THE properties of the nucleus with a respect to photons of high energy (for $kR << 1$, where k is the wave number of the photon, R is the atomic radius) can be characterized by a complex index of refraction $n + i\varkappa/k$, where n is approximately 1 and $\varkappa R << 1$. The magnitude of the absorption coefficient $\varkappa$ can be expressed in terms of general formulas in terms of the experimentally determined cross section for photo-meson production on nuclei:

$$\varkappa R = 3\sigma_c^2 / 4\pi R^2. \qquad (1)$$

The existence of absorption must lead to strong scattering of photons. Using general diffraction relations for polarized nuclei[1] it is easy to show that the cross section for scattering σ_s is

$$\sigma_s = 9\sigma_c^2 / (32\pi R^2). \qquad (2)$$

The scattering amplitude at small angles θ is

$$f(\theta) = ik\varkappa \int_0^R J_0 (k\theta \sqrt{R^2 - s^2})\, s^2\, ds,$$

from which we find for the differential cross section

$$\begin{aligned} d\sigma_s / do &= {}^1/_2\, \sigma_s (kR)^2\, \Phi^2 (kR\theta), \\ \Phi(x) &= x^{-2} (x^{-1} \sin x - \cos x). \end{aligned} \qquad (3)$$

In agreement with the experimental data[2] at photon energies of the order of 300 mev, σ_c is approximately $10^{-28} A$ cm^2. In this case the scattering cross section must be

$$\sigma_s = 10^{-30}\ \text{cm}^2 \text{ for Be}, \quad \sigma_s = 0{,}9\cdot 10^{-28}\ \text{cm}^2 \text{ for U}.$$

Let us compare the diffraction scattering with scattering of photons by a Coulomb field. The cross section of the last σ_γ for $E >> mc^2$ is equal[3] to

$$\sigma_\gamma = 8{,}5\cdot 10^{-35} Z^4 \text{ cm.}^2$$

Thus the ratio σ_s / σ_γ changes from 50 for Be to 10^{-2} for U, that is for heavy nuclei the diffraction scattering is considerably smaller than the coherent scattering by the charge. Nevertheless, it must appear as a consequence of a different angular distribution. In agreement with Eq. (3), diffraction scattering is effective at an angle $\theta_s \sim 1/kR$ while scattering by the Coulomb field is concentrated in the region $\theta_\gamma \sim mc^2/E$. Therefore, for $E = 300$ mev, the differential cross sections for U are comparable for $\theta = 0.015$, after which $d\sigma_\gamma / d\theta$ rapidly decreases, while $d\sigma_s / d\theta$ remains in this region at a constant value which is equal to 0.8 mb ($\theta_s = 0.09$).

We would like to express appreciation to K. A. Ter-Martirosian for discussing this problem.

[1] A. Akhiezer and I. Pomeranchuk, *Some Problems of Nuclear Theory*, 1950.

[2] *Experimental Nuclear Physics*, (edited by E. Segre).

[3] H. Bethe and F. Rohrlich, Phys. Rev. 86, 10 (1952).

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Concerning the Impulse Approximation

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BRUECKNER[1] has examined the problem of the scattering of a particle by a system of two scatterers with zero-range forces [the scattering from each of these centers is spherically symmetric and is characterized by the amplitude $\eta = (1/k) \times \sin\delta\, e^{i\delta}$, where δ is the phase of the S-wave at infinity]. For the scattered amplitude in this problem, we obtain the following expression:

$$f(\vartheta) = \left(1 - \eta^2 \frac{e^{2ikR}}{R^2}\right)^{-1} \Big[\eta \left(e^{i(\mathbf{k}_0 - \mathbf{k})\mathbf{r}_A} + e^{i(\mathbf{k}_0 - \mathbf{k})\mathbf{r}_B}\right) \qquad (1)$$
$$+ \eta^2 \frac{e^{ikR}}{R^2} \left(e^{i(\mathbf{k}_0 \mathbf{r}_A - \mathbf{k}\mathbf{r}_B)} + e^{i(\mathbf{k}_0 \mathbf{r}_B - \mathbf{k}\mathbf{r}_A)}\right)\Big],$$

where $\mathbf{k}_0$ and $\mathbf{k}$ are the wave vectors before and after scattering, $\mathbf{r}_A$ and $\mathbf{r}_B$ are the radius vectors of the scattering centers, and $R = |\mathbf{r}_A - \mathbf{r}_B|$.

From this expression, Brueckner, using a well-known theorem relating the imaginary part of the scattering amplitude in the forward direction with the total cross section, obtains the latter. Comparing this expression for the total cross section with the corresponding one obtained with the aid of the impulse approximation, the author shows that the difference between these two expressions becomes insignificant not for $R \sim \infty$, but for $\delta \to 0$ (for simplicity, it is assumed that the amplitude η is the same for both scatterers). From this the conclusion is reached that the use of the impulse approximation without taking account of multiple scattering is valid only when the Born approximation is applicable.

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:

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

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

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

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.

* 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