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UNIVERSITY OF CALIFORNIA

Radiation Laboratory

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ABSOLUTE PHOTON ATTENUATION CROSS SECTION

FOR NON-PAIR PROCESSES IN BERYLLIUM AT 300 MEV

Robert Warner Kenney
(Thesis)

February 1, 1952

Berkeley, California
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ABSOLUTE PHOTON ATTENUATION CROSS SECTION
FOR NON-PAIR PROCESSES IN BERYLLIUM AT 300 MEV

Robert Warner Kenney

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University of California, Berkeley, California

February 1, 1952

I. ABSTRACT

The total cross section for the attenuation of 300 Mev photons by non-pair forming processes in beryllium has been found to be $0.149 \pm 0.023 \cdot 10^{-25}$ cm$^2$/Be atom. This result is 18 percent higher than the theoretical total Compton cross section in beryllium at 300 Mev.

A table of photon interactions with nuclei is given, their cross sections in beryllium at 300 Mev are estimated, and their theoretical dependences on Z and energy are included. It is seen that the non-pair, non-Compton processes contribute at least 10 percent of the measured cross section. From the data, one can only conclude that the Klein-Nishina formula is correct to within 15 percent at 300 Mev.

Additional experiments are planned to reduce the error to 3 percent. The Z and energy dependence of the non-pair attenuation cross section will be determined in an effort to study the individual effects.

The total absorption cross sections at 300 Mev in beryllium and lead have been found to be $1.587 \pm 0.0063 \times 10^{-25}$ cm$^2$/Be atom and $37.14 \pm 0.26 \times 10^{-24}$ cm$^2$/Be atom, respectively. The ratio of the pair forming cross sections at 300 Mev in beryllium to those in lead have been found to be $3.90 \pm 0.066 \times 10^{-3}$. 
Knowledge of the interaction between electromagnetic radiation and matter has developed rapidly and fairly completely in the last half century. Classical concepts first began to show their limitations in the new radiation theory, and it was Planck in 1900 who found it necessary to introduce the quantum of action to account for black body radiation. The quantum idea led naturally to an explanation of the photoelectric effect by Einstein in 1905, and in 1913 Bohr applied the quantum concept to the atom. Schrödinger and Heisenberg in 1925 and 1926 developed the quantum mechanics which has been so successful in explaining quantitatively the phenomena observed in the small.

These developments were not the last word, for when the theory was applied to radiation fields, divergent integrals were found to exist in the expressions for the interaction of the field and the electron. The Klein-Nishina formula was obtained without divergence difficulties, but the theory is essentially complete only to first order. In general, the higher order approximations in the quantum electrodynamics have, until recently, contained divergences which are of the nature of the ultra-violet catastrophe which exists in classical electrodynamics.
Obtaining a divergence free quantitative classical electrodynamics is made difficult by the infinite self energy of a point charge. Circumventing this difficulty requires that the electron be given some assumed finite structure. For radiation of wavelength \( \lambda \approx r_o \) in the rest frame of the electron, it is expected that details of the electronic structure must be considered in an exact theory. \( r_o \) is the radius of the finite homogeneous electron.

The classical Lorentz expression for the force on a finite electron

\[
e E + e (\vec{v} \times \vec{H}) = \frac{e^2}{r_0 c^2} \vec{r} + \frac{2 \ e^2}{3 \ c^2} \vec{r} + \frac{ae^2 r_o}{c^4} \vec{r} + \ldots
\]

contains \( r_o \) in all terms except the second, or radiation reaction term, which remains in the limit of \( r_o \) going to zero. The first term gives the classical electron radius \( r_o \) from measured values of \( m_0 \). The restriction \( \lambda > r_o \) then leads to the following limiting energy for validity of the classical theory:

\[
\lambda > \frac{e^2}{m_0 c^2} \text{ or } \hbar \omega < \frac{\hbar c}{e^2} \quad m_0 c^2 = 137 \ m_0 c^2
\]

\[
e = 70 \text{ Mev}
\]

The classical theory is then expected to depend upon the detailed structure assumed for the electron at energies of the order of 70 Mev and greater. This limiting energy, in the case of the Compton effect, is extended to \( 137/2 \times 70 \text{ Mev} = (5 \times 10^9) \text{ e.v.} \) by the nature of the interaction. This point will be discussed in Section III.

The infinities which arise in the relativistic quantum electrodynamics are due to the impossibility of using a source function corresponding to a finite electron.\(^3\) Divergences are then associated with
field fluctuations and with pair production fluctuations as well as with the self-energy of the point electron which is employed through necessity. A finite electron source function would eliminate those ultra-violet divergences, since the Fourier components of the radiation above 70 Mev would have rapidly decreasing amplitudes with increasing energy. Recently the radiation theories of Feynman and of Schwinger have been extended by Dyson \(^2\) who has shown that if consistent charge and mass renormalizations are applied, an electrodynamics results which is completely divergence-free. In his formalism, the hamiltonian is expanded as a power series in the fine structure constant. The only outstanding problem is to demonstrate the convergence of the series.

Experimental determination of the high energy cross sections is a necessary check on the electrodynamics. The point electron theories applied to cosmic ray showers give reasonably quantitative information at the highest energies known. \(^4\) This is no proof of the correctness of the electrodynamics for the mathematical difficulties which exist in shower theory provide a source of uncertainty in the results which may mask deviations in the basic cross sections from their best theoretical values by as much as 50 percent.

A straightforward approach, free from nuclear complications, is provided by the Compton effect which involves only a free electron at photon energies much greater than the electron binding energy in an atom. Then if the predictions of a given theory are in satisfactory agreement with experiment up to some energy \(E\), that theory can be regarded as an equally satisfactory description of nature up to energy \(E\).
An experimental value for the total Compton cross section at energies above 88 Mev has not been reported to date, and therefore the experiment described here was undertaken to extend the measurements to the highest available accelerator energies. In carrying out this experiment, an improvement has been made in the best existing statistics for the total attenuation cross section in lead and beryllium for 300 Mev photons, and 1.5 percent statistics for the ratio of pair forming cross sections in the two elements have been secured.

The quantity actually found in this investigation is the contribution to the total attenuation of 300 Mev photons in beryllium by all processes which do not give rise to electron pairs or triplets. These effects are numerous, and will be only listed here. Their detailed treatment is deferred to Section V where the sum of all their cross sections at 300 Mev, except No. 1, is shown to be appreciably smaller than the 300 Mev total Compton cross section. These various electromagnetic effects are: 1. Compton effect; 2. meson production; 3. photonuclear reactions; 4. nuclear photo effect; 5. photoelectric effect; 6. elastic nuclear scattering.

The ultimate objective in performing this experiment is to find a value, with probable error of about 3 percent, for the non-pair contribution to the total attenuation cross section in beryllium. Plans are being made to continue the experiment to that end. Then a comparison of this value with the total Compton cross section calculated from the Klein-Nishina formula will presumably yield a small positive difference if the Klein-Nishina theory is correct. If this difference is not what one should expect from theoretical estimates of the contributing effects, it
is planned that the non-pair attenuation shall be determined as a function of $Z$ and of $k_0$ in an effort to sort out and study the responsible effects.

III. PAIR PRODUCTION

A. Pairs Formed in Nuclear Coulomb Field

Electron pair production is the most probable mode of interaction between a beam of high energy photons and the matter it traverses. Cross sections for electron pair production in the nuclear field have been calculated by Bethe and Heitler\textsuperscript{7} using the fundamental idea of negative energy states, and employing the first order Born approximation for practical reasons. The cross sections so calculated are subject to negative corrections for screening of the nuclear Coulomb field by the atomic electrons, and calculations of this effect\textsuperscript{8} have been made using the Fermi-Thomas statistical model. A small additional correction has been given by Bartlett.\textsuperscript{9}

The Born approximation assumes $Z/137 \ll 1$, which is the condition that the plane waves used for the pair members in the theory remain undistorted by the Coulomb field. For heavy elements this criterion is not strictly true. The departure of the experimental cross sections from their theoretical values was observed first by Lawson at 88 Mev,\textsuperscript{5} and has since been seen at 17.6 Mev by Walker,\textsuperscript{10} between 11 Mev and 20 Mev by Adams,\textsuperscript{11} and at 280 Mev by DeWire, Ashkin, and Beach.\textsuperscript{6} The 280 Mev data for Be, Al, Cu and Pb have been confirmed by the author. At 300 Mev Emigh\textsuperscript{12} found from cloud chamber studies that the departure can be expressed as

$$\frac{\phi_t - \phi_e}{\phi_e} = 1.5 \pm 0.1 \times 10^{-5} Z^2$$
where \( \Phi_t \) includes screening. \( \Phi_t \) and \( \Phi_e \) are the total pair cross sections given by theory and experiment respectively.

B. Pairs Formed in Electron Coulomb Field

Pair production occurs also in the Coulomb field of the electron, giving rise to a so-called "triplet". The third member is the recoil electron in whose Coulomb field the pair creation occurred. Cross sections for this process have been calculated by Wheeler and Lamb,\(^\text{13}\) by Watson,\(^\text{14}\) by Borsellino,\(^\text{15}\) and by others.\(^\text{16}\) The Born approximation theory for the basic triplet cross section is independent of \( Z \). This cross section and the nuclear pair theory for \( Z = 1 \) are equally valid. Hence the failure of the Born approximation at large \( Z \) does not affect the validity of the corresponding theoretical triplet cross section since it is \( Z \) times the basic cross section per electron.

Some experimental and theoretical total absorption cross sections for Be and Pb are given in Table 1 to illustrate the disagreement between theory and experiment for lead.

<p>| TABLE 1 |
|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th></th>
<th>Theoretical, cm(^2)/atom</th>
<th>Experimental, cm(^2)/atom</th>
<th>Probable Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>280 Mev (^6)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td>0.1559 ( \times 10^{-24} )</td>
<td>0.1586 ( \times 10^{-24} )</td>
<td>1.2 percent</td>
</tr>
<tr>
<td>Pb</td>
<td>40.6 ( \times 10^{-24} )</td>
<td>36.7 ( \times 10^{-24} )</td>
<td>1.2 percent</td>
</tr>
<tr>
<td>88 Mev (^5)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Be</td>
<td>0.1482 ( \times 10^{-24} )</td>
<td>0.160 ( \times 10^{-24} )</td>
<td>1.5 percent</td>
</tr>
<tr>
<td>Pb</td>
<td>34.90 ( \times 10^{-24} )</td>
<td>31.27 ( \times 10^{-24} )</td>
<td>1.6 percent</td>
</tr>
<tr>
<td>17.5 Mev (^10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>22.58 ( \times 10^{-24} )</td>
<td>20.56 ( \times 10^{-24} )</td>
<td>0.6 percent</td>
</tr>
</tbody>
</table>
IV. COMPTON EFFECT

A. Work of Thompson and Compton

In 1906 J. J. Thompson showed theoretically that the intensity $I$, of x-rays scattered from an unbound electron is given by

$$ I = I_0 \frac{r_o^2}{R^2} (1 + \cos^2 \theta); \quad r_o = \frac{e^2}{m_o c^2} $$

where $I_0$ is the intensity of the incident beam and $R$ is the distance between scattering electron and detector. He also showed the total cross section to be given by

$$ \Phi_o = (8/3) \pi r_o^2 $$

The experimental single electron x-ray scattering coefficients for wavelengths greater than 0.1 Angstrom agree with the Thompson theory to a very close approximation. For harder radiation, Compton observed in 1922 that the coefficient rapidly becomes smaller, particularly at large scattering angles, and that the shift in wavelength of the radiation scattered through angle $\theta$ is given by $\Delta \lambda = 0.0242 (1 - \cos \theta)$. 

Compton adopted a particle model for the photon-electron interaction by ascribing momentum $\hbar \omega/c$ and energy $\hbar \omega$ to the photon. Treating the problem relativistically, and assuming conservation of energy and momentum, he derived an expression, now known as the Compton shift formula. It gives the wavelength shift $\Delta \lambda$ of radiation scattered through angle $\theta$:

$$ \Delta \lambda = \frac{h}{m_o c} (1 - \cos \theta) \quad (1) $$

The theory also gives the angular dependence

$$ \tan \varphi = \frac{1}{(1 + \alpha) \tan \theta/2} \quad (2) $$
where $\varphi$ is the electron recoil angle, $\Theta$ is the photon scattering angle, and $\alpha = \frac{\hbar \omega}{m_0 c^2}$.

These relations imply that the Compton scattering process is indeed a simultaneous photon scattering and electron recoil, and further that the angle of one determines the angle of the other member of the event. At first, these two equations of Compton were not accepted because the recoil electron had not been observed and also the old controversy on the nature of radiation - wave vs. particle - was again brought to the fore.

Bohr, Kramers, and Slater\textsuperscript{19} proposed a statistical scattering theory, which allowed the photon to remain wavelike, and to be scattered from the electron. But the emission of either member of the event was completely independent. The equations of Compton were to be satisfied in a statistical manner only, and the individual events were presumably entirely random in time. The experiments of Shankland\textsuperscript{20} lent credence to this view. He observed no simultaneity of emission of the recoil photon and electron. However, the refined experiments of Hofstadter and McIntyre\textsuperscript{21} have reduced the uncertainty in the simultaneity to $1.5 \times 10^{-8}$ seconds. The original views of Compton have now gained complete acceptance.

E. Quantum Mechanical Formulation

The early wave mechanical formulations\textsuperscript{22} employed the Schrödinger mechanics, which is not Lorentz invariant. These results are, therefore, correct only to the first power of $\beta$, and they deviate appreciably from the Klein-Nishina formula in the high energy region.\textsuperscript{23}

The approach to the problem of the Compton effect via the Lorentz invariant Dirac electron theory, using negative energy states and also intermediate states in the scattering process where momentum but not
energy is conserved, leads to the well known Klein-Nishina formula,\(^1\) which was derived in 1929. The differential cross section for unpolarized primary radiation is given by

\[
\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2} \left(\frac{k_0}{k_0^*}\right)^2 \left(\frac{k_0 + k_0^* - \sin^2 \theta}{k_0^* - k_0^*} \right)
\]  \tag{3}

where \(k_0\) is the primary energy and \(k_0^*\) is the energy of the photon scattered through angle \(\theta\). A plot of Eq. (3) is shown in Fig. 1.

The \(\theta\) dependence of \(k_0^*\) is given by

\[
k_0^* = \frac{k_0}{1 + \frac{k_0}{m_0c^2}(1 - \cos \theta)}
\]  \tag{4}

Eq. (4) is plotted in Fig. 2.

The detailed derivation of the Klein-Nishina formula is too complicated to be treated here. See Heitler\(^2\), page 146. A short sketch of the procedure follows. The transition of the initial state \(A(k_0, p_0, \theta)\) to the final state \(B(k, p)\) must pass through intermediate states differing by one photon only from the preceding state. \(k\) is the photon energy and \(p\) the electron momentum. Two intermediate states are possible, namely:

1) a. \(k_0\) is absorbed, giving the electron a momentum \(\vec{p}' = \vec{k}_0\) with no photon present.
   b. \(k\) is emitted in the transition to the final state.

2) a. \(k\) is first emitted, both \(k_0\) and \(k\) are present, and the electron has momentum \(\vec{p}'' = -\vec{k}\).
   b. \(k_0\) is absorbed in the transition to the final state.

In the intermediate states, only \(\vec{p}\) is determined, so that the electron
energy may be positive or negative by

\[ E = \pm \left( p^2c^2 + m_0^2c^4 \right)^{1/2} \]

and the spin may be up or down. In the final state, \( E > 0 \) but the spin may be either way. After lengthy calculation of the matrix elements, the transition probability and cross section follows immediately from the matrix element for the entire transition given by

\[ H_{AB} = \sum_{C} H_{AC} H_{CB} \]

\[ \frac{1}{E_B - E_A} \]

As pointed out in Section I, the classical electrodynamics is presumed to begin breaking down around 70 Mev. This criterion was arrived at assuming \( \lambda > r_0 \) in the rest frame of the electron. In the Compton effect, no such single frame exists, for the electron is at rest in the laboratory before the scattering occurs and is extremely relativistic afterward in most cases. The diagram below defines the angles involved.

Thus \( 1/\lambda < 1/r_0 \) is not a correct criterion for it cannot be generalized in a covariant manner. The transformation of this scattering process to a new frame is equivalent to adding a constant vector to \( 1/\lambda_0 \) and \( 1/\lambda \). The physical situation is not altered in this way. Thus \( |\Delta(1/\lambda)| < 1/r_0 \) is the criterion which must be generalized. This leads to the limiting energy \( E < m_0c^2/2 \left( \frac{\hbar c}{e^2} \right)^2 = 5 \times 10^9 \text{ e.v.} \) for the validity of the classical electrodynamics in the Compton effect. One then would not expect failure of the Klein-Nishina formula at our energy of 300 Mev.
C. Experimental Work

The Compton theory has been subjected to experimental investigation by many observers working at energies up to 300 Mev. The early work was done with gamma rays and with high voltage x-rays. By 1927 the angular and energy relations of Compton (see Eq. (1) and (2)) were confirmed experimentally for these low energies.

The more general Klein-Nishina formula has been verified by measuring the total Compton cross section at various energies. Hewlett,²⁵ and Allen,²⁶ have measured the carbon absorption between 100 and 300 XU, Read and Lauritsen²⁷ have studied carbon and aluminum at 20 to 50 XU, and Meitner and Hupfeld,²⁸ and Chao²⁹ have extended the work on carbon to 4.7 XU by utilizing gamma rays from ThC²⁺. Berman³⁰ has recently utilized the 19.5 Mev photons at the quantum limit of a bremsstrahlung spectrum to study the Compton effect at that energy.

High energy work to date has been done by Hofstadter and McIntyre at 100 Mev, by Lawson⁵ at 88 Mev, and by the author at 300 Mev.

These investigations have verified the Klein-Nishina formula quite accurately at energies up to 19.5 Mev. At 100 Mev, only the shape of the angular dependence has been checked. Agreement was within experimental error of 10 percent. Lawson finds the 88 Mev total cross section measured to 15 percent agrees with the theory to within the experimental error. His method is essentially the one employed in the present experiment. See Section VI. This thesis presents evidence for agreement within experimental error of 15 percent between the integrated Klein-Nishina formula and the measured total cross section at 300 Mev.

Berman* has indicated that some work on the Compton cross section

* Private communication.
has been done by Emigh\textsuperscript{12} using a cloud chamber and averaging over a large energy range. More explicit data are lacking at this time.

In each of these investigations, the Compton effect was detected in the presence of background due to photo-electrons at incident photon wavelengths greater than about 300 \textmu m, and electron pairs at shorter wavelengths. At the higher energies, the electron pair backgrounds become excessive, and the subtraction techniques which are usually employed must be applied with care and with knowledge of their limitations.

V. NON-PAIR AND NON-COMPTON PROCESSES

The non-pair forming and non-Compton effects contribute only a small part of the total absorption and scattering of 300 Mev photons, even in light nuclei. Table II contains a summary of the principal non-pair forming processes which may occur when a 300 Mev photon interacts with a beryllium atom. Their total cross sections per 300 Mev photon, and the rough dependence of these values on \( k_0 \) and \( Z \) are included. References to convenient sources are given for more detailed information on each effect.

A. Compton Effect, Included for Comparison

The integrated Klein-Nishina formula,\textsuperscript{1} presumably for any energy, is expressed in terms of the Thompson cross section \( \Phi_0 = \frac{8}{3} \pi \left( \frac{e^2}{m_0 c^2} \right)^2 \) \( = 0.658 \) barns. \( \Phi_c \) is the total Compton cross section per electron.

\[
\frac{\Phi_c}{\Phi_0} = \frac{3}{4} \left( \frac{1 + \gamma}{\gamma^3} \left[ \frac{2\gamma(1 + \gamma)}{1 + 2\gamma} - \ln (1 + 2\gamma) \right] + \frac{1}{2\gamma} \ln(1 + 2\gamma) - \frac{1 + 3\gamma}{(1 + 2\gamma)^2} \right)
\]  

(5)

where \( \gamma = k_0/m_0 c^2 \). Eq. (5) is shown in Fig. 3.
For the extremely relativistic case, Eq. (5) simplifies to

\[ \phi_0 = \frac{3}{8} \left( \ln 28 + \frac{1}{2} \right) \]

The total cross section per atom is simply \( Z \phi_0 \).

At 300 Mev, \( \sigma = 588 \) and \( 4 \phi_0 = 1.266 \times 10^{-26} \text{ cm}^2 \text{/beryllium atom} \).

**B. Meson Production**

In beryllium, photoproduction of \( \pi^+ \), \( \pi^- \), and \( \pi^0 \) mesons has been observed. The cross sections have been found experimentally for \( \pi^+ \) and \( \pi^0 \). Using the relative cross sections for \( \pi^+ \) production as given by Mozley\(^{32}\) and the total cross section for \( \pi^+ \) production in hydrogen as given by Bishop\(^{33}\), the \( \pi^+ \) total cross section in beryllium is found to be \( 2.7 \times 10^{-28} \text{ cm}^2 \text{/photon} \) at 300 Mev to within a factor of 2. The \( \pi^+ \) and \( \pi^- \) cross sections are related by the ratio of approximately 2.2 at 90 degrees obtained by Littauer and Walker\(^{34}\). The angular distributions are in doubt by a sufficient amount to justify taking the ratio of total cross sections to be the ratio of the differential cross sections at 90 degrees. This gives for the charged \( \pi \) production \( 8.9 \times 10^{-28} \text{ cm}^2 /300 \text{ Mev photon} \).

The neutral meson photo production has been studied by Panofsky, Steinberger and Steller\(^{35}\). They give \( 5.6 \times 10^{-28} \text{ cm}^2 \) for 260 Mev photons to within a factor of 2. This value probably rises to \( 6 \times 10^{-28} \text{ cm}^2 \) at 300 Mev. The total meson cross section is then \( 1.5 \times 10^{-27} \text{ cm}^2 /300 \text{ Mev photon} \), accurate to a factor of two.

**C. Photo-Nuclear Reactions**

1. Photo Star Production

Kikuchi\(^{36}\) and Miller\(^{37}\) have observed photo stars in emulsion and have found the total cross section for their production. Their work agrees to within quoted errors, but Miller's data has been used here because of his
much smaller errors.

Miller observes an average cross section for production of three or more prong stars for the photon energy interval from 160 to 300 Mev. For silver this value is $8 \times 10^{-27}$ cm$^2$/photon.

A possible mechanism for star production is suggested by Mozley's data. One might expect that the production of a meson, and its subsequent reabsorption in the same nucleus, would lead to star formation. The stars of three or more prongs may be associated with the production of observable mesons, but the star yield is too great to be accounted for by this mechanism.

A ten percent increase in the cross section is made to account for stars in which only neutrons are emitted.

Assuming the star production depends upon A, the cross section in beryllium becomes $7.3 \times 10^{-28}$ cm$^2$/photon at 300 Mev. This value is accurate to about 50 percent.

2. Photo-Nucleon Reactions

Every known photonuclear reaction, as typified by the ($\gamma$,n) reaction, displays a single strong resonance in its excitation function.

The position in energy of the maximum is a slowly decreasing function of Z (30 Mev in carbon, 20 Mev in copper) and is a rising function of the multiplicity of the reaction. The integrated cross section is a decreasing function of the multiplicity of the reaction. Some small irregularities in cross sections occur; for example in Zn$^{64}$ the ratio of ($\gamma$,2n) to ($\gamma$,p2n) cross sections is 2.5.

One would expect the ($\gamma$,n) resonance in beryllium to be at about 30 Mev, but due to its loosely bound fifth neutron, the principal resonance occurs at about 5.6 Mev and has a maximum value of $1.6 \times 10^{-27}$ cm$^2$/Be nucleus.
The total yields from the low energy resonances have been observed. When 50 Mev and 100 Mev bremsstrahlung yields were compared, they were found to be approximately equal, showing that the cross sections between these energies are very small.

Eyges has recently postulated a rise in the cross sections above the meson threshold, and Terwilliger and Jones find the total yield of neutrons above 160 Mev is about 20 percent of the yield from the low energy resonance in beryllium. It is difficult to interpret their data in terms of photon absorption, because any calculated cross section varies inversely as the unknown average multiplicity of the neutron production. It will be assumed that the high energy neutrons observed arise from stars and from high energy nuclear photo effect.

The cross sections for the \((\gamma,n)\) and \((\gamma,2n)\) processes at high energies behave asymptotically as \(k^{-7/2}\) for a Yukawa potential with half exchange forces. Fitting a resonance curve to the \((\gamma,n)\) data for beryllium, assuming the full width at half maximum to be 7 Mev, and using the asymptotic dependence of the cross section on energy, an upper limit to the high energy cross section is calculated. Allowing an equal high energy contribution for all other photo-nucleon processes gives \(4.6 \times 10^{-33}\) cm\(^2\)/photon for beryllium. This estimate is good to a factor of approximately five.

D. Nuclear Photo-Effect

The electromagnetic ejection of high energy protons from nuclei has been observed by Levinthal and Silverman, and by Walker. The cross section for this process in carbon and in several other elements is fairly well known.
Silverman and Levinthal\textsuperscript{44} give the energy dependence of the cross section per photon as $k^{-3/2}$ for large $k$. Integrating their angular distribution for beryllium, and normalizing the theoretical expression to the data at 40 Mev proton energy, gives $7 \times 10^{-29}$ cm$^2$/photon for the 300 Mev total cross section in beryllium. Linear $Z$ dependence was used to convert the value from carbon to beryllium. Estimated accuracy is a factor of three.

E. Photoelectric Effect

Heitler\textsuperscript{46} gives the following cross section for the photoelectric effect at energies far from an absorption edge. Evaluating it at 300 Mev gives:

$$\frac{\phi_k}{\phi_0} = 5 \times 3 \left( \frac{Z}{2} \right)^5 \frac{1}{2^{1374} \psi} = 9.26 \times 10^{-9}$$

where

$$\phi_0 = \frac{8}{3} \left( \frac{e^2}{m_0 c^2} \right)^2$$

$$\phi_k = 6.08 \times 10^{-33} \text{ cm}^2/\text{beryllium atom}$$

F. Elastic Nuclear Scattering

Four processes for elastic nuclear scattering exist which combine to give a resultant elastic cross section which is negligibly small. They are:

1. Thompson scattering from the nucleus as a whole.
2. Nuclear resonance scattering.
3. Rayleigh scattering from the atomic electrons.
4. Delbruck (potential) scattering.

The calculations of the cross sections follow.

1. Thompson Scattering from the Nucleus.

Scattering from the nucleus as a whole is described by the Klein-Nishina formula,\textsuperscript{1} with the mass of the nucleus substituted for the
electronic mass. This scattering is elastic because the very large nuclear mass allows momentum to be conserved in the collision without appreciable transfer of energy to the nuclear recoil. The expression for the energy \( k \) of the recoil photon is

\[
k = \frac{k_0}{1 + \frac{k_0}{M c^2} (1 - \cos \theta)}
\]

\( M \) is \((mc^2)\) nucleus, and \( k_0 = 300 \text{ Mev} \), so that \( k_0/Mc^2 \ll 1 \), and \( k \approx k_0 \). These are the conditions for classical Thompson scattering. The cross section \( \Phi_{NT} \) for beryllium is

\[
\Phi_{NT} = \frac{8}{3} \pi \left( \frac{\pi \alpha^2}{(mc^2)_{\text{nucleus}}} \right)^2 = \frac{8}{3} \pi \alpha^2 \left( \frac{m_0}{M} \right)^2 \frac{\pi^4}{A^2} = 6.15 \times 10^{-31} \text{ cm}^2
\]

2. Nuclear Resonance Scattering

Nuclear resonance scattering is the result of a photon \( k_0 \) being absorbed and raising the nucleus mainly by dipole transition to an intermediate state of excitation. The emission of the scattered photon of energy \( k_0 \) occurs as the nucleus reverts to the ground state.

At high energy, the scattering is due to the tail of the nuclear resonance at 5.6 Mev in beryllium. At resonance, the scattering cross section is of the order of one barn. It was shown in part C 2 of this section that the \( (\gamma,n) \) cross section is down by a factor of \( 7 \times 10^5 \) at 300 Mev, and one might expect the resonance scattering to be down by about this amount also. This gives \( 1.4 \times 10^{-30} \text{ cm}^2 \) for the nuclear resonance scattering in beryllium.

3. Rayleigh Scattering from the Atomic Electrons

Rayleigh scattering from the atomic electrons occurs when the electron is raised to an excited state, remains bound and emits the scattered
photon upon returning to the ground state. In beryllium, the binding energy of the k shell electrons is of the order of $13.5 \frac{Z^2}{2} = 216$ e.v. In comparison with the incident energy of 300 Mev, one sees that the electron is free to an exceedingly high approximation and hence is not able to absorb the energy of the incident photon. The cross section for the Rayleigh scattering can be completely neglected at 300 Mev.

4. Delbruck Scattering

The potential scattering of Delbruck is elastic scattering from the nuclear Coulomb field. It may be visualized as a three step process; 1. a virtual pair is formed in the nuclear field, 2. one pair member scatters in the Coulomb field, 3. the virtual pair recombines into a recoil photon. The cross section was estimated using the Weizsacker-Williams method. Transforming to the center of momentum system of photon and a proton, one has the photon scattering from the virtual quanta field of the proton. This scattering is calculated using the cross section for scattering of light by light as given by Karplus and Neuman. At 300 Mev one assumes the effect is a nucleon – photon interaction and the cross section turns out to be $4 \times 10^{-33}$ cm$^2$, in the laboratory with first power Z dependence.

VI. METHOD

In making an experimental verification of the Klein-Nishina formula, the most definitive procedure is to measure the absolute differential cross section for photons of a given energy. Thus the maximum of theoretical detail can be checked. If one detects the effect by recoil photon-electron coincidences, one necessarily must know the efficiency of both counters over the energy range from nearly zero to the incident photon energy. Cloud
chamber methods must be able to detect the emission angle of the recoil electron as well as its energy. For a given electron energy, the recoil angle is a slowly varying function of the incident photon energy. This method is not wholly suited to determining the Compton cross section at a given energy because of the difficulty in identifying that energy from an incident bremsstrahlung continuum.

A somewhat easier approach can be taken by measuring the total attenuation cross section for a given energy photon and subtracting from this value an experimental value for the pair and triplet cross sections. This yields a total cross section for the sum of all the effects listed in Section V, the principal contributor to which is the Compton effect. This is the method employed.

This experiment is essentially a two stage investigation, with a change in point of view upon entering the latter phase. In its preliminary stages the work is a check of the integrated Klein-Nishina formula, after having subtracted theoretical estimates for the residual contributing effects listed in the preceding section. However, one should expect from the assumptions which go into the theory that the Klein-Nishina formula is valid at 300 Mev in the laboratory system.* This experiment is then, in its refined stages a measurement of all sources of scattering and absorption of high energy photons which are not due to pairs or to Compton effect. Comparing the Klein-Nishina formula and the non-pair attenuation should presumably yield a small positive difference if the Klein-Nishina theory is correct. If the indicated difference is not what one expects on theoretical grounds, the dependence on Z and on k₀ of the non-pair processes will be determined in an effort to sort out and study the responsible effects.

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* See Section IV.
The present data are not sufficient to resolve any discrepancy which may exist between the measured non-pair absorption and the Klein-Nishina formula. Experiments are planned to carry this work on to a more definitive conclusion.

A. Angular Distribution and Geometry

The present experiment is essentially a check of the total Compton scattering made in good geometry. At 300 Mev the Compton scattered photons are peaked very strongly forward, as is shown in Fig. 1. But the geometry employed, namely, a 1/2 inch diameter circular hole 10 feet from the absorber, excludes nearly all of the scattered photons from the detecting apparatus. A positive correction to the measured cross section to account for the finite geometry is negligibly small.

B. Basic Equation of the Method

The total attenuation cross section for element \( Z \), \( \phi_A^Z \), can be written as the sum of the partial total cross sections:

\[
\phi_A^Z = \phi_p^Z + \phi_t^Z + \phi_c^Z + \phi_s^Z \quad \text{where}
\]

\( \phi_p^Z \) = nuclear pair cross section

\( \phi_t^Z \) = atomic triplet cross section

\( \phi_c^Z \) = atomic Compton cross section

\( \phi_s^Z \) = atomic cross section for all other photon scattering and absorption.

In an investigation of the last two cross sections, the effect of pairs and triplets must be minimized. This dictates Be as the most practical element with which to work. To obtain an absolute value for the pair cross section in Be, the ratio of Be and Pb pair cross sections is determined experimentally.
The latter can be calculated from the measured value of the Pb attenuation since pair creation constitutes nearly all of the absorption in Pb.

Rewriting (1) and multiplying and dividing by

\[ \phi_p^{g2} + \phi_t^{g2} = \phi_A^{g2} \left( 1 - \frac{\phi_c^{g2} + \phi_s^{g2}}{\phi_A^{g2}} \right) \]

we have the equation upon which the method of this paper is based, namely:

\[ \phi_c^{g} + \phi_s^{g} = \phi_A^{g} \left( \frac{\phi_p^{g} + \phi_t^{g}}{\phi_p^{g2} + \phi_t^{g2}} \right) \phi_A^{g2} \left( 1 - \frac{\phi_c^{g2} + \phi_s^{g2}}{\phi_A^{g2}} \right) \]

The right side is then in the proper form for experimental determination of each of the factors.

C. Total Attenuation Cross Section

In making these measurements, the synchrotron pair spectrometer was equipped with a single channel coincidence apparatus which is described in detail in Section VII. This instrument will be mentioned here only as the means for finding the intensity of the photon beam at a given energy \( k \) and with the resolving power shown in Fig. 4. Its adjustment for response to photons of energy \( k \) is treated below in this section.

The cross sections observed are values averaged over the resolution of the instrument. Since the cross sections are all slowly varying functions of the energy at 300 Mev, the spectrometer need not possess a high resolving power.

The attenuation of a monochromatic beam of photons of energy \( k \), intensity \( I_0(k) \), in passing through a slab of some element \( Z \) of thickness \( t \) is given by

\[ I_1(k) = I_0(k) e^{-\phi_A^Z(k)t} \]
and $\phi_A^Z(k) = 1/t \ln \frac{I_0^Z(k)}{I_1^Z(k)}$, where $I_1$ is the intensity of photons of energy $k$ emerging from the absorbing slab.

In working with the bremsstrahlung continuum, which is plotted in Fig. 4, one might wish to make an attenuation measurement at some small energy $k < k_0$. Attenuation of incident photons in the region of $k$ would occur. But in addition cascade processes in the absorber would degrade the energy of incident photons in the interval from $k$ to $k_0$, some of which would appear in the band of energies near $k$ which the spectrometer sees. The intensity of degraded photons, for large $k_0$, is a function only of the ratio $k/k_0$ and the geometry. At best, a calculation of this effect is not dependable to more than 10 percent for practical mathematical reasons only, and the simplest choice is to readjust the synchrotron so that $k/k_0 \approx 1$. (For $k/k_0 \approx 0.8$, the geometry employed gives systematic error of less than 1 part in $10^3$.) Operating very near to the quantum limit $k_0$ avoids having more than a negligible fraction of the total photon energy subject to degradation into the acceptance band of the spectrometer. Since the measurement described in this paper is concerned with the highest available energies, $k/k_0 = 300/322$ and hence one may neglect degradation effects.

The units of $I(k)$ are total pair counts in the single coincidence channel,* per $Q$, where $Q$ is the total energy in the bremsstrahlung beam divided by the quantum limit 322 Mev. The observed pair yield $I(k)$ from a converter of thickness $t$ and atomic number $Z$, illuminated by photons of energy $k$ and intensity $I'(k)$ Mev/Q is

$$I(k) = \frac{I'(k)}{k} \left( \phi_p^Z(k) + \phi_t^Z(k) \right) tf$$

(6)

where $\phi_p^Z(k)$, $\phi_t^Z(k)$ are the pair and triplet cross sections. $f$ is a constant of the spectrometer and is less than unity. Thus $I(k)$, the observed

* See Section VII for details of the apparatus.
counts per Q, is proportional to the actual flux of photons entering the spectrometer. It is then clear that in finding an attenuation ratio, \( \frac{I_0(k)}{I_1(k)} = \frac{I_0'(k)}{I_1'(k)} \), and all the spectrometer constants cancel. A measurement of \( \phi_A^Z(k) \) then consists only of determining \( I_0 \) by removing all absorbers, and \( I_1 \) by interposing absorbers of thickness \( t \) at the position shown in Fig. 5.

This method allows one, in principle, to remain completely ignorant of the beam intensity fluctuations. Response of the monitor ionization chamber with different beam intensities was found to be satisfactory.\(^*\)

In both lead and beryllium the attenuation was observed to be an exponential function of the absorber thickness to within the statistical errors of about 1/2 percent.

D. Ratio of Pair Forming Cross Section

The ratio \( \frac{\phi_0^4}{\phi_0^8} + \frac{\phi_1^8}{\phi_0^8} + \frac{\phi_1^8}{\phi_t^8} \) is obtained by removing all absorbers and observing separately the pair yields of thin converters of beryllium and lead in the spectrometer. In Eq. (6), \( I' \) was constant, \( f \) was the same for both converters, and hence the observed pair yields from the converters

\[
\frac{I_1^4(k)}{I_1^8(k)} = \frac{\phi_0^4(k) + \phi_1^4(k)}{\phi_0^8(k) + \phi_1^8(k)} \frac{t^4}{t^8}
\]

give the ratio of pair forming cross sections directly. The pair electrons are ejected in the forward direction at angles of the order of \( \theta = \frac{m_0}{E} c^2 / k \). For 300 Mev photons, \( \theta = 1/588 \) radians. Nearly all triplets appear in the laboratory system as a normal pair accompanied by the third recoil electron with energy of the order of \( m c^2 \).\(^{14}\) Thus, the conservation equations guarantee that the two fast members will look like a normal pair.

\(^*\) See Section VIII for details.
and one can treat the triplet and pair cross sections additively. Some additional details from Watson's paper are contained in Section VIII.

Both converters used for the pair ratio were approximately $4 \times 10^{-3}$ radiation lengths thick in order to make the radiation and scattering losses small and as nearly equal as possible. The scattering for an 150 Mev electron, averaged over the converter, gives an expected vertical displacement at the detector which results in negligible loss of electrons. As a check on the calculations, curves of observed pair yield vs. thickness of converter were taken and the final runs were made on the linear portion of the curves. See Figs. 6 and 7. Small scattering losses are not important since they nearly cancel when the ratio of pair yields is taken.

Ten radiation lengths of lead were placed between each detector and the converter to shield against recoil Compton photons which might convert in one counter in coincidence with the Compton electron in the other counter. The lead was placed in a manner which both avoided the high energy pair trajectories and did not allow electrons scattered from the lead to reach the counters.

VII. APPARATUS

A. Geometry

The geometry used in this experiment is shown in Fig. 5. The 1/8 inch main collimator was a brass lined hole in a lead wall 10 inches thick. The secondary 1/2 inch collimator was also 10 inches thick and was slightly larger in diameter than the beam at that point. Photographs of the beam at the converter position showed a circle sharply cut off, whose diameter was independent of the presence of the secondary collimator.
The collimators and other apparatus were aligned with the beam by means of a telescope positioned photographically.

B. Pair Spectrometer and Sweeping Field

The pair spectrometer was built in the gap of a 22 ton electromagnet. The maximum useful magnetic field in the 5 1/2 inch gap was 14.5 Kg. The pole faces were trapezoids 32 inches high with bases of 32 inches and 13.5 inches. The magnet rested on a truck which rolled into position on railroad rails. At present, it is equipped with a portable set of rails which allows the magnet to be placed at many convenient positions in the synchrotron room. A rotating base, which is awaiting installation, will allow the magnet to be rotated 360° about the vertical axis, adding greatly to its versatility. Leakage flux was shielded from the synchrotron by partially enclosing the magnet with double steel plates. The magnet current was controlled by an electronic regulator which exhibited no observable time drift to one part in 1500. The current was observed by a Leeds and Northrup 50 millivolt potentiometer connected across a 200 ampere shunt in the magnet circuit.

Calculation of the resolving power of a pair spectrometer, in the geometry employed, has been treated by Dr. L. Aamodt.50 Fig. 4 shows the resolution of this instrument, and Fig. 11 gives details.

The spectrometer was set up to detect 300 Mev photons by positioning the pair fragment detectors properly.

The magnetic field was normally run at 8.5 kilogauss. A detailed relative field plot was made at that field intensity using a search coil and magnetometer apparatus. The absolute magnetization curve was run using a proton moment apparatus. The estimated accuracy of the field intensity over the trajectories is 0.3 percent.
The trajectories of 150 Mev pair fragments were computed from the absolute field data, and the detectors were appropriately placed in 60 degree geometry as shown in Fig. 5. The calculated detector positions were found to be within approximately 10 Mev of the positions determined from the experimental shape of the bremsstrahlung spectrum. The spectrum was taken to be a plot of the coincidence counting rate times the computed energy versus the energy, and the curve obtained was in satisfactory agreement with the fold of the resolving power and the computed spectrum, shown in Fig. 4, near the quantum limit.

A completely shielded sweeping field is available for use close to the synchrotron. It develops 15 Kg\textperthousand over a path of 30 inches long by 12 inches wide and a gap of 2-3/4 inches and deflects all charged particles out of the beam. The pair spectrometer then "sees" only a clean beam of photons. For best use of the pair spectrometer, particularly for thin converters, one should use a vacuum system extending from the entrance of the sweeping field to the counters in the spectrometer and including the entire trajectories of those electrons being detected. This vacuum system does not exist at the present time, and hence one is forced to work with electron backgrounds about equal to the pair yield from a converter 4 x 10^{-3} radiation lengths thick.

C. Electron Detectors and Electronics

The electron pairs formed in the converter were detected by stilbene crystals 1 inch by 1/2 inch by 1/2 inch in size, mounted on lucite light pipes of dimensions 1/2 inch by 1 inch by 24 inches. The scintillations were viewed by magnetically shielded 1P21 photomultipliers at the outer ends of the light pipes. The 1P21 output pulse was first limited, then clipped
to $2 \times 10^{-9}$ seconds at the phototube, and fed into a bridge type coincidence circuit located at the spectrometer. The bridge output pulses passed through a preamplifier in the same chassis and were further amplified in the counting area and scaled. A block diagram is shown in Fig. 8. The signal-to-singles feed through ratio was at least 50. The resolving time curve obtained during a run is shown in Fig. 9. The fast electronics design and development is due to Mr. Lee Neher.

D. Monitor

The monitor ionization chamber preceding the main collimator was used to indicate only relative energy flux for a given run. Its absolute calibration was not required. Checks were made for non-linear response of the monitor ionization chamber by running the beam at intensities differing by a factor of 10 and observing the pair counts per Q. This was independent of beam intensity to less than 0.4 percent. Observed ionization per Q in a secondary ion chamber operating at a point where the beam intensity was down by an inverse square factor of ten from its value at the monitor, was also observed to be independent of the beam intensity to less than 0.5 percent.

VIII. ANALYSIS OF DATA

A. Data

The amplified coincidence pulses exhibited a counting rate vs. pulse height slope of about 0.6 over the range of 20 to 70 volts. Accordingly, the amplifier output was pulse height analyzed and the data reduced for each channel. The final result was independent of the pulse height channel to about 0.5 percent. The fluctuations were of a random nature and were partially due to rounding off numbers at various points in the compu-
tations. The average of the channel results was used to get the final result.

The data were taken in a manner which will cancel out time drifts in the pulse height observed. The required number of counts for $I_0$, $I_1$, and their backgrounds were computed. One tenth of the required number of counts were first taken in the order $I_0$, $I_1$, background 0, background 1. This procedure was then repeated until the required number of counts were obtained. Summing all the counts for each counting rate yields four numbers, the ratio of any two of which will be independent of long time drifts in the electronics to first order. No pulse height drifts were observed to within statistical counting errors over 16 hour running periods.

B. Background

The converter-out background in the spectrometer was due not only to pairs created in the air column between the sweeping field and the spectrometer, but also to Compton recoils from the air in the spectrometer gap. Pairs alone will account for nearly all of the observed background since there were $5 \times 10^{-3}$ radiation lengths of air between the sweeping field and the spectrometer. This background arose from the beam itself. The counting rate dropped to zero when the main collimator was closed and the synchrotron operated at full intensity.

In reducing the data, the background was multiplied by a factor $\alpha = 0.77$ before subtracting to account for radiation straggling in the 0.013 inch Ta converter. It is observed that $bg_0/I_0 = bg_1/I_1$, indicating no appreciable fixed background. The attenuation cross section is not sensitive to this correction since it is a function of the ratio
\[
\frac{I_1 - \alpha^* b_{g1}}{I_0 - \alpha^* b_{g0}} = \frac{I_1}{I_0} \frac{1 - \alpha^* b_{g1}}{1 - \alpha^* b_{g0}}
\]

In the case of the \(4 \cdot 10^{-3}\) radiation length converters used for the pair cross section ratio, \(\alpha \approx 1\). A small correction was applied in view of the increased importance of background in this measurement.

The calculation of \(\alpha\) was made with the aid of Heitler's expression for the energy straggling of an electron traversing a given path length in matter.

C. Geometry Correction

The secondary collimator which defined the geometry was a 1/2 inch circular hole 10 feet distant from the absorber. The Compton scattering is peaked very sharply forward at 300 Mev, as shown in Fig. 1.

The variation in energy of the recoil Compton photons as a function of scattering angle is shown in Fig. 10 for very small angles. It is seen that the variation over the collimator, which subtends \(\Theta = 2 \times 10^{-3}\), is negligible. A positive correction of \(3.4 \times 10^{-2}\) percent obtained by integrating the distribution over the acceptance region of the geometry, allows for the finite geometry, assuming the correctness of the Klein-Nishina angular distribution for the recoil photon. This correction is negligibly small. Strength is given to the assumption by Hofstadter's verification of the distribution at 100 Mev.

D. Cascade Processes

In low Z absorbers of the order of a radiation length, a 300 Mev cascade shower will nearly attain maximum development. We will show that the probability is negligibly small for the following cascade process to occur, namely, for a 300 Mev photon to create a full energy electron which in turn
loses all its energy in one radiative collision in a direction which will allow the photon to pass through the secondary collimator. The scattering of the electron per radiation length gives an average deflection of thirty times the probable emission angle for radiation and pairs. Therefore, it will be assumed that the pair members and photons are emitted exactly in the forward direction and only the scattering of the electrons will be taken into account.

Let the probability for a 300 Mev photon to make a pair in thickness \( dt \) at depth \( t \) radiation lengths of absorber be simply \( dt \). Say that one percent of the pair electrons has 300 Mev energy, then the probability of having this event is \( 10^{-2} dt \). Similarly, the 300 Mev electron will radiate a 300 Mev photon with probability \( 10^{-2} dt \). The electron will have scattered meanwhile, through angle \( \Theta = 1/\sqrt{2} \times 1/300 \sqrt{\frac{\sqrt{t}}{t}} = 5 \times 10^{-2} \sqrt{\frac{t}{t}} \). Let \( t \) be the distance from the point of creation \( T \). The electron can travel only far enough for \( \Theta = 1/4 \times 120 = 1/480 = \Theta_0 \) before the cone of probable scattering defined by \( \langle \Theta \rangle \) exceeds the acceptance angle of the geometry. This distance is given by \( 5 \times 10^{-2} \sqrt{t} = 1/480; t = 1.73 \times 10^{-3} \) radiation length.

At depths \( t \) greater than \( 1.73 \times 10^{-3} \) radiation length the probability that the scattered electron be in the cone of acceptance is \( \Theta_0^2/\langle \Theta \rangle^2 = \Theta_0^2/(2.5t \times 10^{-3}) \). Then for an electron created in \( dt \) at a depth \( T \) in the absorber, the probability for the process occurring is the product of the independent probabilities for production and scattering. Let the absorber length be \( L \). Then, the probability \( P \) for scattering a 300 Mev photon into the geometry is:
\[ P = 10^{-4} \left( \int_0^L \frac{1.73 \times 10^{-3}}{2.5 \times 10^{-3}} \frac{dt}{t} \right) \]

or

\[ P \approx 10^{-7} \left( 3.5 + 1.8 \ln \frac{10^3 L}{1.73} \right) \]

In the case of lead, 3.3 radiation lengths of absorber were used. This gives \( P = 1.6 \times 10^{-5} \). For beryllium, \( P \) will be smaller by a factor of four since \( L < 1 \) for this case.

**E. Triplet Correction**

No correction was made for triplet loss due to the third member having large energy in the laboratory system. Watson gives only qualitative conclusions, but he points out that for \( k_0 > 5 \text{ Mev} \) the positron and one electron have high energies compared to the second electron. These two high energy triplet members recoil forward with angles of the order \( \frac{mc^2}{k_0} \). The energy of the slow member is distributed about \( mc^2 \) for energies up to 30 Mev, and tends to zero with increasing photon energy \( k_0 \). It seems justified to assume all 300 Mev triplets look like 300 Mev pairs to the spectrometer.

**F. Impurities in Beryllium**

The most important correction in the experiment is for impurities in the beryllium absorber. The observed attenuation cross section \( \phi_A \) varies as

\[ \phi_A \left( 1 + \frac{2}{\phi_A^0} \sum_i \phi_A^i \frac{c_i}{A_i} \right) \]

where \( c_i \) is the fractional concentration by weight and the sum is taken over all impurity elements. Iron is the chief contaminant of the smaller beryllium absorber which comprises 30 percent of the total absorber stack. The second beryllium absorber (70 percent) and the beryllium converters used in the pair ratio measurement are free of contaminants to better than one part
in $10^4$ by weight. These analyses were made by Conway and Tuttle of the spectrochemical laboratory.

G. Accidentals

Accidental counts were observed by delaying one coincidence input by $1.6 \times 10^{-3}$ seconds. The accidentals rate was less than one part in $10^3$ at the highest counting rate available. This background was taken for the highest counting rate and an appropriate fraction of this value subtracted from the smaller counting rates.

IX. RESULTS AND CONCLUSIONS

The total cross section for attenuation of 300 Mev photons by non-pair forming processes was found to be $(0.149 \pm 0.023) \times 10^{-25}$ cm$^2$/Be atom. The Klein-Nishina formula for this energy gives $0.127 \times 10^{-25}$ cm$^2$/Be atom. The two values are in disagreement by 18 percent of the theoretical value.

Table 2 indicates that photon attenuation from star production and from meson production might account for the discrepancy.

The total absorption cross sections in beryllium and lead were found to be $(1.587 \pm 0.0063) \times 10^{-25}$ cm$^2$/Be atom and $(37.14 \pm 0.26) \times 10^{-24}$ cm$^2$/Be atom respectively.

The pair forming cross sections include only the cross sections for 1. nuclear pair production and 2. pair production in the field of the electron (triplet). The ratio of the sum of these cross sections for beryllium to that for lead was found to be $(3.90 \pm 0.066) \times 10^{-3}$.

The probable error obtained for the total non-pair cross section is 15 percent. This large error allows one to say only that the Klein-Nishina formula is correct to within 15 percent at 300 Mev. Implicit in this result is the essential validity of the Dirac electron theory at these energies.
The largest contributor to the statistical error is the ratio of pair forming cross sections, which is observed in a signal to background ratio of unity. By installing a vacuum system, as outlined in Section VI, the background should be virtually eliminated. This permits a decrease by a factor of five in the time required to obtain a given statistical error in the pair ratio. With the addition of another channel, a tenfold increase in the effective counting rate becomes possible through changes in the apparatus alone. Pursuing the experiment further appears to be a very feasible undertaking.

When the statistics are improved to 3 percent, one will be able to detect deviations from the Klein-Nishina formula of the order of 0.5 millibarn. If a real deviation exists, which cannot be explained theoretically, it is planned to determine the non-pair cross section as a function of $Z$ and of $k_0$ in an effort to sort out and study the responsible effects.
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XI. REFERENCES

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<table>
<thead>
<tr>
<th>Interaction</th>
<th>Total cross section cm$^2$ per 300 Mev photon</th>
<th>Error</th>
<th>$Z$ dependence</th>
<th>$k_0$ dependence for $k_0 \gg m_0 c^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Compton Effect</td>
<td>$1.266 \times 10^{-26}$</td>
<td>-</td>
<td>$Z$</td>
<td>$1/k_0$</td>
</tr>
<tr>
<td>B. Meson Production</td>
<td>$1.5 \times 10^{-27}$</td>
<td>factor 2</td>
<td>$A^{2/3}$</td>
<td>rising with $k_0$</td>
</tr>
<tr>
<td>C. Photonuclear Reactions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Photo Star Production</td>
<td>$7.3 \times 10^{-28}$</td>
<td>50 percent</td>
<td>$A$</td>
<td></td>
</tr>
<tr>
<td>2. Photo-Nucleon Reactions</td>
<td>$4.6 \times 10^{-33}$</td>
<td>factor 10</td>
<td>$A$</td>
<td>$k_0^{-7/2}$</td>
</tr>
<tr>
<td>D. Nuclear Photo Effect</td>
<td>$7 \times 10^{-29}$</td>
<td>factor 3</td>
<td>$Z$</td>
<td>$k_0^{-3/2}$</td>
</tr>
<tr>
<td>E. Photoelectric Effect</td>
<td>$6 \times 10^{-33}$</td>
<td>-</td>
<td>$Z^5$</td>
<td>$1/k_0$</td>
</tr>
<tr>
<td>F. Elastic Nuclear Scattering</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1. Thompson scattering from nucleus as a whole</td>
<td>$6.1 \times 10^{-31}$</td>
<td>-</td>
<td>$z^4/A^2$</td>
<td>constant</td>
</tr>
<tr>
<td>2. Nuclear resonance scattering</td>
<td>$1.4 \times 10^{-30}$</td>
<td>factor 10</td>
<td>decreasing with $Z$</td>
<td>$k_0^{-7/2}$</td>
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<tr>
<td>3. Rayleigh scattering from atomic electrons</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Delbruck scattering</td>
<td>$4 \times 10^{-33}$</td>
<td>factor 50</td>
<td>$Z$</td>
<td>decreasing with $k_0$</td>
</tr>
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</table>
XII. ILLUSTRATIONS

Fig. 1. The Klein-Nishina formula in differential form, giving the cross section per steradian for Compton scattering of 300 Mev photons through angle \( \theta \). The unit is the total Thompson cross section (per electron per photon).

Fig. 2. The ratio of scattered to incident photon energies versus the photon scattering angle for 300 Mev incident photons in the Compton effect.

Fig. 3. The ratio of total cross section for Compton scattering to the total Thompson cross section versus incident photon energy.

Fig. 4. Bremsstrahlung spectrum and pair spectrometer resolving power plotted in arbitrary units.

Fig. 5. Schematic arrangement of apparatus.

Fig. 6. Pair yield from beryllium converter versus converter thickness. The curve is a straight line drawn through the first few points.

Fig. 7. Pair yield from lead converter versus converter thickness. The curve is a straight line drawn through the first few points.

Fig. 8. Block diagram of electronics.

Fig. 9. Resolving time curve of bridge coincidence circuit using \( 2 \times 10^{-9} \) sec. input pulses from 300 Mev electron pairs. Counting rate in arbitrary units versus delay of either input pulse.

Fig. 10. Photon energy change in Compton scattering versus photon scattering angle.

Fig. 11. Detailed shape of pair spectrometer resolving curve shown with bremsstrahlung spectrum. See Fig. 4 also.
FIG. 1 MU3195

\[ \frac{\delta \phi}{\delta C} \text{ IN UNITS OF } \Phi_{\theta} = 0.658 \text{ BARNs} \]
BREMSTRAHLUNG DISTRIBUTION FROM SYNCHROTRON

A UNCORRECTED
CORRECTED FOR ABSORPTION, SCATTERING AND INTENSITY LOSS OF X-RAYS
CORRECTED FOR SPREAD OUT BEAM
MAX INTENSITY 1200μ sec BEFORE PEAK FIELD

FIG. 4

MU3198
MAGNET ROOM ELECTRONICS

COUNTING AREA ELECTRONICS

LINEAR AMP

DISCRIMINATOR

SCALER

SCALER

SCALER

SCALER

SCALER

25 V

35 V

45 V

55 V

65 V

75 V

FIG. 8

MU 3202
COUNTING RATE
IN ARBITRARY UNITS

INPUT 2 4 3 2 0 2 3 4

$10^9$ SEC DELAY

FIG. 9

MU 3203
FIG. 10