coincidence to the remaining three counters. This is followed by a 12-in. long Be converter, a scintillator, a Pb electron filter, a sweeping magnet, the gas Čerenkov counter, and a final scintillator. Neutrons are detected by the charged pions produced in the beryllium converter and recorded by the triple coincidence of the two scintillators and Čerenkov counter. The threshold energy of 3 Bev for detecting pions is set by the gas pressure in the Cerenkov counter. The Pb electron filter and the sweeping magnet serve to deflect out of the telescope the conversion electrons, originating from decaying π^0 mesons of all energies produced in the beryllium converter. Protons made in the converter have too low a β to count in the Čerenkov counter.

The neutron-counter telescope is placed at a fixed distance of 30 feet from the collimator. A similar telescope at the rear of the collimator monitors the neutron flux by detecting charged pions produced in the lead filter. Absorption measurements in "good" and "poor" geometry were done by placing the sample at various distances from the neutron detector. Figure 2 shows the results of such a series of measurements on Pb. Similar measurements have been performed on carbon and copper. The limiting values of the cross section for "good" and for "poor" geometry yield the total and reaction cross sections listed in Table I. The most interesting feature of the data is that the elastic cross sections, especially for the heavy elements, are considerably smaller than at lower energies, whereas the absorption cross sections remain essentially constant from 300 Mev up to our energy.

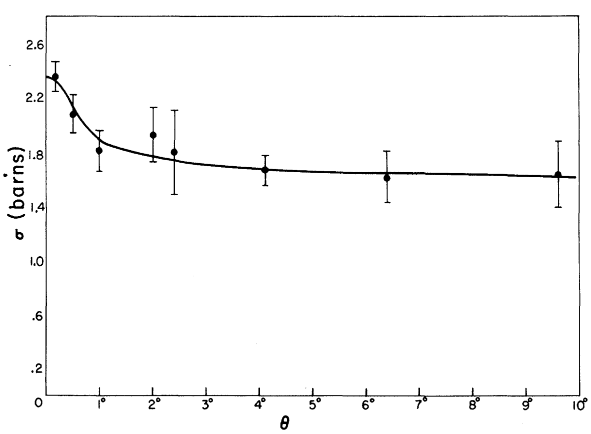

FIG. 2. Cross section of neutrons in lead as a function of the half angle subtended by the neutron detector. The solid curve is a least-squares fit to the data according to an opaque-nucleus calculation for a mean neutron energy of 4.5 Bev.

Table I. Neutron total and reaction cross sections.

	σ_t (in mb)	σ_r (in mb)
Pb	2320±130	1660±90
Cu	1088±22	638±24
C	354±11	218±8

The following Letter discusses the interpretation that can be placed on these values, in relation to the Brookhaven measurements performed at a mean energy of 1.4 Bev, and lower-energy data.[3]

We should like to acknowledge the support of Professors A. Carl Helmholz and Burton J. Moyer for this experiment. We should also like to thank Dr. Edward J. Lofgren and the Bevatron crew for their help and unfailing courtesy in the performance of this experiment.

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

[1]Fred N. Holmquist, University of California Radiation Laboratory Report UCRL-8559, December, 1958 (unpublished).

[2]V. Perez-Mendez and J. H. Atkinson, University of California Radiation Laboratory Report UCRL-8570, December, 1958 (unpublished).

[3]Coor, Hill, Hornyak, Smith, and Snow, Phys. Rev. 98, 1369 (1955).

GENERALIZED DIFFRACTION THEORY FOR VERY-HIGH-ENERGY COLLISIONS*

A. E. Glassgold and Kenneth R. Greider
Lawrence Radiation Laboratory,
University of California,
Berkeley, California
(Received January 26, 1959)

It has become customary to interpret nuclear scattering experiments in terms of the optical model in which one introduces a general single-particle operator (optical potential) for the incident projectile and attempts to determine its properties from experiment. Although this procedure has yielded many useful results it has a number of drawbacks, particularly for very high energies. On the other hand, there are a number of simplifications which obtain at very high energies which permit a more satisfactory treatment to be given.

To be specific, we consider the scattering of a neutral spinless particle by a spherical symmetric object. The scattering amplitude $f(\theta)$ in the usual notation is

$$kf(\theta)=\frac{1}{2i}\sum_{l=0}^{\infty}(2l+1)(\eta_l-1)P_l(\cos\theta).$$

The amplitude η_l of the lth outgoing wave is related to the phase shift δ_l by the equation $\eta_l=\exp(2i\,\delta_l)$. We propose to treat the scattering in terms of these coefficients rather than with a potential model. In doing so we shall make the quasi-classical approximation in which η is a continuous function of l. In addition we emphasize the role of strong absorption at high energies by writing the scattering amplitude as a sum,

$$f(\theta)=f_0(\theta)+f_1(\theta).$$

The amplitude $f_0(\theta)$ corresponds to the complete absorption of L partial waves: $\eta_l=0$ for $l\leq L$ and $\eta_l=1$ otherwise. Thus $f(\theta)$ is the amplitude for the "black-sphere" model,[1,2] for which exact solutions exist.

We now generalize the simple diffraction theory by writing

$$\eta(l)=|\eta(l)|e^{i\alpha(l)},$$

and by assuming that (a) the opacity function, $1-|\eta|^2$, decreases monotonically with l from an essentially constant value β for small l to zero for large l, (b) this transition occurs mainly within an interval of width 2Δ centered about a large value of the angular momentum L, and (c) the phase function α is continuous and vanishes for sufficiently large l. By expressing these assumptions in terms of certain definite analytic functions for $1-|\eta|^2$ and α, one can find closed expressions for $f(\theta)$, $\sigma^{(r)}$, and $\sigma^{(t)}$. We have chosen various functional forms to represent the transition region, assuming constant phase, but find the results to be independent of the details in this region.

The significant feature of this result is that a scattering formalism of sufficient generality for high-energy collisions has been obtained which eliminates the need for any lengthy calculations. Closed-form expressions are thus available to discuss a large number of measurements in terms of a few physically significant parameters. Assuming constant phase, these parameters are: L, the number of partial waves strongly absorbed; 2Δ, the range over which the opacity function decreases from β to 0; β, the opacity for small l; and α, the phase.

As an example of this method we consider neutron total and reaction cross sections in the energy range from 0.3 to 4.5 Bev for C, Cu, and Pb. The measurements at the highest energy are reported in the preceding Letter.[3] The following reasonable assumptions are made about the dependence of L and Δ on k and A (atomic mass):

$$L\propto kA^{1/3},\qquad \Delta\propto k.$$

Good agreement can be obtained only if the phase is close to zero. In other words the scattering amplitude is practically pure imaginary. The results are plotted in Fig. 1, and the values deduced for β are:

	Energy (Bev) 0.3	1.0	4.5
Pb	0.97	1.00	0.94
Cu	0.94	0.99	0.92
C	0.80	0.93	0.90

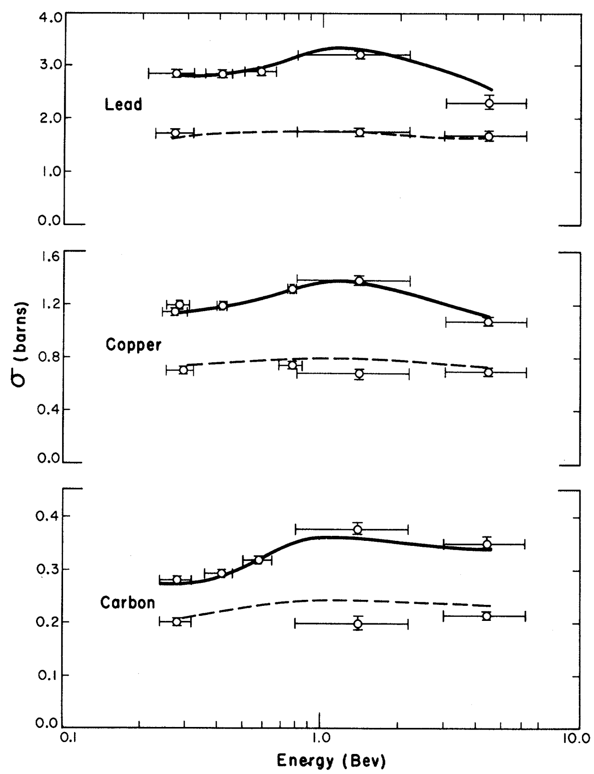

FIG. 1. Neutron total and reaction cross sections. The solid curves are the theoretical total cross sections and the dash curves are the theoretical reaction cross sections. The circles are the experimental measurements. The following values were used in the analysis: $L=(1.26\times10^{-13}\text{ cm})kA^{1/3}$ and $\Delta=(0.672\times10^{-13}\text{ cm})k$.

The dependence of β on k and A can be interpreted in terms of a classical picture of exponential absorption with distance, the absorption coefficient being related to the observed nucleon-nucleon total cross sections. The energy variations of the cross sections are best understood in terms of the basic formulas for the partial reaction and total cross sections:

$$\sigma_l^{(r)} = (1 - |\eta_l|^2)(2l+1)\pi\lambda\!\!\!^{-2},$$

$$\sigma_l^{(t)} = (1 - \mathrm{Re}\,\eta_l)\, 2(2l+1)\pi\lambda\!\!\!^{-2}.$$

For small real η, $\sigma_l^{(r)}$ is less sensitive to changes in η than $\sigma_l^{(t)}$, since the former is a quadratic function of η whereas the latter is linear. In addition, the reaction cross section does not depend on the phase of η, whereas the total cross section does. The observed large energy variation in the total cross section can only be obtained by choosing the phase for η close to zero.

---

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

[1]H. A. Bethe and G. Placzek, Phys. Rev. 57, 1075(A) (1940).

[2]A. Akhieser and I. Pomeranchuk, J. Phys. 9, 471 (1945).

[3]Atkinson, Hess, Perez-Mendez, and Wallace, preceding Letter [Phys. Rev. Lett. 2, 168 (1959)]. The writers would like to thank these authors for early communication of their results.

SECOND RESONANCE IN PION PHOTOPRODUCTION *

Michael J. Moravcsik
Lawrence Radiation Laboratory,
University of California,
Livermore, California
(Received January 15, 1959)

Recently several authors have made attempts[1-3] to determine the angular momentum and multipole state in which the alleged second resonance in pion photoproduction takes place. Qualitative arguments have been advanced concerning the features of the angular distribution[2] and the recoil nucleon polarization[3] in case of unpolarized incident photons. The present note discusses another type of experiment which might help to determine the resonating state. It is the measurement of the differential cross section for polarized photons. In particular, it is proposed that $(d\sigma/d\Omega)_\perp$, the differential cross section for photons polarized perpendicular to the production plane, be measured. This quantity has the great advantage that even in the case of charged pions the meson current (or photoelectric term) does not contribute to it. It has been shown[4] that due to the change in sign of its interference terms, the meson current term becomes very important for charged pions in the region between the first resonance and 500-Mev photon laboratory energy. No investigations have been made above 500 Mev, but there is no reason to believe that at high energies we would again encounter the somewhat fortuitous situation that prevails below the first resonance, where the interference terms of the meson current contribution cancel to a great extent its own square contribution. On the other hand, it is not simple to include the effect of the meson current term in qualitative considerations, and in fact for instance reference 2 omits it. Whether this omission alters the qualitative conclusions is not known at the present. It is an advantage, therefore, to be able to say that the considerations in this note, like those in reference 3, are completely independent of the meson current term.

In the absence of the meson current term the important contribution, at the second resonance, will come from the S-wave term and the resonance state. In making this statement we assume that the various nonresonating P states (including the state which gives the first resonance) contribute relatively little, compared to the two states mentioned above. The goodness of this assumption is open to question until a quantitative study is made of the entire problem of high-energy photoproduction. Assumptions of similar nature, however, are also made in the arguments of references 2 and 3.

With the above assumptions it can be shown that if and only if the second resonance is in the $D_{\frac{3}{2}}$, $E1$ state as Peierls[2] suggests, will $(d\sigma/d\Omega)_\perp$ be isotropic. This conclusion can be arrived at from the equations

$$|M|_\perp^2 = \sum_{i=0}^{5} A_i x^i, \qquad (1)$$

where

$$A_i = \sum_{j+k=i} U_j^{(k)}, \quad j = 0, \ldots 4;\ k = 0,1 \qquad (2)$$

and

$$U_j^{(0)} = \sum_{\alpha+\beta=j} (H_{1\alpha}^{*} H_{1\beta} + H_{2\alpha}^{*} H_{2\beta}), \quad \alpha, \beta = 0,1,2 \qquad (3)$$