In reality, however, this conclusion is true only for the total cross section (and even then with reservations, which will be discussed below). Calculation of the differential cross section for small angle scattering on the basis of the impulse approximation gives correct results, which, evidently, is physically related to the fact that for small angle scattering interference of the wave scattered by each of the centers becomes significant, and this is correctly taken account of in the impulse approximation. Indeed, from Eq. (1) we obtain the following exact expression for the differential cross section $d\sigma/d\Omega$ per unit solid angle, averaged over all directions of the vector R:

$$\frac{d\sigma}{d\Omega} = 2\,\frac{d\sigma_0}{d\Omega}\,\frac{1 + \frac{\sin(|\mathbf{k}_0 - \mathbf{k}|R}{|\mathbf{k}_0 - \mathbf{k}|K} + \frac{\sin^2\delta}{\lambda^2}\left(1 + \frac{\sin|\mathbf{k}_0 + \mathbf{k}|R)}{|\mathbf{k}_0 + \mathbf{k}|R}\right) + 4\sin\delta\cos(x+\delta)\,\frac{\sin x}{\lambda^2}}{(1 - x^{-2}\sin^2\delta)^2 + 4x^{-2}\sin^2\delta\sin(x+\delta)}, \qquad (2)$$

where $x = kR$, and $d\sigma_0/d\Omega = k^{-2}\sin^2\delta$ is the differential cross section for scattering by one of the centers.

In the impulse approximation we obtain, with no difficulty, the expression

$$d\sigma/d\Omega = 2(d\sigma_0/d\Omega)\,\{1 + \sin(|\mathbf{k}_0 - \mathbf{k}|R)/|\mathbf{k}_0 - \mathbf{k}|R\}. \qquad (3)$$

For large incident energies ($kR \gg 1$) and small scattering angles ($\theta \gtrsim 1/kR$) Eqs. (2) and (3) differ only by small quantities of the order of x^{-2}. Therefore, for these conditions ($\eta/R \ll 1$), the impulse approximation, as could have been expected leads to the correct results, which are identical with the exact ones for $kR \to \infty$. For large scattering angles, however, the second term in the curly brackets of Eq. (3) (whose absolute value is of the order of $1/x$) oscillates rapidly*, and therefore its contribution to the total cross section is small, of the order of x^{-2}. This explains why the expression obtained for the total cross section in the impulse approximation differs, in this case, from the exact one** [compare Eqs. (6) and (5) of Brueckner[1]] by a quantity of the same order of magnitude as those retained in the impulse approximation.

Let us note, in addition, that for $kR \gg 1$, both the exact formula and that obtained in the impulse approximation lead to a result according to which the total cross section is, to a high degree of accuracy, equal to the sum of the cross sections for each of the centers [there is a deviation only for terms of the order of $(kR)^{-2}$].

I should like to thank Professor K. A. Brueckner for discussions concerning this problem during the Moscow conference of May, 1956.

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* Thus, Eqs. (2) and (3) differ by quantities which are small in comparison with those retained in the impulse approximation for all values of ϑ except for small intervals in the neighborhood of the zeros of the function $\sin(2x\sin\vartheta/2)$.

** It is not difficult to show that integrating expressions (2) and (3) over all scattering angles leads to results identical with those for the total cross sections obtained by Brueckner[1].

[1] K. A. Brueckner, Phys. Rev. **89**, 834 (1953).

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Scattering of Fast Neutrons by a Nuclear Coulomb Field

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As is known, the principal contribution to the scattering cross section of neutrons scattered by nuclei is made by the nuclear forces. Other effects, due to the interaction between the magnetic and perhaps also the electric moments of the neutron and the nuclear Coulomb field are also to be expected. The interaction of the neutron magnetic moment with the nuclear Coulomb field was theoretically investigated by Schwinger[1] and Sample[2]. Hereafter, we shall call the scattering that results from this interaction the Schwinger scattering. The Schwinger scattering cross section is practically independent of the energy.

The question of the existence of an electric dipole moment in the neutron was already discussed in the literature[3]. It follows from Smith's experiments[4] that the electric dipole, if it exists, should be less than or approximately equal to $5 \times 10^{-21} e$ CGS, where e is the electronic charge. In addition to intrinsic electric dipole moment, the neutron may exhibit (in a strong Coulomb field) an electric moment caused by the deformation of the meson shell. The neutron becomes "polarized", so to speak. This problem has not been investigated theoretically or experimentally.

The above phenomenon will contribute the most to the scattering cross section if the neutrons are scattered by heavy nuclei, and should manifest itself in an anomalous behavior of the differential scattering cross section at small angles, since the Coulomb forces act at greater than nuclear distances. A simple estimate shows that the effect due to an intrinsic neutron electric dipole moment of the order of magnitude indicated above is negligibly small.

Attempts by Longley and others[5] to detect Schwinger scattering of neutrons by lead gave inconclusive results. An analogous attempt by Sample and others[6] was also unsuccessful.

The angular distribution of fast neutrons emerging from a reactor and scattered by Pb and Cu was studied and the data given below are the preliminary results of the investigation. The neutron beam was restricted by a steel collimator to 0.9 × 3.6 cm.

Scattering was effected with a Pb or Cu plate 1 cm thick mounted 10 cm from the edge of the collimator. The detector, located 325 cm from the plate, was a photomultiplier with plastic scintillator (ZnS in plexiglass), having a low sensitivity to gamma-rays and to neutrons with energies above 1.5 mev. The degree of collimation is characterized by the curve of Fig. 1. Before starting the work, the total effective number of neutrons incident on the scatterer was determined, so as to permit subsequent calculation of the differential scattering cross section $\sigma(\theta)$. The effective neutron energy as determined from the nuclear scattering cross section, was 3-4 mev.

The measured angular distribution is shown in Fig. 2, the curve being plotted from Schwinger's theoretical equation [Eq. (10) of Ref. 1]. The measurement results show the increase in cross-section, characteristic for the Schwinger scattering for Pb ($Z = 82$) at angles less than 2°. The value of the cross section is in agreement with the Schwinger and Sample theoretical investigations. For Cu ($Z = 29$) the increase in cross section is

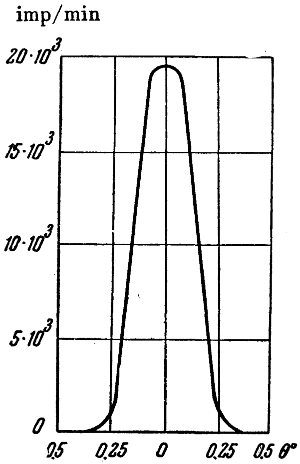

FIG. 1

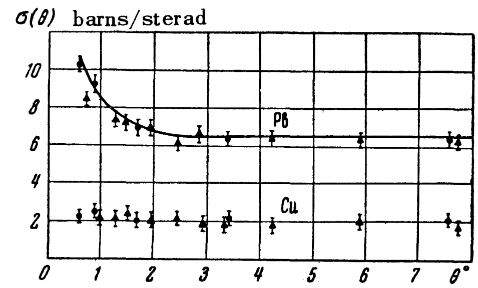

FIG. 2

within the limits of experimental error.

In a recently published work, Voss and Wilson[7] report observed Schwinger scattering of 100 mev neutrons by uranium. The variation of the scattering cross section with the angle is close to the theoretical curve, but the authors did not cite the numerical values of $\sigma(\theta)$.

In conclusion, one must remark that estimates indicate that if the neutron exhibits a "polarizability" $\alpha \sim r^3$ (where r is the nucleon dimension), the additional contribution to the cross section of the scattering of neutrons by heavy nuclei becomes noticeable. The effect increases with diminishing energy, but more careful experiments are needed for its detection.

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Multiple Formation of Particles in 5.3 bev Nucleon-Nucleon Collisions

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WE calculated theoretically the distribution of nucleon-nucleon collisions at 5.3 bev from the number of secondary particles, using the statistical theory of multiple-particle formation[1] with and without the isobar states[2]. In the calculations we employed the method suggested in Ref. 3, with which statistical weights can be accurately calculated.

The percentage statistical weights of the various processes are given in Table I. A classification by charged state, as required for conservation of the isotopic spin, is given in Table II for(p-p)-collisions and in Table III for (n-p)-collisions (N---nucleon, N'---isobar state, M---number of pions). Thus, for example, for (p-p)-collisions the process $NN\ 2\pi$ (the statistical weight of which is indicated in Table I) gives a probability of 0.300 for the charged state ($pp+-$), a probability of 0.100 for the charge state ($pp00$), etc. (see Table II).

From the data cited it is easy to obtain the distribution of the inelastic collisions from the number of charged particles ("prongs") which, in the case of (p-p)-collisions, can be compared with the experimental data by Fowler and others[4]. Such a comparison is shown in Table IV. It is seen from this Table that allowing for the resonant interaction between the nucleons and mesons by introducing the isobar states leads to a better agreement with experiment.

In conclusion, I thank I. L. Rozental' for useful advice.

We note with gratitude the constant interest of the late Professor S. Z. Belen'kii, who stimulated the performance of the calculations.

TABLE I

Number of mesons	Type of process	Statistical Weight (%) $p-p$	Statistical Weight (%) $n-p$	Number of mesons	Type of process	Statistical Weight (%) $p-p$	Statistical Weight (%) $n-p$
0	NN	0.3	0.4	3	$NN3\pi$	4.5	4.5
1	$NN\pi$	6.5	6.8		$NN'2\pi$	31.8	31.0
	NN'	1.0	0.7		$N'N'\pi$	11.7	11.1
2	$NN2\pi$	11.5	12.0	4	$NN4\pi$	2.7	2.7
	$NN'\pi$	16.7	17.4		$NN'3\pi$	1.2	1.2
	$N'N'$	0.9	1.2		$N'N'2\pi$	11.2	11.1