$

where k_1 is a non-dimensional constant.

Second, the mechanism of turbulent energy transport is not affected by the viscosity; therefore k_1 is a universal constant.†

The energy that must be passed to higher frequency becomes less and less as the viscosity dissipates more and more energy into heat. We may define the viscous dissipation between frequencies zero and n as

$$\epsilon v(n)=60\pi^2\nu\int_0^n n_1{}^2F(n_1)dn_1. \quad (3)$$

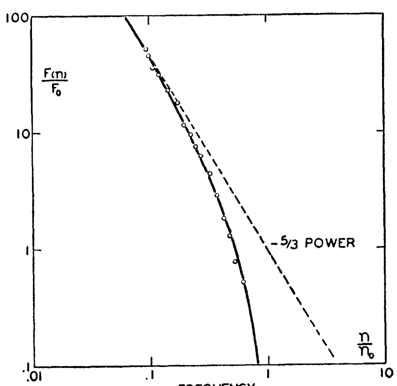

FIG. 1. Spectrum of locally isotropic turbulence.

In steady state the rate of change of energy transport is equal to the negative of the rate of dissipation

$$(dS(n)/dn)=-(d\epsilon v(n)/dn). \quad (4)$$

From (2), (3), and (4) we get an equation for $F(n)$:

$$dF/dn+(5/3)(F/n)+(40\pi^2\nu)/k_1(F/n)^{\frac{1}{2}}=0. \quad (5)$$

The solution is

$$F(n)=F_0(n/n_0)^{-5/3}[1-(n/n_0)^{4/3}]^2, \quad (6)$$

where F_0 and n_0 are constants and

$$R_0=\frac{1}{\nu}(F_0/n_0)^{\frac{1}{2}} \quad (7)$$

is a universal constant (Reynolds number).

The spectrum function goes to zero at $n=n_0$ with a zero slope, and joins the "five-third law" for $n\ll n_0$. The only constant in the present theory is R_0, and this can be obtained from spectrum measurements. Uisng the results of L. F. G. Simons†† (3-in. grid $U_0=35$ ft./sec.), it was found that $R_0=11.5$. Using this value the measured points seem to check the theoretical curve well (Fig. 1).

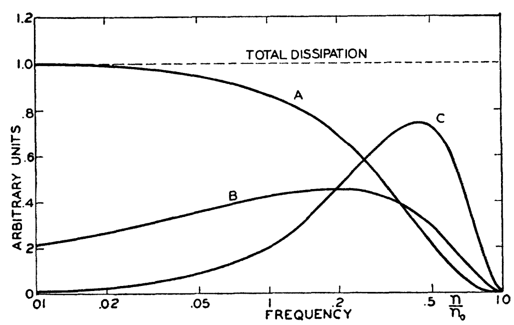

FIG. 2. Energy balance of turbulence spectrum.