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Elastic Scattering of 1.33 MeV Gamma Rays from Lead

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ELASTIC SCATTERING OF 1.33 MEV GAMMA RAYS FROM LEAD

by

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INTRODUCTION

Currently there is an interest in the experimental detection of Delbrück scattering, a radiative correction of the Compton process from the nucleus. This interaction with the Coulomb field of the nucleus is predicted by quantum electrodynamics but cannot be derived from linear classical theory[1]. The existence of a virtual electron-positron pair, present during the Delbrück interaction, has been verified by experimental work involving the Lamb shift[2]. However the detection of Delbrück scattering would be an independent check on the existence of these virtual pairs.

Since Delbrück scattering is elastic, it combines coherently with Rayleigh, nuclear Thomson, and nuclear resonance scattering. The cross sections for the latter interactions must be accurately known if one hopes to identify the Delbrück process from experimental data. The situation is further complicated by inelastic effects which also must be separated out.

Comparison of earlier work in this area reveals large discrepancies in experimental results which are beyond the range of quoted uncertainties, indicating that the experimental situation is not yet clear. Also the proper treatment of the L-shell contributions to the Rayleigh amplitudes is a matter of importance which must be settled before the data can be used to verify the existence of Delbrück scattering.

The work in this paper concerns itself with the measurement of the differential cross sections of 1.33 MeV gamma rays scattered from lead at various angles in the 60-120° range. The results are compared with previous experiments of this nature and also with theoretical calculations. It is found that there is a discrepancy between experimental results and the conventional theoretical calculations. This discrepancy is discussed and it is shown that it can be resolved by making certain reasonable assumptions about the L-shell contributions to the Rayleigh amplitudes.

THEORY

Inelastic Scattering and Absorption

The interaction of gamma radiation with matter can be characterized by three processes: absorption, inelastic scattering, and elastic scattering. The predominant contributions to absorption are the photoelectric effect and pair production. In the former process, which predominates at low energies, the incident photon gives all of its energy to a bound electron in the target atom. In pair production, which occurs in the field of a nucleus, the photon annihilates, creating an electron-positron pair. This process has a threshold at 1.02 MeV and becomes the dominant mode as the energy of the photon increases. The main contribution to inelastic scattering is the Compton effect, which is scattering by the atomic electrons. The differential cross section per electron for this process is given by the Klein-Nishina formula[3]; and it is the dominant mode of interaction at gamma ray energies around 1 MeV.

Elastic Scattering

Considering elastic processes, the differential cross section for the scattering of initially unpolarized radiation is[4]

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left\{ |A^{\parallel}|^2 + |A^{\perp}|^2 \right\}$$

where $A^{\parallel}$ and $A^{\perp}$ are the coherent sums of the amplitudes for different elastic processes:

$$A^{\parallel} = r_0\left(a_T^{\parallel} + a_R^{\parallel} + a_{NR}^{\parallel} + a_D^{\parallel}\right)$$

$$A^{\perp} = r_0\left(a_T^{\perp} + a_R^{\perp} + a_{NR}^{\perp} + a_D^{\perp}\right)$$

for the nuclear Thomson, Rayleigh, nuclear resonance, and Delbrück components, r_0 being the classical radius of the electron.

The amplitudes associated with Thomson scattering are

$$r_0 a_T^{\parallel} = -(Z^2e^2/M_n)(\bar{e}_1\cdot\bar{e}_{1s}) = -(Z^2e^2/M_n)\cos\theta$$
$$r_0 a_T^{\perp} = -(Z^2e^2/M_n)(\bar{e}_2\cdot\bar{e}_{2s}) = -(Z^2e^2/M_n)$$

where $\bar{e}_1$ and $\bar{e}_2$ are unit polarization vectors for the incident wave transverse to the direction of propagation; $\bar{e}_{1s}$ and $\bar{e}_{2s}$ are similar unit vectors for the scattered wave corresponding to a rotation of the reference frame through the scattering angle θ about an axis perpendicular to the scattering plane. M_n is the mass of the nucleus, and e is the charge of the electron.

Elastic scattering from the bound electrons of the atom is known as Rayleigh scattering. It has been thoroughly investigated in the X-ray region where it accounts for Bragg scattering. In the X-ray energy region the differential cross section is accurately given by the cross section for Thomson scattering from an electron multiplied by the square of a form factor to take into account the atomic charge distribution. The form factor $F(q)$ is a function of the momentum change q of the photon and is given by

$$F(q) = \int e^{i\bar{q}\cdot\bar{r}}\,|\Psi(r)|^2\,d^3r$$

where $q = 2(\hbar\omega/c)\sin(\theta/2)$. $\Psi(r)$ is the electron charge density, and ω is the frequency of the photon.

The semiclassical and nonrelativistic quantum theory methods of derivation used for X-rays have proved to be inadequate for large angle scattering from heavy elements of gamma rays in the 1 MeV region. The first treatment for $\hbar\omega$ comparable to mc^2 was given by

Franz[5], using the Thomas-Fermi model of the atom and second-order perturbation theory. The form factor approximation was also made by Bethe[6] who used the Dirac K- shell wave functions for the electrons. The result of his calculation is

$$F(Q) = \sin(2\gamma \tan^{-1} Q)/\gamma Q (1+Q)^{\gamma}$$

where $Q = (137/Z)(\hbar\omega/mc^2)\sin(\theta/2)$ and

$\gamma = (1-\alpha^2 Z^2)^{1/2} \cong 1-\epsilon$, α being the fine structure constant and ϵ the binding energy in units of the rest mass of the electron (m_0c^2).

The effect of binding of the electron in the intermediate states was taken into account by Brown and Mayers[5] who subsequently found that the Rayleigh amplitude for no polarization change was much smaller than that predicted by the form factor approximation, while the amplitude for polarization change was in close agreement with the previous calculations.

The contribution of nuclear resonance scattering to the elastic cross section was investigated by Levinger[6] and found to be negligible for our situation.

Delbrück scattering involves two processes: the annihilation of an incident photon in the electric field of a nucleus producing a positron-electron pair, and then the annihilation of this pair to produce a photon of essentially the same energy as that of the incident photon but, in general, different momentum.

The differential cross section for Delbrück scattering is obtained from $d\sigma/d\Omega = |a_1(h\nu) + i a_2(h\nu)|^2$

where a_1 is the real or dispersive part and a_2 is the imaginary or absorptive part of the scattering amplitude. In the forward direction the real part is most important up to about 10 MeV but for higher energies the imaginary part predominates. The imaginary part of the amplitude is related to real pair production, and since the theory for this process is comparatively well established, experimental results which will throw light on the real part of the scattering amplitude are of most interest. For this reason most of the experimental studies of Delbrück scattering have been made at energies of 1 to 3 MeV. Both the real and the imaginary amplitudes have been calculated by Ehlotzky and Sheppey[7] to within 5-10% for energies from 1-20 MeV and over an angular range of 0-120°.

The relative magnitudes of the Thomson, Rayleigh K-shell, and Delbrück differential cross sections are shown in Figure I.

Relative Phases in Elastic Scattering

There has been much confusion regarding the phase relationships among the amplitudes in the expression for the differential elastic scattering cross sections. When the Bethe form factor calculations were used to derive the Rayleigh amplitudes the argument of reflection symmetry for the electron charge density resulted in a real, positive form factor F which led to the conclusion that the Rayleigh and Thomson amplitudes were in phase. The elastic scattering amplitudes were in the form

$$(\bar{e}_j \cdot \bar{e}_{js})(F + Z^2 m/M)$$

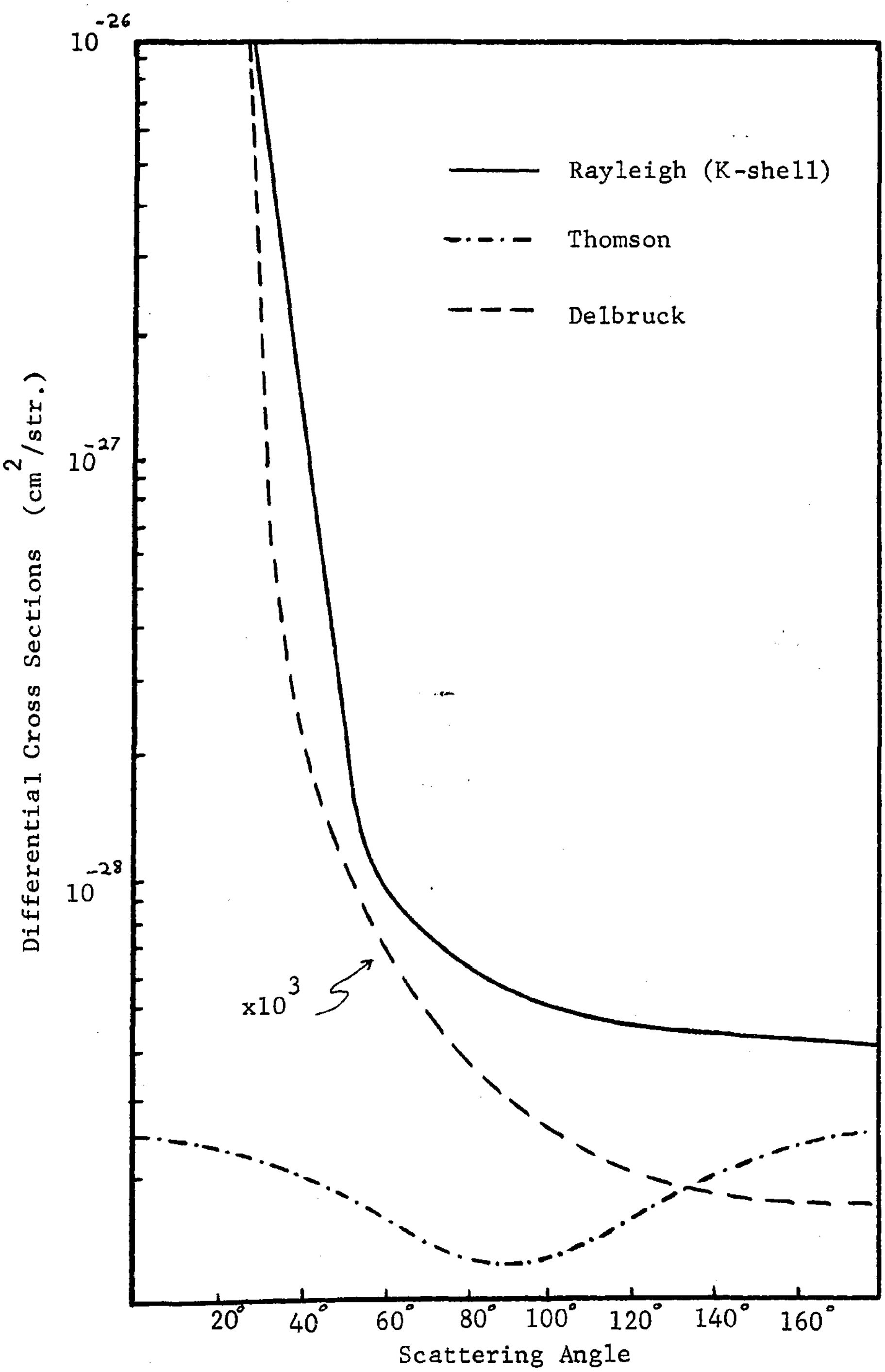

Figure I. Differential Cross Sections

where F is the form factor for Rayleigh scattering.

The exact calculations of Brown and Mayers[5] demonstrated that the Thomson and Rayleigh amplitudes could no longer be related in the simple form given above, although it was still assumed that they were in phase. This assumption has led to quite good agreement between calculated and experimental values for angles less than 90°, but the situation at larger angles is far from resolved. While the Brown and Mayers calculations have been confirmed by polarization measurements for angles less than 90°[8], there has been no convincing experimental check for angles greater than 90°. This has prompted some[9] to suggest a possible phase shift between Rayleigh and nuclear Thomson scattering at 90°. (This will be pursued more fully in a later chapter.)

It would appear, however, that some of the relative signs between the various amplitudes can be assigned unambiguously with the aid of the Bohr-Peierls-Placzek relation[10], also known as the optical theorem. This relationship gives the following connection between a cross section (which is positive) and the imaginary part of the scattering amplitude at 0°:

$$\mathrm{Im}\,(a_T + a_{RK} + a_{RL} + a_D + a_{NR}) = (k/4\pi)\,\sigma$$

where k is the wave number of the incident photon and a_T, a_{RK}, a_{RL}, a_D and a_{NR} are the amplitudes for Thomson, Rayleigh K-shell, Rayleigh L-shell, Delbrück, and nuclear resonance scattering respectively. $\mathrm{Im}(a_T)$, of course, is zero, and a_{NR} is negligible in our case.

Since $|a_{RL}| + |a_D|$ is certainly smaller than a_{RK} the expression above implies $Im(a_{RK})$ is positive. If we assume the relative signs given by Brown and Mayers[5] to be correct then the signs of all the K- shell Rayleigh amplitudes are determined for all scattering angles. Nuclear Thomson scattering is well known and the signs of its amplitudes are given by quantum electrodynamics (see page 4). Finally, since Delbrück scattering is actually a radiative correction to nuclear Thomson scattering[10] the relative signs of the Delbrück amplitudes can also be unambiguously determined from quantum electrodynamics.

Thus one is led to conclude that the Thomson and Rayleigh scattering amplitudes are in phase at 0° with the Delbrück amplitudes being 180° out of phase[11]. From the exact calculations of the Rayleigh K-shell and the Delbrück amplitudes it is then possible to determine the relative signs among Rayleigh, nuclear Thomson, and Delbrück amplitudes for all scattering angles. As nuclear resonance scattering is negligible in the present work no attempt will be made to determine its phase relative to the other processes.

EXPERIMENTAL MEASUREMENTS

Method of Measurement

Experimentally the absolute cross section for elastic scattering can be determined by two relative measurements. If n_a is the detected number of counts per second for gamma radiation scattered from the target at a given angle and n_b is the number of counts per second resulting from an auxiliary Co^{60} source placed in the target position and having the same dimensions as the target, then the cross section is given by[12]

$$\left(\frac{d\sigma}{d\Omega}\right)_{el} = \left(\frac{n_a}{n_b}\right)\left(\frac{b}{a}\right)\left(\frac{r^2}{N}\right)$$

where (b/a) is the ratio of the auxiliary source strength to the primary source strength (which must be determined in a separate experiment), r is the distance from the primary source to the target, and N is the number of scattering centers in the target. This method of determining the elastic cross section makes it unnecessary to know such factors as the efficiency of the detector, solid angles, and absolute source strengths, which are not easily measured.

The ratio of source strengths b/a was found using two additional sources of intermediate strengths along with inverse-square and absorption curve techniques.

Experimental Arrangement

The arrangement used was typical for this type of experiment. A schematic of the apparatus and a block diagram of the electronics are shown in Figure II. The Co^{60} source had a strength of approximately 111 curies and was enclosed, along with a mercury shutter system, in a lead-brick "pile" to insure sufficient shielding. The apparatus was designed to produce a conical beam with a half-angle of 6°. A cylindrical collimater (not shown in Figure II) was used to decrease the beam size in forward angle measurements in order to reduce scattered radiation in the room and allow for sufficient shielding of the detector.

The scattering measurements were taken using a lead target of dimensions 14.0 cm by 16.5 cm and a thickness of 0.178 cm. It was suspended in the beam by nylon threads which were fastened to a precalibrated device enabling accurate target orientation with a minimum of uncertainty and effort. To insure minimum angular dispersion the angle ϕ between the target and the beam axis was related to the scattering angle θ by $\sin\phi / \sin(\theta-\phi) = r/R$ where r is the source-target distance and R is the detector-target distance. Initial target alignment was made with the use of a laser; fine adjustments were made with the help of X-ray film exposures of the beam with the target in position. An aluminum target of the same dimensions and containing the same number of electrons as the lead target was used for background studies.

The detector of the scattered radiation was a 10cc lithium drifted germanium crystal operated at a reverse bias of 1800 volts in conjunction with a Tennelec Model 135 M preamplifier and a 200 series amplifier. It was mounted on a moveable table, along with a sufficient amount of lead shielding, to simplify the changing of

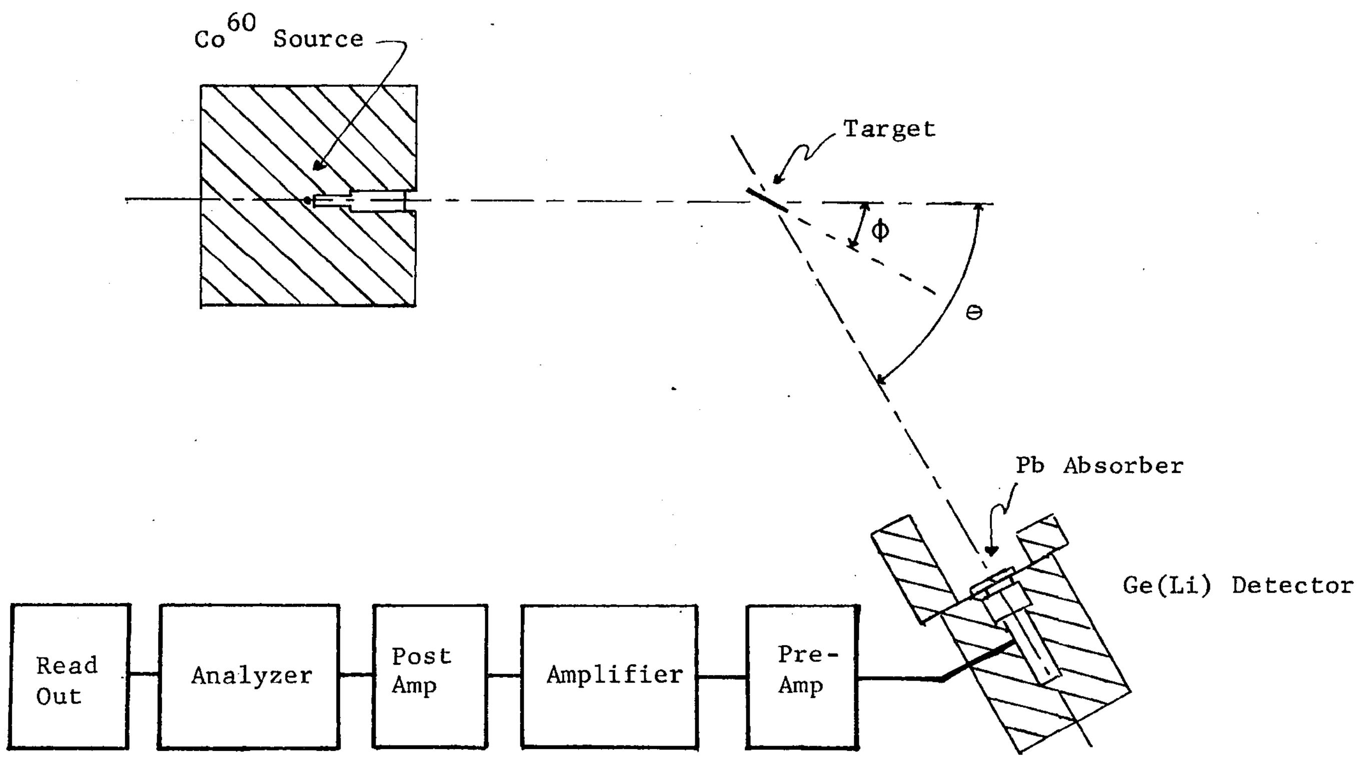

Figure II. Experimental Arrangement and Electronics scattering angles. A lead absorber 1/8 in. or 1/4 in. thick (depending on θ) was placed in front of the detector to reduce the number of inelastically scattered gamma rays in the region of the 1.33 MeV photopeak without appreciably decreasing the counting rate of the elastically scattered events. A typical measurement of the elastic cross section for a given scattering angle involved three 800 minute counting runs with the target in place and two 800 minute runs with the auxiliary source in the target position. Background radiation was subtracted electronically for the same period of time for all runs. The total number of counts was sufficient to provide less than 3% statistical uncertainty in the count ratio n_a/n_b. Each individual run was plotted on semi-log paper for a direct comparison of the elastically scattered 1.33 MeV peaks as a check against electronic drift and possible resolution variations. The target runs were then normalized to the same peak channel (if a small analyzer drift was detected) and the counting rate n_a, corrected for target absorption, was calculated. A similar procedure resulted in a value for the auxiliary source counting rate n_b.

The count ratio n_a/n_b, the source ratio b/a, the number of target atoms, and the source-target distance r were then combined to give the absolute scattering cross-section for the interaction of the 1.33 MeV photons with lead. The results, uncertainties, and corrections will be discussed in the next chapters.

CORRECTIONS

The primary correction to the experimental data was for attenuation of the radiation in the target. This correction is given by

$$n = n_0 \left(\frac{\sin\phi}{\mu \delta w} \right) \left[1 - \exp\left(- \frac{\mu \delta w}{\sin\phi} \right) \right]$$

where n_0 is the counting rate for no attenuation, n is the recorded counting rate, w is the target thickness, μ is the absorption coefficient of the target material at the incident beam energy, ϕ is the acute angle between the plane of the target and the axis of the beam, and $\delta = 1 + [\sin\phi / \sin(\theta - \phi)]$ where θ is the scattering angle. The value of μ used in this experiment was that obtained by Colgate[14].

In the derivation of the expression for the differential cross section[12] it was assumed that the gamma ray flux over the entire target area was constant. Actually, for extended targets, one must calculate the average flux. The correction necessary in our case was negligible[14].

RESULTS AND UNCERTAINTIES

The largest uncertainty in the experiment was in the value for the source ratio b/a which was found to be[14] $1.14 \times 10^{-7} \pm 3.5$ %.

The counting rate n_a of the scattered radiation was on the order of $2\text{-}3 \times 10^3$ counts for 2400 minutes; the magnitude of n_b , the counting rate of the radiation from the auxiliary source, was on the order of 1.5×10^4 counts for 1600 minutes. The statistical uncertainty in the ratio n_a/n_b was therefore assigned to be 3% at all scattering angles (see Table I).

The uncertainties in the corrections for target attenuation include errors present due to possible nonuniformities in target thickness, the uncertainty in the value for the absorption coefficient μ[13], and deviations of the scattering angle. It was estimated that the attenuation correction was uncertain to 10% at each angle (see Table I).

The source-target distance r was measured to be 125 cm with an uncertainty of 1%.

Finally, the value for the number of atoms in the target was calculated to be $1.35 \times 10^{24} \pm 1\%$. The assigned uncertainty includes the results of a spectroscopic analysis of the target to determine the amount of any impurities.

The final values for the differential cross sections of the elastic scattering of 1.33 MeV gamma rays from lead are given in Table I.

Table I

SCATTERING ANGLE	COUNT RATIO $n_o/n_o \times 10^{-2}$	ABSORPTION CORRECTION (%)	DIFFERENTIAL CROSS SECTION (μb/sr)
60° ± 1.0°	12.15 ± .36	18.4 ± 1.8	196 ± 12
75° ± 1.5°	7.97 ± .24	16.0 ± 1.6	125 ± 8
90° ± 1.7°	7.02 ± .21	14.0 ± 1.4	108 ± 6
105° ± 2.0°	6.30 ± .19	12.6 ± 1.3	95 ± 5
120° ± 2.5°	6.32 ± .19	11.9 ± 1.2	94 ± 5

COMPARISON WITH OTHER WORK

The results of this work are compared with the values obtained by Dixon and Storey[9] and those of Standing and Jovanovich[12] in Table II. The results of earlier experiments[15-18] dealing with this subject have not been included. The values quoted in these papers reflect a difficulty in the treatment of the continuous background and disagree by a large factor with each other.

Table II

Cross Sections for Scattering of 1.33 MeV Gamma-Rays from Lead (μb/sterad)

Angle	Present Work	Dixon and Storey	Standing and Jovanovich
60°	196 ± 12	185 ± 13	206 ± 11
75°	125 ± 8	118 ± 9	136 ± 4
90°	108 ± 6	113 ± 7	111 ± 3
105°	95 ± 5	99 ± 6	105 ± 11
120°	94 ± 5	93 ± 6	105 ± 11

COMPARISON WITH THEORY

The cross sections in Table II are presented in graphical form in Figure III. The solid line is obtained from the theoretical nuclear Thomson and Rayleigh amplitudes, assuming that they are in phase with one another at 0°. The Rayleigh amplitudes are essentially those calculated by Brown and Mayers[5] modified to lead at 1.33 MeV. They also include an L-shell correction for the spin-flip amplitude which was taken to be the K-shell amplitude multiplied by the ratio of the L-shell form factor to the K-shell form factor. The total L-shell form factor amounts to about 20% of the K-shell form factor at large angles[9].

It is clear that there is significant disagreement between the theoretical curve and the experimental values. It does not appear that this discrepancy can be explained by Delbrück scattering. Figure IV includes the theoretical contribution of Delbrück scattering calculated from the amplitudes of Ehlotzky and Sheppey[7]. The dashed curves are obtained by taking the Delbrück amplitudes to be either in phase or 180° out of phase with the Thomson and Rayleigh amplitudes at 0°. It is apparent that the explanation for the discrepancy must be sought elsewhere.

One suggestion[9] to resolve this discrepancy is that the Rayleigh and nuclear Thomson processes became incoherent at angles beyond 90°. If there is a constant phase angle δ between the scattered waves from different processes in the same atom, then incoherence could result

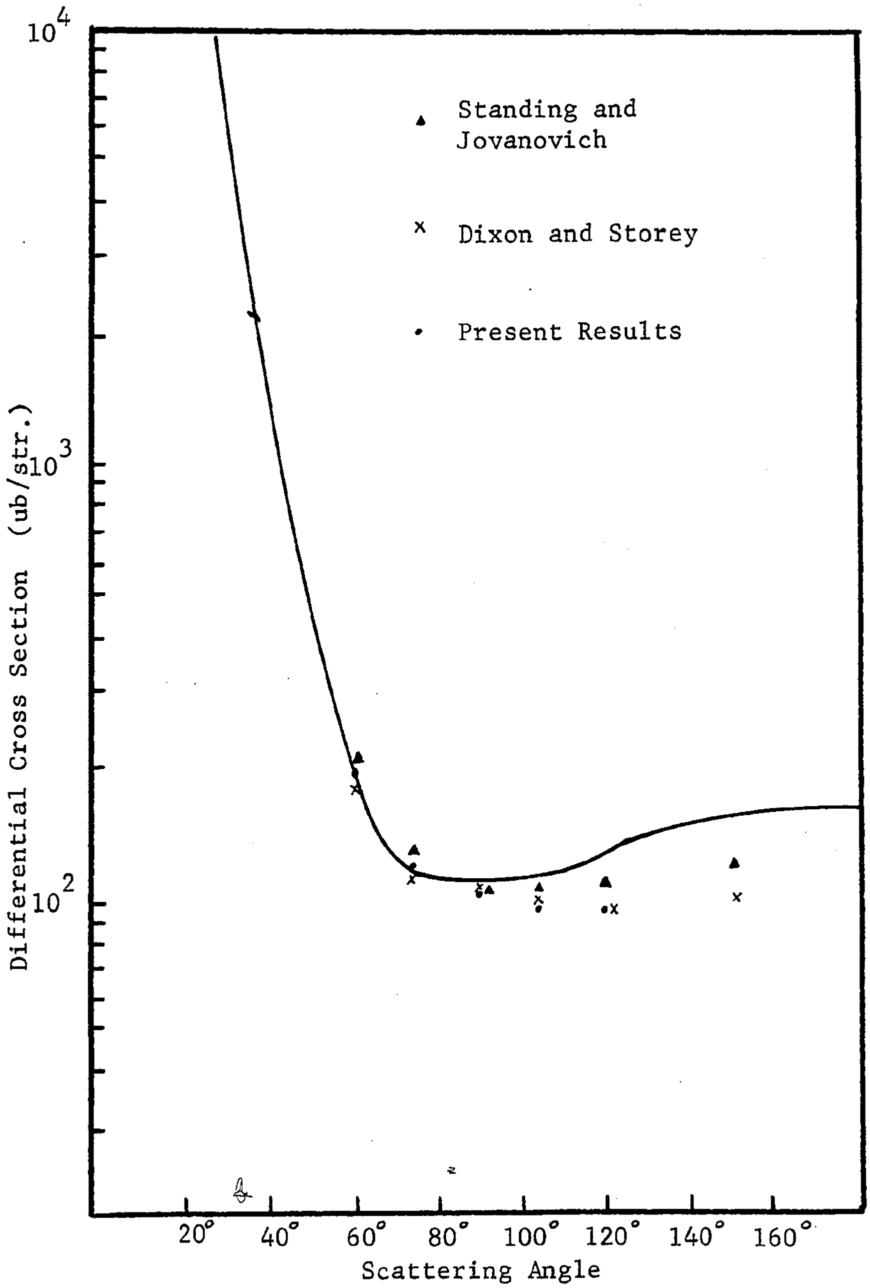

Figure III. Comparison of Results with Previous Work and Theoretical Curve.

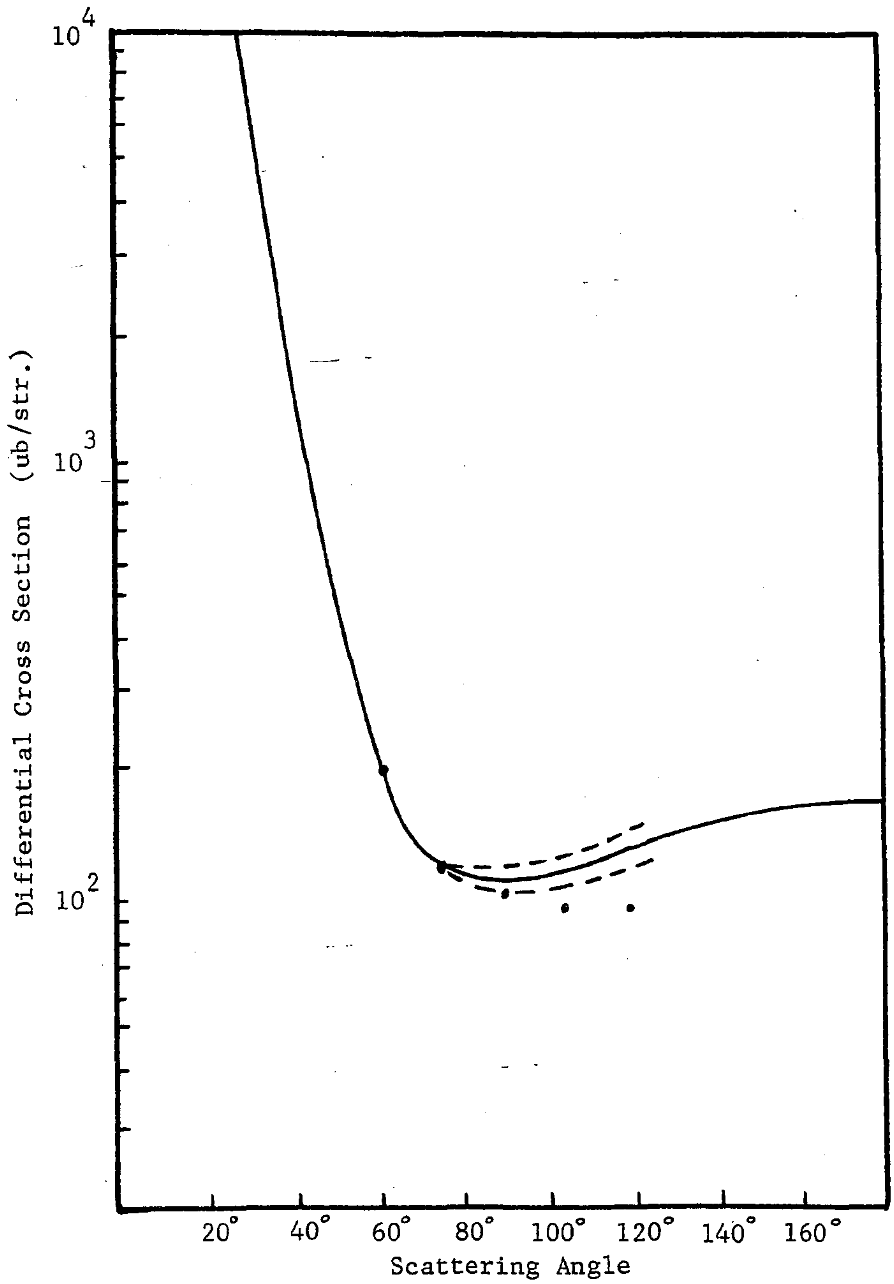

Figure IV. Contribution of Delbrück Amplitudes from a large range of δ values by $\cos\delta$ average to zero even though the scattering is elastic. In Figure V the solid curve was obtained by combining incoherently the Rayleigh and nuclear Thomson amplitudes at all angles; the dashed curve results from a coherent treatment as described above (see Figure III). Although the agreement between theory and experiment is somewhat improved at larger angles the argument supporting such a treatment seems rather tenuous.

A second explanation[9] is that there is a phase shift of 180° between the parallel components of the Rayleigh and Thomson amplitudes, the perpendicular components remaining unchanged. The only support for this argument lies in the fact that the polarization measurements[8], which are sensitive to a change in $a_P^{\parallel}$, cannot distinguish between the two sign choices in the 0-90° region where the only results have been reported. Figure VI shows the effect of this phase shift. Although the agreement with experimental results is good the material presented in the section on relative phases indicates that the signs among the various amplitudes can be determined unambiguously.

A more likely explanation may lie in the addition to the Rayleigh amplitudes of the L - shell contribution to the scattering. Previous values for this correction have been obtained by multiplying the K- shell amplitude by the ratio of the L-shell form factor to the K- shell form factor, the L-shell form factor being calculated using Dirac wave functions. This correction was made only in the spin-flip Rayleigh K - shell amplitudes (since the no spin-flip amplitudes are small at large angles[5]) and amounted to approximately 20%[9].

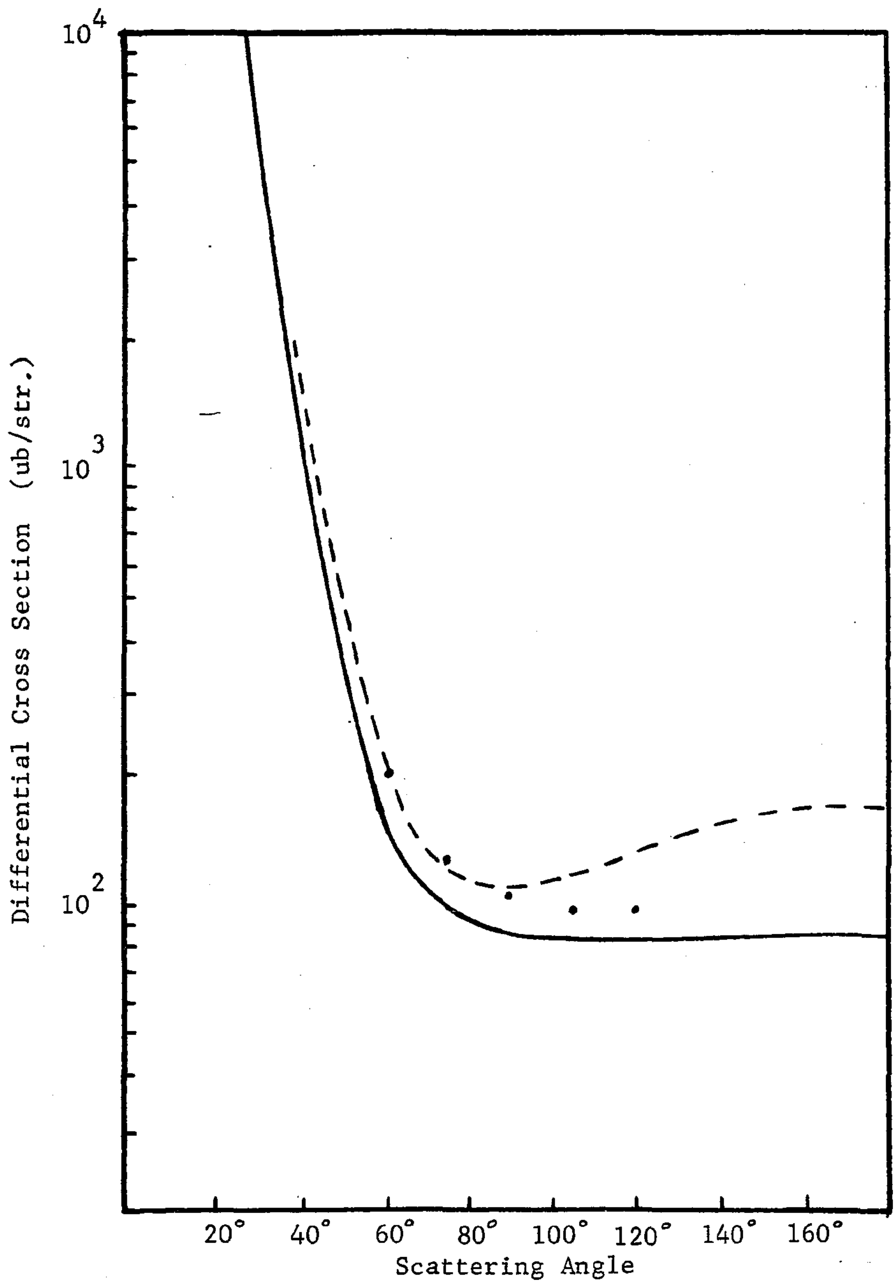

Figure V. Cross Section Resulting from the Addition of Rayleigh and Thomson Amplitudes Incoherently

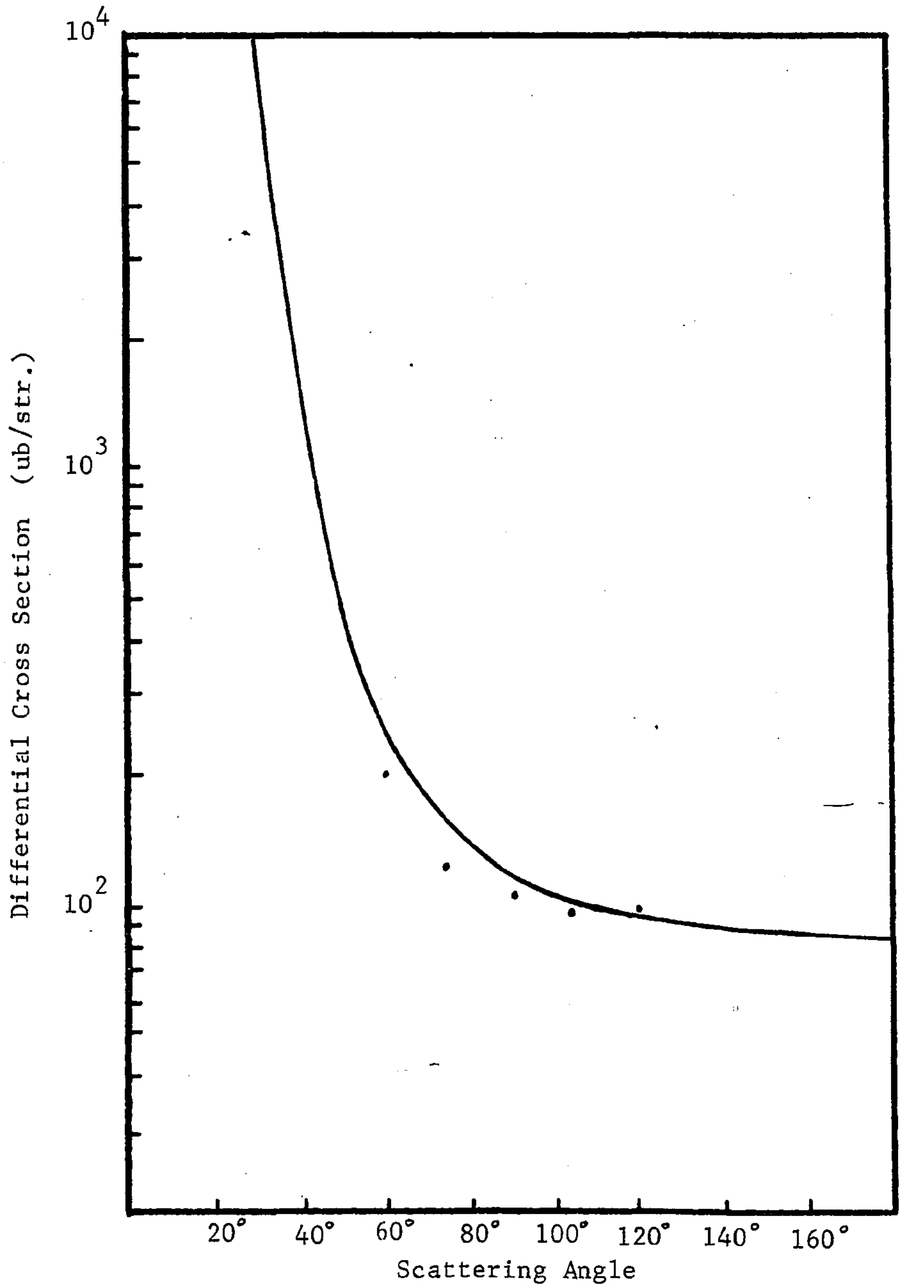

Figure VI. Cross Section Resulting from 180° Phase Shift in a_T''

The solid curves in Figure VII are the Rayleigh K- shell amplitude for spin-flip $a_R^{K'}$ calculated by Brown and Mayers and modified to lead at 1.33 MeV, the L-shell contribution $a_R^{L'}$ as described above, and the final corrected amplitude $a_R^{(K+L)'}$. The resulting cross sections for this case were given in Figure III.

It was found, however, that excellent agreement could be achieved if the L-shell contribution was allowed to change sign at large angles. In Figure VII the lower dashed curve is the proposed L-shell correction $a_R^{L'}$ and the upper dashed curve is the combined K- and L-shell amplitudes. The resulting cross sections for this case are shown in Figure VIII along with the experimental values. No significance should be attached to the good agreement, which was assured by the choice of the L-shell amplitude. The point to be made is that the discrepancy can be resolved with an L-shell of reasonable magnitude which varies smoothly with scattering angle. It is interesting to note that a similar discrepancy occurs when the target is Uranium[14] and that it can be resolved with an L-shell amplitude of reasonable magnitude which crosses the axis around 90° .

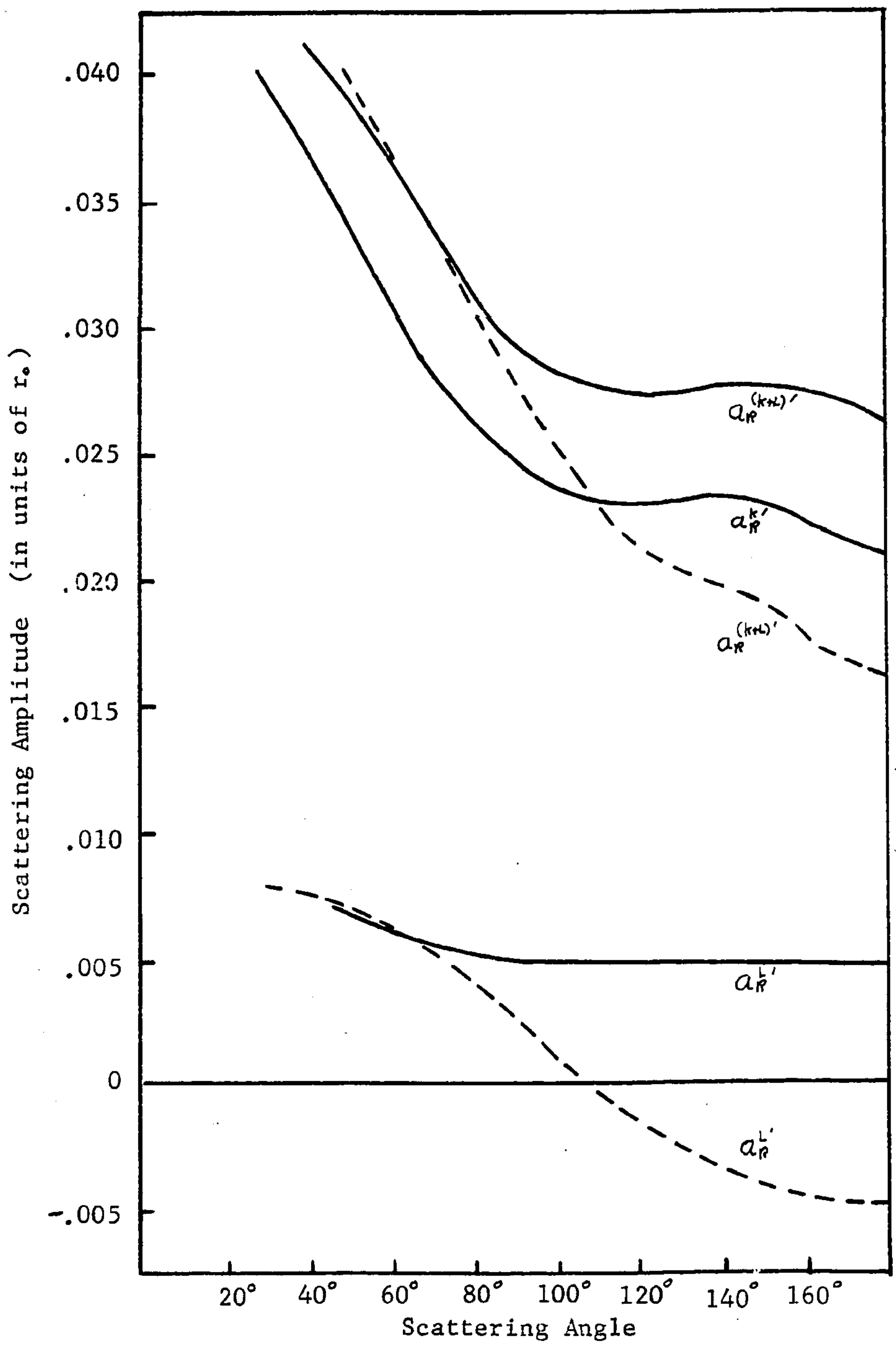

Figure VII. Rayleigh Spin-Flip Amplitudes

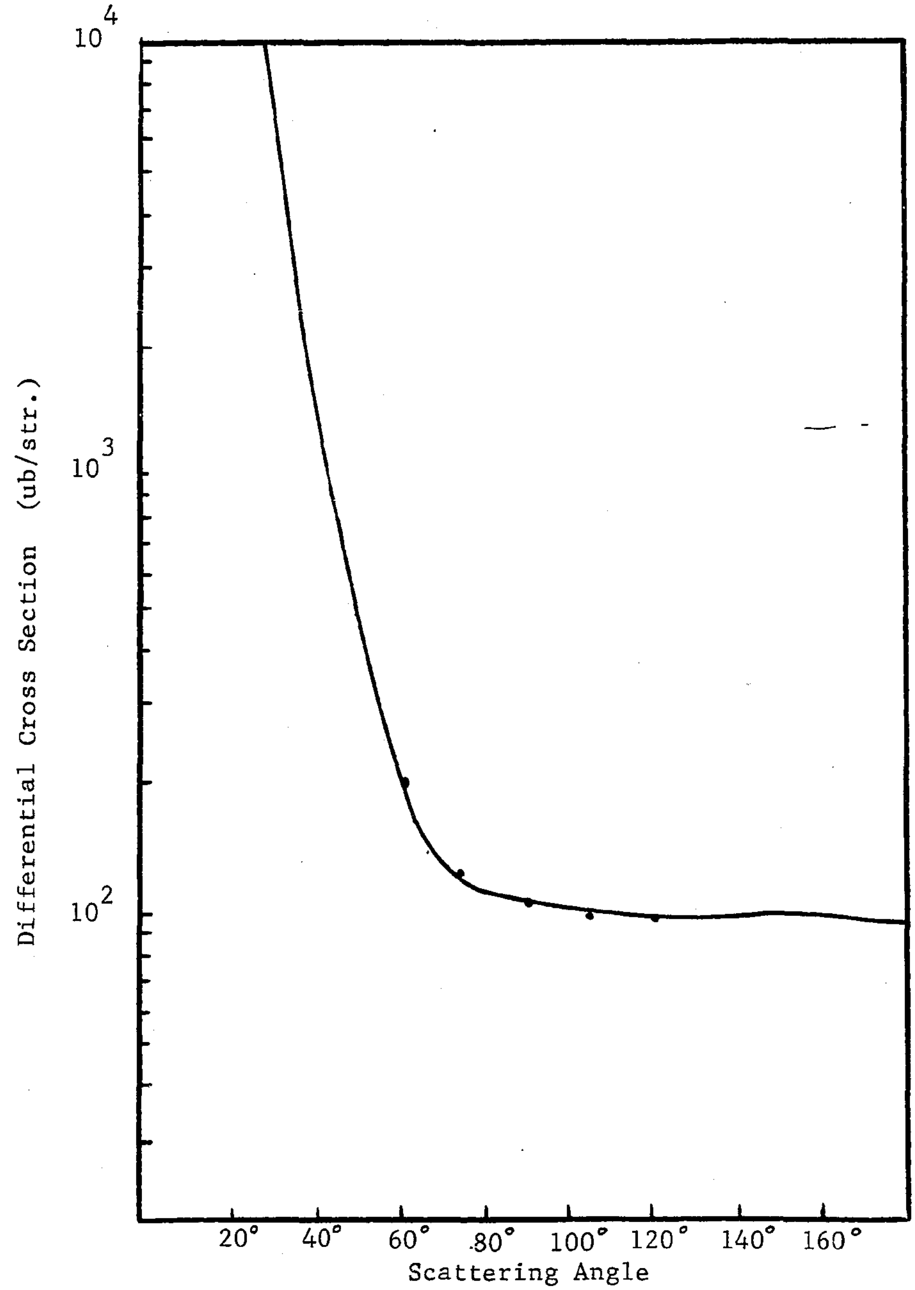

Figure VIII. Cross Section Resulting from Proposed L-Shell Contribution

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