DEPARTMENT OF COMMERCE ★ BUREAU OF STANDARDS

NBS TECHNICAL NOTE 955

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Electromagnetic Interactions from 5 to 500 MeV and Nuclear Research—A Position Paper as of March 1977

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Issued August 1977

National Bureau of Standards Technical Note 955
Nat. Bur. Stand. (U.S.), Tech. Note 955, 51 pages (Aug. 1977)
CODEN: NBTNAE

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1977

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock No. 003-003-01816-3

CONTENTS

Abstract

We present the current status of both experimental measurements and theoretical expressions for cross sections for the majority of the electromagnetic processes that are intimately connected with nuclear research using electromagnetic probes, emphasizing in particular those theoretical papers which are both reliable and useful for an analysis of the experiments, and indicating those regions in which the theoretical calculations are inadequate. Serving as a structure for this presentation, four areas of experimental research have been chosen, and we discuss in reasonable detail the status of the latest experiments in these areas: Total photoabsorption cross section measurements, Elastic photon scattering and Delbrück scattering, Electron scattering and its corrections-radiative, recoil, dispersive and relativistic-,and the Bremsstrahlung spectrum tip. In addition, a guide to the more pertinent articles (experiment and theory) on the subject of virtual photons is presented.

Key Words: Bremsstrahlung spectrum tip; Delbrück scattering; electromagnetic interactions; electron scattering; radiative corrections; total photon absorption cross sections; virtual photon theory.

Electromagnetic Interactions from 5 to 500 MeV and Nuclear Research --

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Introduction

The use of electromagnetic probes, electron and photon beams in particular, as a tool in nuclear research has been widespread for the past few decades. Their great usefulness is generally spoken of as being due both to the smallness of the coupling constant, $\alpha \approx 1/137$, and to the fact that quantum electrodynamics is considered to provide a well-understood theoretical basis for calculating the electromagnetic processes that are associated with the use of these probes. While this view is not without substance, it has perhaps also been partially responsible for the relative paucity, during the last decade, of useful and pertinent calculations of those electromagnetic processes which enter unavoidably any experiment using electrons or photons to learn something about the nucleus. In contrast, the accuracy of experimental measurements has increased considerably during the past ten or fifteen years: Total photon absorption cross sections have been measured to a few tenths of a percent, absolute cross sections for electron scattering to better than one percent. The available theoretical expressions for the accompanying electromagnetic processes such as radiative corrections to electron scattering, or pair production, most of which were calculated at a time when no such accuracy was needed, are simply not adequate for an extraction of the nuclear cross sections at this level of precision. The objective of this report is, therefore, to present the current status of both experimental measurements and theoretical expressions for cross sections for the majority of the electromagnetic processes that are intimately connected with nuclear research using electromagnetic probes, emphasizing in particular those theoretical papers which are both reliable and useful for an analysis of the experiments, and indicating those regions in which the theoretical calculations are inadequate. Serving as a structure for this presentation, four areas of experimental research have been chosen, and we discuss in reasonable detail the status of the latest experiments in these areas: Total photoabsorption cross section measurements, Elastic photon scattering and Delbrück scattering, Electron scattering and its corrections-radiative, recoil, dispersive and relativistic- and the Bremsstrahlung spectrum tip. A fifth, closely allied, subject might have been discussed: In the context of this paper the importance of the bremsstrahlung tip is that it has been the main source of (real) photons for nuclear research for over twenty years. On the other hand, there are a significant number of experiments on electrodisintegration of nuclei and electroproduction of pions. Here the electron beam serves as the source of photons (virtual). In addition, a number of electrodisintegration experiments have been performed using positron beams. It is then of interest to relate the cross sections for electron induced reactions to those for photoreactions, this forming the subject of virtual photon theory. It is our opinion that this subject is of sufficient importance that it warrants a more complete review than is currently to be found in the literature, and one that would require more original material than is presented here. We have therefore restricted the scope of the last section;

it is merely intended to be a guide to what we consider to be the more pertinent articles on this subject.

We have thus aspired to present a survey, both of the latest experiments that will be of help to the theoretician and of the most recent or most useful calculations that will serve the experimenter. In contrast to the style of review that lists every existent publication on the subject, a conscious, subjective, choice has been made in the references listed, with the aim of presenting the current "state of the art" in theory and experiment. Thus, for example, direct reference to calculations or measurements which have been superseded by later research has been generally omitted, particularly if the more recent papers include an historical review.

Although the primary objective in each of the experiments was to obtain nuclear information, that was not always the sole or even the most important information that resulted, given the intertwining of electromagnetic and nuclear processes. For example, in the case of the total photoabsorption measurements, while the electromagnetic processes are generally thought of as an unwanted background to the sought after nuclear absorption, these experiments in fact constitute, over much of the energy region, (in which the electromagnetic "background" is more than 95% of the total cross section), a very accurate measurement of the various electromagnetic cross sections: pair production, Compton, triplet, and photoelectric. In the case of elastic scattering of photons, particularly in the experiments in the energy range 8-11 MeV, while one wants to obtain the nuclear scattering amplitudes, the contribution to the differential cross section at 90° may, for the appropriate nucleus and energy, come more or less equally from nuclear scattering and

Delbrück scattering. In view of the fact that only in the last two or three years have there appeared some clear experimental measurements of Delbrück scattering and a correct theoretical calculation for comparison, one might well consider the electromagnetic process to be the more interesting one in this case.

The conclusion to which we are lead at the end of this presentation is that for each of the electromagnetic processes involved, the energy region 10 - 100 MeV, of primary concern to nuclear physics, is lacking, certainly in accurate and reliable theoretical calculations and often in experimental data.

1. Total photoabsorption cross section measurements.

One of the clearest examples of the difficulty of extracting nuclear cross sections from the concomitant electromagnetic processes occurs in connection with measurements of the total cross section for the absorption of photons. Of particular interest for nuclear research is the photonuclear cross section, but to obtain this from the total cross section one must subtract the numerous cross sections for atomic (electromagnetic) processes, and these contribute at least 95% of the total, even in the region of the giant dipole resonance, where the photonuclear cross section has its greatest value. This implies that the atomic cross sections must be known very accurately if one is to derive any meaningful information on the photonuclear cross section. The most precise measurements of the total absorption cross section for photons are those of Ziegler, Ahrens and coworkers [1] at the Max-Planck Institute in Mainz, in the energy range 10 - 160 MeV, in elements ranging from lithium to lead, an effort that goes back over 15 years [2]. The situation is well illustrated by the figure below (taken from fig. 2, p. 361 of the article of Ahrens et al [3]) showing the energy dependence of the partial atomic cross sections and the total cross section in H_2O as a function of photon energy.

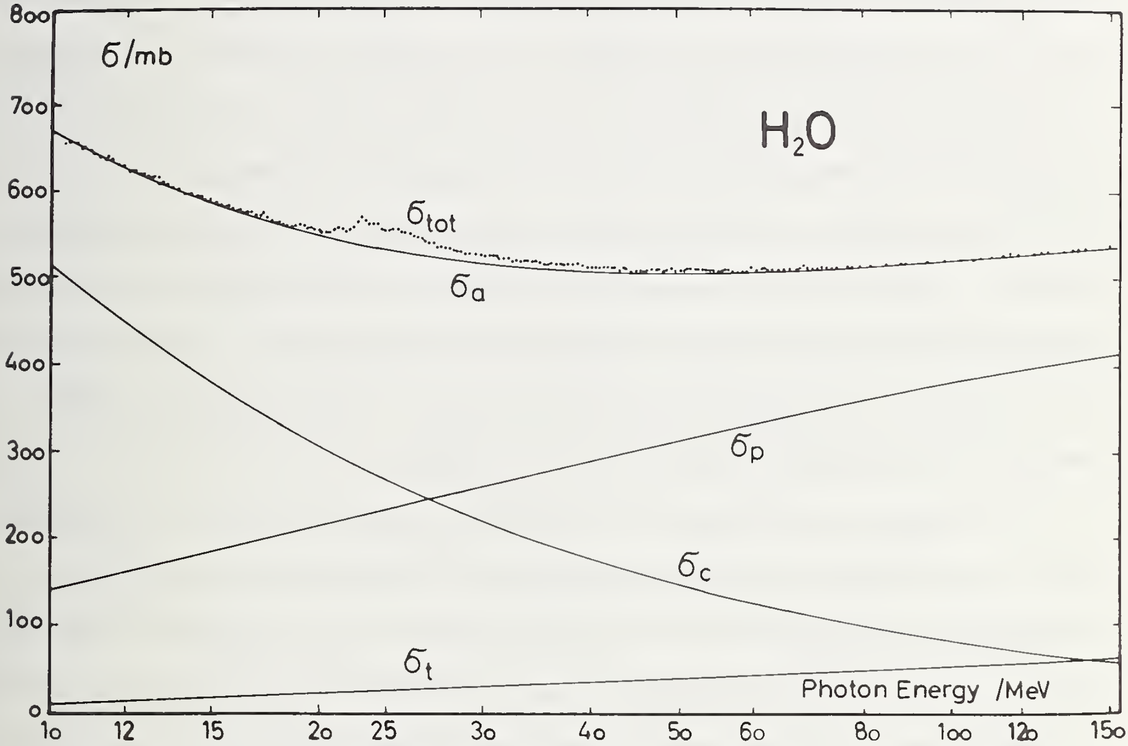


Figure 2: Energy dependence of the partial atomic cross-sections and σ_{tot} in H_2O.

The atomic cross section is a sum of the partial cross-sections:

$$\sigma_a = \sigma_\tau + \sigma_c + \sigma_p + \sigma_t \quad ,$$

where the subscripts τ, c, p and t denote the absorption due to photo-electric, Compton, pair-production (in the field of a nucleus) and triplet (pair-production in the field of an electron) processes respectively. (The photoelectric cross section in H_2O in this energy region is negligible and is not shown in the figure.) In their most recently published work [1] the authors estimate the error in the sum of all non-nuclear cross sections to be smaller than 0.1% for elements with $Z \leq 20$ in the energy range 10 - 160 MeV. While this is probably the accuracy that is needed in the atomic cross sections in order to obtain useful photonuclear cross sections, it is not evident that such accuracy is in fact currently available - even using their combination of empirical and theoretical corrections - for example in obtaining the Coulomb corrections to the pair production cross section. To be sure, their calculations of the various atomic cross sections have been refined over the past five years, as may be seen from their various interim reports (compare for example, [1] and [3]), and significant refinements of the procedure used in [1] have been made subsequent to the publication of that paper.* Nonetheless, the lack of sufficient accuracy in our knowledge of the electromagnetic cross sections in the region of 10 - 100 MeV is clear.

For example, in the case of pair production in the field of the nucleus, there are uncertainties in both the screening correction and the Coulomb correction. With regard to the Coulomb correction, this is given for photon energies below 5 MeV by the very fine work of Øverbø [4] (who does not consider screening) and for photon energies above approximately 100 MeV by the work of Davies, Bethe and Maximon [5]. However, there exists no theoretical treatment of the Coulomb correction to the total pair production cross section in the intermediate region between 5 and 100 MeV. Given this lack of theoretical knowledge, the Mainz group has determined the Coulomb correction experimentally by attenuation measurements in high-Z elements (Cu, Sn, Ta, Pb), assuming that the nuclear cross section for these elements is either known (from (γ,n) experiments [6]) or negligible (above 50 MeV). But they recognize that "the lack of reliable theoretical calculations for the Coulomb correction between 10 and 50 MeV certainly restricts the range in Z available for absolute

*private communication

$\sigma_{\gamma,T}$ measurements to $Z \leqq 20$." With regard to the screening correction, it too presents problems, given the accuracy required in these experiments. Although the latest analysis of the Mainz group* has made use of the more accurate (and older) expression of Jost, Luttinger and Slotnick [7] for the total Born approximation cross section for pair production with screening in place of the high energy expression of Sørenssen [8] used in their latest published work [1], there remain at least two problems. The first is the question of just what form factor should be inserted in these expressions which have the form of a weighted integral over the square of the atomic form factor, or, more exactly of $(1-F(q))^2$. The Mainz group* has done the analysis using several different form factors, each purporting to be the result of a highly accurate, relativistic, self-consistent Hartee-Fock calculation. Nonetheless, some of the form factors do not give results consistent with the total absorption measurements. Indeed, as has been recognized, for high-Z elements, for which the uncertainties in the theoretical expressions for the screening and Coulomb corrections to the pair production cross section constitute the largest uncertainty in the determination of the nuclear cross section from the measured total photon absorption cross section, the measurements of the Mainz group, particularly those above 50 MeV, constitute more truly an accurate determination of the atomic form factor than a measurement of the photonuclear cross section. In addition to the lack of sufficiently accurate atomic form factors, there is an additional uncertainty not dealt with in their analysis. There, as is generally done, the screening and Coulomb corrections are added independently to the unscreened Born approximation (Bethe-Heitler) cross section. The justification for this procedure at high energies was given by Davies, Bethe and Maximon [5]. It is quite probably a reasonable approximation in the intermediate (10 - 100 MeV) region, where the screening correction itself becomes less important with decreasing energy. However, it is far from clear that this separation is valid to a level of 0.1% -- such accuracy was never claimed in any of the theoretical works.

*private communication

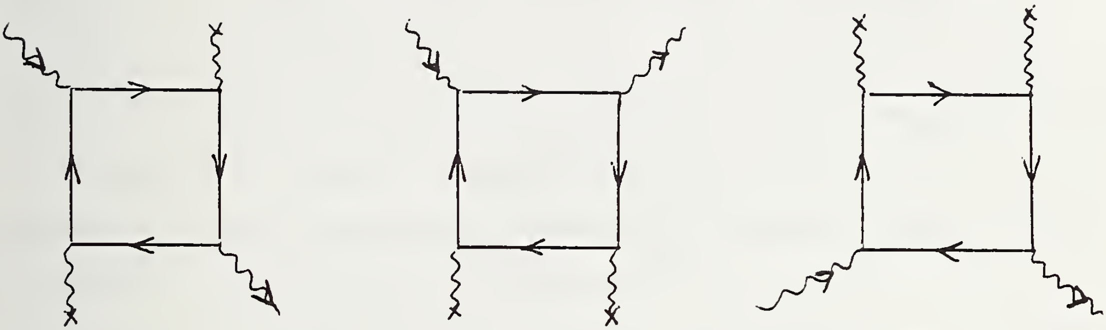
In the case of triplet production I do not know of any treatment of the effects of screening and atomic binding with the accuracy required in these total absorption experiments. Although refinements subsequent to [1] include a screening correction using very recent tabulated incoherent scattering functions [9], the basic unscreened cross section used [10] is that of Borsellino and Ghizzetti [11], which has errors of approximately 1.2%, as has been shown in the most recent and comprehensive theoretical treatment of bremsstrahlung and pair production in the field of a free electron, by E. Haug [12]. The most recent experimental determination of the triplet cross section is that of J. Augerat *et al.* [13], who also gives reference to earlier experiments

In summary, at energies above, say, 100 MeV, there exist high energy theoretical expressions for the electromagnetic cross sections. For energies below 10 MeV, roughly, exact numerical calculations are feasible. In the region 10 - 100 MeV only the Born approximation cross section is available without further (high-energy) approximation, -- and in the case of triplet production, even this only as recently as last year.

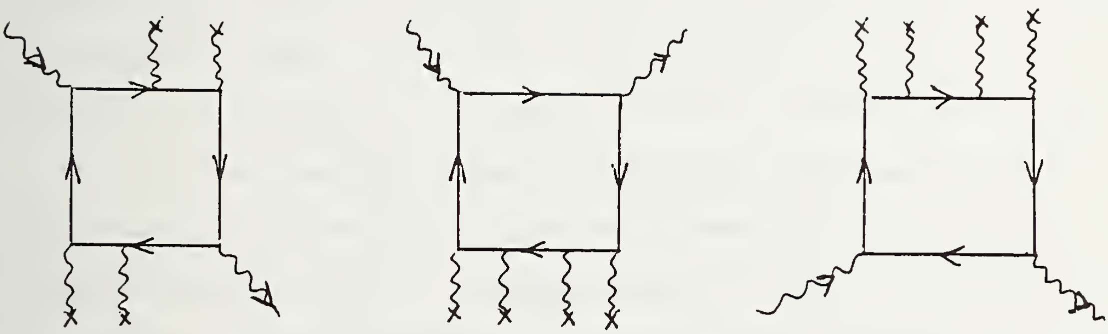
2. Elastic photon scattering and Delbrück scattering.

The scattering of light in the field of a potential, known as Delbrück scattering, is an essentially quantum electrodynamical process: An incident photon creates a virtual electron-positron pair which scatter in the potential field and then annihilate, creating a photon having (apart from the kinetic energy of the recoiling nucleus, neglected in all theoretical calculations) the same energy as the incident photon, but an arbitrary direction, the cross section being peaked strongly in the forward direction. The explanation for this process was first proposed by Delbrück in 1933, but it is only within the last two or three years that there have appeared both a correct theoretical evaluation of the experimentally measureable cross section and measurements having an accuracy sufficient to make a significant comparison with the theoretical calculations.

The lowest order ("Born approximation") Feynman diagrams for Delbrück scattering are



Examples of the higher order ("Coulomb corrections") diagrams are

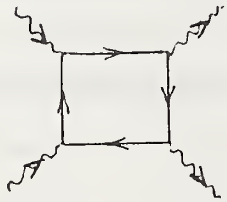


It is to be noted that they all have an even number of interactions with the potential -- a fact known as Furry's Theorem. The cross section for this process is thus of order

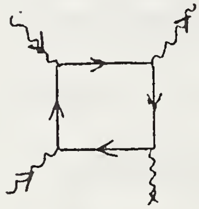
$$\left[Z^2 \left(\frac{e}{\sqrt{\hbar c}}\right)^6 \frac{\hbar}{mc}\right]^2 = (Z\alpha)^4 \; r_o^2$$

where $r_o = \frac{e^2}{mc^2}$ is the classical electron radius. From these diagrams it is clear that Delbrück scattering is closely related to other processes for which the initial and final states consist only of photons:

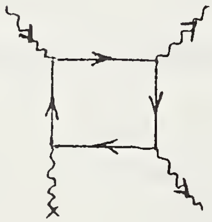
Photon-photon scattering:



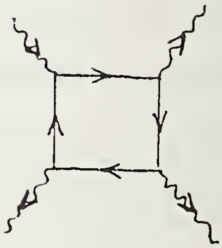
Photon coalescence:



Photon splitting:



and



(For a survey of theory and experiment for photon splitting, see [22].)

Attempts to measure Delbrück scattering prior to 1969 were largely unsuccessful. (The reasons for this, as well as a review of earlier experiments, are given quite clearly in the Introduction (pp. 1153-1154) of the article by Jackson, Thomas and Wetzel [14a] and in the survey of Papatzacos and Mork [15] (see pp. 109-116) who also give a fine review of the various theoretical calculations.) Recent experiments which provide an evaluation of the Delbrück scattering cross section all consist of measurements of the differential cross section for the elastic scattering of monochromatic photons from high-Z targets (necessitated by the fact that the lowest order cross section is proportional to $(\alpha Z)^4$). They have been performed at a number of energies and at various laboratories. The separation of the Delbrück cross section from these measurements is always complicated by the presence of the other coherent electromagnetic and nuclear scattering amplitudes: Thomson, Rayleigh and nuclear resonance scattering. Use is made, however, of the different energy and angular dependences of these processes, so that for a judicious choice one or another of them may dominate.

For the determination of the Delbrück scattering cross section, the experiments of principal interest are the following: At 1.33 MeV there are measurements by three different groups: Basavaraju and Kane [16], Hardie, DeVries and Chiang [17], and Schumacher, Smend and Borchert [18].

Using 2.754 MeV photons scattered by Pb, the group at Gottingen (Schumacher, Borchert, Smend and Rullhusen [19]) have measured the differential cross section at angles between 15^o and 150^o.

The group at the Nuclear Research Center at Beer-Sheva (Moreh, Kahane and Bar-Noy [20]) has performed elastic scattering experiments using monochromatic photons obtained from thermal neutron capture in the energy range 7.9 - 11.4 MeV with a number of targets (^{159}Tb, ^{165}Ho, ^{175}Lu, ^{181}Ta, ^{232}Th, ^{237}Np, ^{238}U). At these and higher energies, the Rayleigh scattering amplitude is negligible.

Next, Jackson, Thomas and Wetzel [14a] at Argonne have measured differential cross sections for 10.83 MeV photons scattered from Pb and ^{238}U at angles between 20^o and 150^o, [14a], and for 11.4 MeV photons scattered from ^{141}Pr, ^{159}Tb, ^{165}Ho, ^{181}Ta, ^{232}Th and ^{238}U at 90^o and 150^o, [14b].

The measurements between 2.75 and 11.4 MeV have been of particular interest in connection with a determination of the real part of the Delbrück amplitude, the real and imaginary parts being of the same order of magnitude in this energy range. At higher energies (> 100 MeV) the contribution of the real part to the total cross section is negligible, while at lower energies (e.g., at 1.33 MeV), where the real part is much larger than the imaginary, the entire contribution of the Delbrück amplitude to the elastic scattering cross section is negligible, being an order of magnitude less than the Rayleigh amplitude.

At energies above the 10 MeV region there are at present only two sets of significant measurements:

1. That of Moffat and Stringfellow [21] (1960) in which photons of 87 MeV were scattered from a variety of targets $(13 \leqq Z \leqq 92)$.
2. That of Jarlskog et al. at DESY [22] (1973) using photons of energies from 1 to 7.3 GeV scattered from Cu, Ag, Au and U.

Now what is the current status of theoretical calculations and how do theory and experiment compare? There are at present only two sources of calculations of the cross section for Delbrück scattering that are both reliable and present numerical or analytical results which are useful for the analysis of experiments, -- the Born approximation calculation of Papatzacos and Mork (PM) [15,23,24], who give as well a fine review of earlier work, and the high energy approximation calculation of Cheng and Wu (CW) [25,26]. This is but a slight exaggeration. There is an earlier, correct, calculation of the Delbrück cross section in Born approximation by Constantini, De Tollis and Pistoni [27a]. Although they give no numerical or analytic results (other than the low energy limit of the Delbrück amplitude) a recent revision of that work by De Tollis, Lusignoli and Pistoni [27b] does give numerical values for one of the amplitudes for circularly polarized photons at one energy (10.83 MeV) and finds agreement in this case with the results of PM. Further, the most accurate numerical calculations of the Delbrück amplitudes currently available are those given by Bar-Noy and Kahane [28] in a computer program based on Constantini et al. [27a] for the imaginary part of the Delbrück amplitude and on PM [15,23,24] for the real part.

The cross section given by PM is calculated to lowest (non-vanishing) order in the Coulomb interaction -- "Born approximation" -- and the final result is in the form of four-fold integrals which are performed numerically.

The expression is valid at all energies. On the other hand, the cross section given by CW is valid only for very high energies, but includes the Coulomb interaction to all orders -- "cross section with Coulomb correction." Their final result is in the form of a five-fold integral which in general is to be evaluated numerically. However, for photon energies, ω, and momentum transfers, Δ, satisfying $\Delta \ll m \ll \omega$, (i.e., scattering close to the forward direction) or satisfying $m \ll \Delta \ll \omega$, they have given relatively simple analytic expressions -- for the former case* in [25] and for the latter case (which is the one required for comparison with the high energy experiments [22]) in [26].

Concerning the high energy limit of the amplitude (including the Coulomb correction) note should be made of the paper by W. Czyż [29], who arrives at the same expression for the amplitude as do CW, but uses an approach which brings out more clearly the basic physics of the high-energy limit.

Before comparing the theoretical calculations with experiment, it would be well to compare each of them with the other. As just stated, the cross section given by PM is good at all energies but neglects Coulomb corrections. The cross section of CW includes Coulomb corrections but is good only at high energies. This is analogous to the situation for pair production in the field of a nucleus, where the Born approximation, given by Bethe and Heitler [30], is good at all energies but neglects Coulomb corrections, while the cross section of Bethe and Maximon# [31] includes Coulomb corrections but is good only at high energies.

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*An error in sign in eq (7.7) of CW [25], p. 2453 is corrected in the footnote on p. 103 of PM [15].

#Actually the analysis of CW is closer to the derivation of the pair production cross section given by Olsen, Maximon and Wergeland [32a]. See also, T. Jaroszewicz and J. Wosiek [32b].

There are thus two questions which come immediately to mind:

1) How large are the Coulomb corrections; i.e., what is the accuracy of the Born approximation value given by PM.

2) How rapidly does the amplitude for Delbrück scattering approach the asymptotic value given by CW with increasing energy; i.e., for a given energy, what is the accuracy of the high energy limit given by CW.

The answer to each of these questions depends very strongly on the momentum transfer, Δ (or, alternatively, on the scattering angle, θ). In the case of identically forward scattering $(\Delta = \theta = 0)$ one can make a relatively clear statement. This should not be surprising: From the optical theorem, the imaginary part of the forward amplitude for Delbrück scattering is (neglecting corrections of higher order in α) proportional to the total cross section for pair production [33], and the real part of that forward amplitude is related to the total pair production cross section by a dispersion integral [34], and is (at least in Born approximation) smaller than the imaginary part for $\omega > 10$ MeV [35]. It should not, therefore, be surprising that the forward scattering amplitude has, as in pair production [36], Coulomb corrections of the order of 10% above 10 MeV. Indeed, the Coulomb correction for high energy forward scattering given by CW [37] is precisely that given earlier for pair production by Davies, Bethe and Maximon [38]. Similarly, the approach of the forward scattering amplitude towards its asymptotic expression is the same as for pair production [39], namely, errors in the high energy expression [40] are (with ω in units of the electron rest energy) of relative order $\ell n^2\omega/\omega^2$ -- and this is true both for the real and imaginary parts of the amplitude. The rapid approach to the asymptotic value for $\omega > 40$ MeV shown earlier for pair production [41] is noted again for the forward Delbrück scattering amplitude [42].

Thus the qualitative, and, to a great extent, the quantitative features of the Delbrück scattering amplitude in the forward direction, can be understood from the total pair production cross section. Unfortunately, from the experimental point of view it is of very little interest -- and once one gets away from the forward direction $(\Delta \gtrsim m)$ the situation changes drastically. For example, at photon scattering angles of interest in connection with the experiments of Jarlskog et al. at DESY [22] in the energy range 1 - 7 GeV, the Coulomb "corrections" reduce the cross section by a factor of 10, as contrasted with a correction of order 10% in the forward direction (CW, [26] p. 3084 Fig. 5 and Jarlskog et al., [22] pp. 3820, 3821 Figs. 8 and 9). Although the agreement of the Born approximation calculation of PM with experiment (Jackson et al., [14]) at 10.83 MeV (PM, [24] p. 216, Fig. 6) would seem to indicate that the Coulomb corrections are small at that energy, there exists no theoretical calculation which provides an estimate of the Coulomb corrections, at either lower energies (of, say, a few MeV) or in the region 10 MeV to several hundred MeV. As we have mentioned, this latter region is almost equally devoid of experimental data. Nevertheless, despite the striking difference between the Coulomb correction to the forward scattering amplitude and the Coulomb correction to the amplitude for non-zero scattering angle $(\Delta \gtrsim m)$, the latter may also be understood qualitatively in terms of the cross section for pair production. Consider, for example, the amplitudes for Delbrück scattering in the high energy limit: For very small scattering angles, those for which $\frac{\Delta}{m} \gtrsim O(\frac{m}{\omega})$, the main contribution to the amplitude comes from momentum transfers to the nucleus (from one or the other of the intermediate state pair particles) of order $\frac{m}{\omega}$ and of order m, as in the case of the total cross section for pair production at high energy. The

Coulomb correction to the Delbrück amplitude is then identical with that of the total pair production cross section, and this is the result found by CW [25]. On the other hand, if $m \ll \Delta \ll \omega$, then the main contribution to the Delbrück amplitude comes from momentum transfers of order Δ to the nucleus from one of the particles of the virtual pair in the intermediate state. The Delbrück amplitude is, in this case, a convolution of two pair production amplitudes, one of which is associated with a momentum transfer of order $\Delta \gg m$, (the other being or order $\lesssim m$), and consequently has a large Coulomb correction, which is again the result found by CW [26].

With regard to the approach with increasing energy to the asymptotic expression of CW, the region 10 - 200 MeV is poorly understood. The rather rapid convergence to the asymptotic limit just mentioned in connection with forward scattering no longer exists for non-forward scattering. In fact, the difference between the values calculated by PM and those given by CW are shown by PM ([24], p. 214, Table IX and p. 215 Table X) to diverge slowly, albeit less rapidly than $O(\omega/m)$, for a momentum transfer $\Delta = m(m/\omega)^{1/2}$. Moreover, this discrepancy between the two theoretical calculations is not changed significantly by including the correction terms given by CW [43], p. 1885, Eqs. (4.12), (4.13)). Their correction terms, being less than $0.1 \cdot (\Delta/m)^2$ relative to the main term, are far too small to account for the difference between the values of PM and those of CW. An examination of this apparent disagreement will be given in a later note. In any event, the theoretical calculations do not at present provide a clear answer to either of the two questions posed earlier for the situation of experimental interest (non-forward scattering). In particular, the theory is particularly lacking in providing an estimate of the Coulomb corrections in the region 10 - 200 MeV.

Now let us look at the comparison between theory and experiment. For those in the energy range 1.33 - 11.4 MeV, the only reliable calculations are those of PM, and their analysis of these experiments should be consulted. The only experiment that has appeared after that analysis is that of Schumacher *et al.* [19] at 2.754 MeV. In the case of each of the three different experiments at 1.33 MeV, the interference with Thomson and Rayleigh scattering is very strong at this energy, and the theoretical knowledge of the Rayleigh scattering available when the analysis was done was not such as to permit a significant extraction of the Delbrück scattering cross section. In the analysis by Schumacher et al of their experiment at 2.754 MeV, use was made of two very recent theoretical studies of Rayleigh scattering:

a) W. R. Johnson and K.-t. Cheng [44]

b) V. Florescu and M. Gavrila [45]

The agreement between theory (using PM) and experiment is good at 15°, 120° and 150°, but shows a discrepancy of up to a factor 1.7 at intermediate angles.

The experiments of Bar-Noy, Kahane and Moreh in the energy range 7.9 - 11.4 MeV were analyzed by PM. (It should be noted that the analysis of PM differs, in some cases, from that given in the original experimental papers, some of which used older, incorrect, theoretical calculations.) They find good agreement between theory and experiment for ^{181}Ta, but for Th and U the experimental values are consistently below the theoretical ones for scattering angles smaller than 90°.

In their analysis of the data of Jackson, Thomas and Wetzel at 10.83 MeV, PM [24] find rather good agreement between their theory and the experiment. The two exceptions to this are the bump in the experimental cross sections for Pb at 50° - 60°, and that for U the theory seems to give values which are too low for large angles.

In the energy region between 11.4 MeV and 986 MeV there is only one significant measurement -- that of Moffat and Stringfellow at 87 MeV [21]. Their experimental data were compared with both the PM calculation ([26] p. 216, Table XI) and that of CW ([43], p. 1886, Fig. 4 and [22], p. 3821, Fig. 9(a)). Unfortunately, neither the accuracy of the theoretical calculations nor that of the experiment is such that a significant statement, other than that of "general agreement", is possible.

Finally, the experimental measurements of Jarlskog et al. of the scattering of photons of energies between 1 GeV and 7.3 GeV on U and Au nuclei show good agreement with the calculations of CW for momentum transfers between 1 and 10 MeV, but are somewhat larger than the theoretical values for momentum transfers between 10 and 20 MeV.

Again, as in the case of the closely related process of pair production, it is the energy region 10 - 100 MeV in which there is the greatest uncertainty in the theoretical calculations, and for which there are practically no experimental data of sufficient accuracy.

3. Electron scattering and its corrections - radiative, recoil, dispersion and relativistic.

High energy electron scattering and the various corrections that must be applied (radiative, recoil, dispersion and relativistic) provide another case of a quantum electrodynamic process for which the increase in the accuracy of the experiments in the past decade has far exceeded that due to advances in theoretical calculations. A striking example of this is provided by a number of recent experiments [46,47,48,49] in which electrons in the energy range 50-250 MeV were scattered inelastically from various high-Z targets (^{208}Pb, ^{197}Au, ^{181}Ta, ^{150}Nd, ^{142}Nd, ^{141}Pr, Ce, and ^{139}La) in order to investigate giant multipole resonances other than dipole. However, to obtain the nuclear cross sections associated with these broad resonances, background radiation including the radiative tail must be subtracted. The situation is quite analogous to that described in connection with total photoabsorption measurements and depicted there. Once again, a relatively large electromagnetic background must be subtracted in order to get out nuclear data, as may be seen in the figures below.

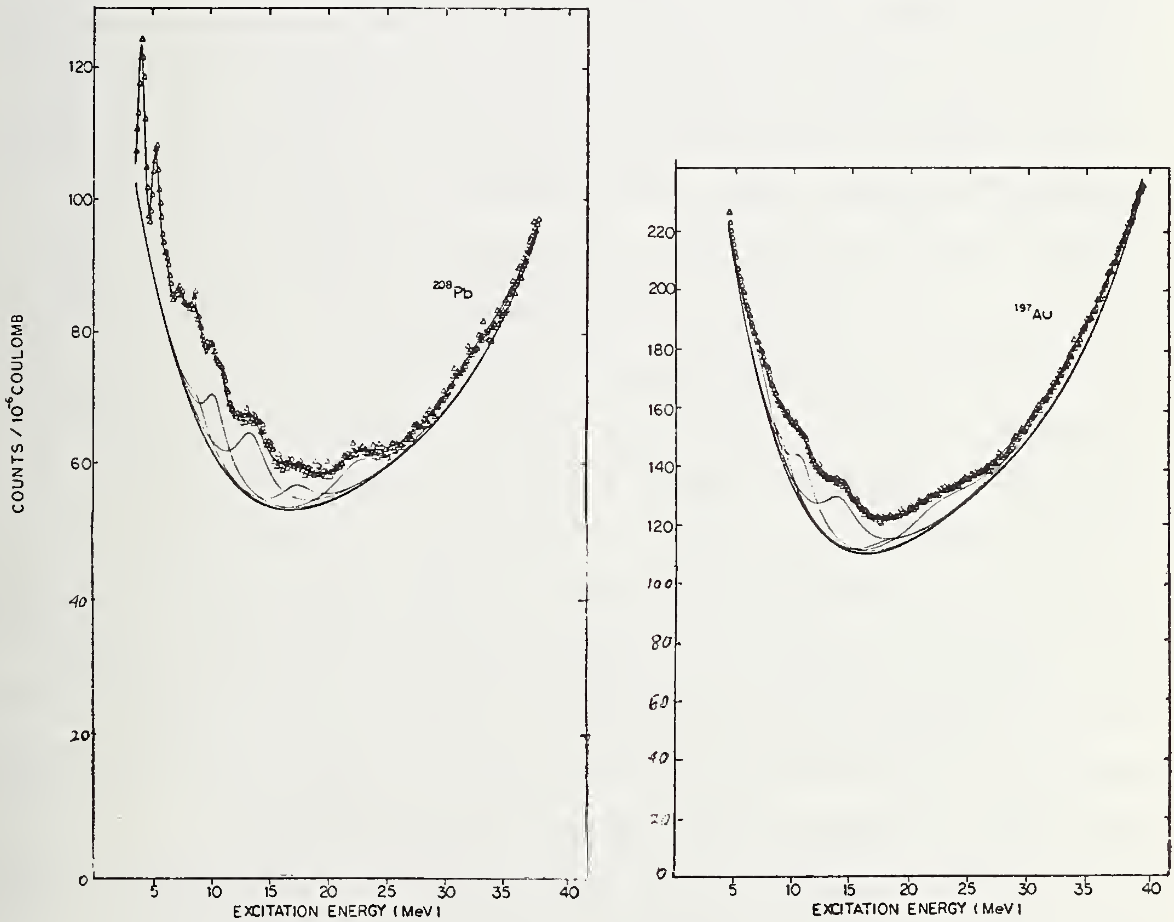

FIG. 1. Spectrum of 90-MeV electrons, scattered inelastically from Pb and Au. The fitted background which consists of the radiation tail and the machine background is shown. The counting rate is corrected for the constant momentum dispersion of the spectrometer. Thus the error increases with the excitation energy.

In the present inelastic electron scattering experiments, background subtraction is important in deducing the multipolarity and strength of the giant resonances. However, the only existing theoretical expressions for the radiative tail [50] have all been calculated in first Born approximation, valid for low-Z targets, but off by as much as a factor of two for heavy elements. The procedure that has been used generally [46,47,48] to calculate the radiative tail of the elastic peak in the case of high-Z elements is rather ad hoc: Starting with the Born approximation expression for bremsstrahlung (in some analyses [48,49] using in addition the peaking approximation), the form factor (which is correct in first Born approximation) is replaced by a pseudo form factor, defined as the cross section in the absence of radiation (obtained, for example, from a DWBA calculation) divided by the Mott cross section. While this procedure may be reasonable very near the elastic peak, its validity in the region of the giant resonances is open to question and has not been investigated. To this uncertainty in the radiative tail there is compounded the complication of other sources of background, such as instrumental scattering and quasi-elastic processes. In some of the analyses [46,47,49] this requires the addition of an empirical background term, which may be a function of the electron energy, in order to match "theory" with experiment. Given that the nuclear cross sections obtained after subtracting the radiation background often have errors of the order of 50%, an accurate calculation of the radiative tail for some high-Z elements would certainly be very useful as a guideline in the analysis of these experiments.

Other recent examples of the increase in accuracy of experiments exceeding advances in theoretical calculations are provided by the subject of elastic electron scattering. In an experiment carried out recently at the Saclay linac [51], electrons of 502 MeV were scattered elastically from ^{208}Pb, and the differential cross section was measured as a function of momentum transfer,

q, between 1.7 fm^{-1} and 3.7 fm^{-1}, the results showing excellent agreement in the region of overlap with the data from Stanford (which covered 0.5 fm^{-1} $< q <$ 2.7 fm^{-1}). In the analysis of this experiment, the expressions which were used for the radiative correction (essentially the Schwinger correction, exponentiated as in [52], p. 201), neglected terms of order $\alpha(\alpha Z) \ln q^2$ relative to the cross section itself.* These terms, which come from radiative corrections (due to hard virtual photons) to second Born approximation elastic scattering, may be of the order of a few percent for a lead target, energies of a few hundred MeV, and large scattering angles, and this may easily be as large or larger than the present experimental errors. Specific mention of these terms was made almost a decade ago ([52], p. 202) but to my knowledge they have still not been calculated. It would clearly be desirable to be able to calculate terms of this form, and indeed, all terms of the form $\alpha(\alpha Z)^n \ln q^2$ $(n = 1, 2, \ldots)$ for the case of high-Z targets. Unlike the term in the radiative correction associated with soft real photons, of the form $\alpha \ln(E/\Delta E) (\ln q^2 - 1)$, one cannot simply assume that terms of the form $\alpha(\alpha Z)^n \ln q^2$ should also be exponentiated. Their calculation would thus seem to be extremely difficult. However, it is not inconceivable that one could develop a procedure by which the high energy limit of the matrix element is considered before performing any of the integrations, and the terms with a factor $\ln q^2$ are extracted early in the calculation, thus eliminating the necessity of calculating the cross section for arbitrary energies (a truly formidable task, once one goes beyond the Schwinger correction) and then taking the high energy limit. With such a procedure, the neglected terms would be of order $\alpha(\alpha Z)$, which is less than ½%, even for $Z = 92$.

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*Here, and in similar expressions, q is in units of mc.

A detailed analysis of the errors involved in the determination of the nuclear charge distribution from a finite number of elastic electron scattering cross section measurements, applied in particular to ^{12}C and to ^{208}Pb, has been reviewed by Friar and Negele [53]. The aim of their paper is broader than the corrections we are discussing here. It is concerned rather with the larger question of what one actually learns about the nucleus from electron scattering and muonic x-ray experiments.

A second illustration of the advance in experimental accuracy over that of theoretical calculations is provided by the determination of the absolute cross section for the elastic scattering of electrons from ^{12}C in the energy region 25 to 115 MeV, in progress at the National Bureau of Standards during the past few years. The measurements cover the range of momentum transfers from 0.12 fm^{-1} to 1.0 fm^{-1}, have errors somewhat less than 1%, and are expected to resolve some of the inconsistencies between the earlier absolute cross section measurements on ^{12}C performed at Stanford, Mainz and Amsterdam. In particular, the NBS data seem to indicate that the terms in the radiative correction associated with soft real photons, viz.,

$$\delta_{real} = \frac{2\alpha}{\pi} \ln (E/\Delta E) [\ln q^2 - 1] \quad ,$$

should indeed be exponentiated. The proper radiative correction is then $e^{-\delta_{real}} (1 - \delta_{virtual})$ rather than $1 - \delta_{real} - \delta_{virtual}$, where $\delta_{virtual}$ includes both the contribution from virtual photons (the vertex correction) and the vacuum polarization. (See [52], pp. 200-202.)

Although the terms of the form $\alpha(\alpha Z) \ln q^2$ just discussed in connection with the radiative corrections to electron scattering from high-Z targets are unimportant for the measurements on ^{12}C, the modification of the radiative correction due to recoil must be included, at least to the extent that the kinematics is treated correctly, since this is needed to establish the energy from which the cut-off energy, ΔE, is measured. As has been noted elsewhere ([52], pp 202-203), the effects of recoil on the radiative correction may be categorized as kinematic and dynamic. The kinematic corrections involve precisely the same diagrams that enter when recoil is neglected, but take proper account of the kinematics due to recoil. The dynamic corrections involve additional diagrams in which the target nucleus may emit and reabsorb virtual photons or emit real photons. Although no existing calculation of either the radiative correction or the radiative tail treats the recoil corrections in a clear, unambiguous, manner, the kinematic recoil corrections to both the radiative correction and the radiative tail can certainly be done properly, and this alone would be worthwhile. A proper treatment of the dynamic recoil corrections is clearly much more difficult, particularly if one wishes to treat the emission and reabsorption of photons by a recoiling nucleus rather than, as is the case in most work on this subject, a proton. (The distinction between nucleus and proton implied here is that the nucleus is a composite system with structure that may be of relevance in the electron scattering experiment, whereas the proton may be treated as a elementary particle. Clearly for sufficiently high momentum transfers, the proton structure is also of significance, so that it too presents all the complications of a nucleus. And, at the other end of the scale, for sufficiently small momentum transfers, the inner structure of the nucleus may be ignored, so that it may be treated as a static charge distribution.) The difficulty inherent in the problem of dynamic recoil corrections is intimately related to the fact that they involve the exchange of at least two photons with the nucleus, introducing the possibility of nuclear excitation in the intermediate state. In contrast, in treating the kinematic corrections the main contribution comes from the exchange of one photon (first Born approximation), and even if the exchange of more than one photon is considered (as in an eikonal or DWBA approximation), the nucleus is treated as a static charge distribution: -- its internal structure is neglected.

The difficulties just mentioned in connection with the dynamic recoil corrections to the radiative correction form the subject of dispersion corrections. They constitute the largest source of uncertainty in the analysis of elastic electron scattering and are the least well understood of all the corrections, involving not merely the problem of the proper wave function for the electron, but the full complexity of the structure of the nucleus -- transition amplitudes and energy levels of the excited states as well as the correct treatment of the center of mass motion of the nucleus. In treating the intermediate excited states of the nucleus, all of the theoretical work done prior to 1970 has made either of two significant approximations. In the first, one considers the infinite, complete set of intermediate states of the nucleus, but neglects the variation of the excitation energy in the energy denominator (taking some "average" excitation energy, usually zero, -- the same one for all levels) and then uses closure to sum over intermediate states. The justification generally given for this approximation is that the energies of the important excited states are much less than the incident electron energy. In the second, almost antithetical approximation, it is assumed that one, or perhaps a very few, low-lying excited states are of importance. The energy of these particular states may be introduced explicitly, but transitions to all other states are neglected. The justification for this approximation is that these low-lying states have relatively large transition strengths. While one or the other of these approximations may be valid for particular regions of energy and momentum transfer, q, in fact neither is correct in general: Many excited states contribute to the dispersion correction, and the energy of each excited level must be taken into account. The reasons for this are, in part, the very significant cancellations which occur in the total dispersion correction. Thus, although for small q the contributions from successive excited levels are of the same sign (and are largest from the lowest level), in the case of moderate or large q the contributions from successive levels alternate in sign, and the largest contributions come from more highly excited states. A further source of cancellation comes from the correction for the center of mass motion of the nucleus. This contribution may be of almost equal magnitude, but of opposite sign to the other terms comprising the dispersion correction. It is therefore extremely important that the various contributions be calculated consistently, using a single model, and that center of mass effects be considered. These points have been shown most clearly in three short papers by de Forest, Friar and Rosen [54], who have calculated the dispersion corrections to elastic electron scattering from ^{12}C and ^{16}O. All of these calculations employ a number of approximations: Only the longitudinal (Coulomb) part of the electron-nucleus interaction (using the Coulomb gauge) is included -- the transverse parts are neglected. Only one- and two-photon exchanges with the nucleus are considered (thus limiting the validity of the cross section to light, low-Z, nuclei). And, most importantly, the harmonic oscillator shell model is used for the nucleus, which permits both an exact numerical calculation of the dispersion amplitudes and the inclusion of corrections due to the center of mass motion. Particularly to be noted is the fact that the dispersion corrections have a diffraction minimum at approximately the same position as the elastic form factor, with the consequence that, relative to the first Born approximation cross section, the dispersion corrections are not much different near the diffraction minimum than elsewhere -- the diffraction minima are not strongly filled by the dispersion corrections. The most careful, detailed, examination of the problem of dispersion corrections is that given by Friar and Rosen [55], where one may find a discussion of a number of approximations that are made in all work on this subject, but not referred to elsewhere. It is nonetheless clear that this subject is far from being well-understood and that present calculations are not adequate for the analysis of the most accurate electron scattering experiments. In particular, all of the theoretical work just mentioned is limited to second Born approximation. For heavier nuclei, where this is insufficient, two sets of recent calculations should be noted. The first is the work of Rosenfelder and Knoll [56], who use a partial wave calculation for the non-dispersive part of the electron scattering amplitude and an eikonal approximation for the electron wave function to calculate the dispersive corrections. However, a somewhat modified approximation of the usual closure approximation is utilized, and its validity has not been investigated. In contrast to the second Born approximation results mentioned previously, the present work finds the dispersion corrections to be relatively much larger near the diffraction minima. Clearly, a more thorough investigation of this discrepancy in the conclusions of these different calculations is required. The second and most recent work is that of Ravenhall and Mercer [57], who use the coupled-channel method to calculate the electron scattering cross section from deformed nuclei: samarium and oriented holmium. While these appear to be the most thorough coupled channel calculations to date, it must be noted that only a few intermediate excited levels have been included. In view of the aforementioned conclusions of the work of de Forest, Friar and Rosen [54], a direct comparison of the results predicted by these two groups for a light, spin zero nucleus such as ^{12}C or ^{16}O would be instructive.

The comments just presented on dispersion corrections have been in connection with elastic electron scattering. It should be noted that, under the appellation "nuclear polarizability", this same effect, -- the contribution of virtual excitations of the nucleus when at least two photons are exchanged, -- is also of great interest currently in connection with a precise determination of the energy difference between the $2P_{3/2}$ and $2S_{1/2}$ levels in the muonic ion $(\mu^4He)^+$. The most recent and precise measurement is that of Carboni, et al. [58], who refer as well to earlier measurements. The experimental errors are of the order of magnitude of the second-order vacuum polarization corrections; this measurement constitutes, therefore, one of the most precise tests of QED. Of the several effects which contribute to this energy difference and must be calculated to analyze the experiment, the one with largest uncertainty is (as in the case of electron scattering) the nuclear polarizability. The lack of a sufficiently accurate theoretical evaluation of this contribution is the major theoretical limitation in the interpretation of this experiment. A discussion of the various theoretical calculations of the polarizability correction and the discrepancy between them is given by Bernabéu and Jarlskog [59]. The latest calculation of the nuclear polarization, by Rinker [60], appears to have resolved these discrepancies; he estimates errors in his theoretical evaluation of the energy difference to be of the order of 10 to 20%. Also to be noted is the relation of this problem to the discrepancy between theory and experiment in μ-mesic x-rays, for which one should see R. Barbieri [61] and the references given therein.

The complications which enter once one goes beyond one-photon exchange with the nucleus are present also in the next set of correction terms that should be considered: -- the recoil correction. We are aware of only two articles that attempt to treat recoil terms beyond the first Born approximation. (For a detailed discussion of the recoil corrections in the first Born approximation, see the review articles on electron scattering and nuclear structure by Drell and Walecka, deForest and Walecka, and Donnelly and Walecka [62], and more recently, de Forest [63], and Friar [64].) In the most recent work in which contributions to the second Born approximation are investigated, that of Friar [64], terms of order E_o/M and q/M (E_o being the incident electron energy, q the momentum transfer, M the mass of the target) are kept. But not even all of these terms can be calculated at present; the analysis remains very incomplete at this time.

Finally, mention should be made of the relativistic corrections to electron scattering. These corrections, of relative order $(q/M)^2$, modify the first Born approximation cross section, and have been considered (in this approximation, and including only the longitudinal form factor) by Friar [65] for elastic and inelastic electron scattering. Although these corrections are, for many experiments, only of the order of 1%, it should be noted that they also modify the argument of the form factor: $F(q^2) \rightarrow F(q^2/(1 + q^2/4M^2))$, in which $q^2 = \underset{\sim}{q}^2 - q_o^2$. The relativistic corrections thus have the effect of shifting the non-relativistic diffraction minima out to higher values of q^2.

4. Bremsstrahlung spectrum tip

For over twenty years, the main sources of photons for nuclear research in the energy range 5 to 500 MeV has been the bremsstrahlung produced by electron beams. In order to obtain a reasonably monochromatic source of photons it is the tip of the bremsstrahlung spectrum (for which the emitted photon has almost all of the incident energy, and the final electron has relatively little energy) that is of particular interest; a comparison of the various experimental techniques that are employed to this end may be found in an article by Matthews and Owens [66]. The tip of the spectrum also distinguishes itself from the rest of the spectrum with regard to the existence of reliable theoretical expressions for the cross section: Away from the tip, when the final electron has more than a few MeV, the Born approximation suffices for light elements, and for heavy elements, for which Coulomb corrections are important, calculations have been performed in the high energy limit [6,31,32], and are applicable when the final electron energy is greater than about 50 MeV. Thus, outside the tip region theoretical expressions for the cross section are well known and are satisfactory except for heavy elements and moderate electron energies (5 - 50 MeV). In contrast, for the tip region the Born approximation is not applicable even for light elements, and no truly satisfactory theoretical calculations exist at present.

In considering the existing measurements of the bremsstrahlung cross section it is important to categorize them according to the energy resolution of the detector that is used. Different detection systems have energy resolutions which differ by several orders of magnitude, and by this fact they reveal very different aspects of the physics of the process.

Most of the existing experiments, at least those of the past few decades, have used either a NaI scintillation crystal or a Ge(Li) solid state detector. Measurements of the entire bremsstrahlung spectrum [67] (rather than just the tip) made prior to 1970 have, for the most part, used NaI spectrometers, which have the advantage of high efficiency, but their resolution ($\Delta E/E$) is at best of the order of a few percent, and large corrections must be made for the spectrometer response near the bremsstrahlung tip, where the spectrum varies rapidly. The tip cross sections obtained from these experiments are thus extrapolations from lower points on the spectrum (where the photon energy is less than 0.9 of the maximum) and are not very accurate. More recently [68,69], Ge(Li) detectors have been used.[*,#] These have a rather low efficiency, but

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[*] Ref [68] uses a Ge(Li) detector for much of the experiment, but in measurements near the bremsstrahlung tip a NaI crystal is employed.

[#] Ref. [69] is a measurement of the bremsstrahlung polarization for initial electron energies between 50 and 100 keV. The energy resolution of the Ge(Li) spectrometer was of the order of 1%.

their resolution is roughly an order of magnitude better than that of NaI crystals. (For Ge(Li), $\Delta E/E \approx 10^{-3}$ for E of the order of a few MeV, and the minimum observable ΔE is ≈ 200 eV.) It should be noted, however, that although the resolution of the NaI crystal is significant when one looks at the spectrum of bremsstrahlung from an incident electron with fixed energy, it is not of particular importance when an isochromat is utilized, as in the experiments of Fuller, Hayward and Koch [70] and of Hall, Hanson and Jamnik [71]. In these measurements of the bremsstrahlung tip, the 15.1 MeV resonance line in ^{12}C was used as an isochromat selector: The incident electron energy is varied (in the neighborhood of 15.1 MeV) and the yield of 15.1 MeV photons is measured. Since the 15.1 MeV line is very narrow (37 eV wide), it is not the detector resolution which determines the structure that can be observed in the tip, but the accuracy with which the incident electron energy can be measured (of the order of 10 keV).

Within the last decade, there appears to be only one accurate measurement of the bremsstrahlung tip cross section - that of Starek, Aiginger and Unfried [72] for an incident electron energy of 1.84 MeV on a number of targets (Li, Aℓ, Cu, Ag, Au and Pb), using a Ge(Li) detector with a resolution (FWHM) of 3.34 keV ($\Delta E/E \approx 0.2\%$). The agreement with the theoretical calculations cited in their paper is poor. A later calculation of Pratt and Tseng [73] gives moderate agreement with the experiment for high-Z targets, but poor agreement for low-Z elements.

The discussion of the bremsstrahlung spectrum presented up to this point has, as in the previous sections, been from the perspective of electromagnetic interactions and nuclear research in the energy region 5 to 500 MeV. The tip region has thus been used loosely to refer to the upper 10 keV to 1 MeV of the spectrum. Also included in this perspective is the experiment of Starek et al. [72], with incident electron energy 1.84 MeV and a detector resolution of 3.34 keV. However, interest in the tip region of the bremsstrahlung spectrum is by no means limited to nuclear physics. It has been a significant subject of research in atomic physics for almost forty years. There the initial electron energies are generally in the keV region, and the tip generally refers to the region within 100 eV of the endpoint of the spectrum. Although those investigations clearly fall outside the main subject of this paper, we shall nonetheless give a brief review of the work in that region, not only because of its intrinsic interest, but also in the belief that even a consideration of the bremsstrahlung tip that does not focus on the last 100 eV of the spectrum, should be cognizant of the physics in that region. Measurements performed there use crystal diffraction instruments, for which the resolution is $\Delta E/E \approx 10^{-4}$ (an order of magnitude better than for Ge(Li) detectors) and have a minimum observable $\Delta E \approx 1$ eV. The crystals used most extensively in these high resolution experiments are calcite, topaz, OAO (dioctadecyladipate), OHM (octadecyl hydrogen maleate), and KAP (potassium acid phthalate). The method of isochromats, already mentioned in connection with some of the measurements in the MeV region [70,71], is also the one employed in all of the experiments using crystal diffraction instruments. For a rather clear and detailed description of the differences between the classical bremsstrahlung spectroscopy and a bremsstrahlung isochromat, there are two articles by K. Ulmer [74] that are worth reading.

Having observed that among the experiments using NaI or Ge(Li) detectors there is only one accurate measurement of the tip, and that there is disagreement between this experiment and the theoretical calculations, it is important to distinguish the aspects of the physics that are elucidated with these detectors from those investigated using crystal diffraction instruments. In the measurements of the spectrum tip that have been made using either NaI or Ge(Li) detectors, the final electron generally has an energy of a few keV, and certainly has an energy of at least a few hundred eV, the minimum resolution of the Ge(Li) detector. The final electron is thus, like the initial electron, in a continuum state. The theoretical calculations with which one should compare these experiments are, therefore, of the cross section for the transition of an electron between two continuum states, with the emission of a photon, in the screened field of a nucleus. The situation that pertains when one uses crystal diffraction instruments, with a resolution $\Delta E/E \approx 10^{-4}$, and a minimum observable $\Delta E \approx 1$ eV, is quite different. In such experiments one can and does observe structure in the bremsstrahlung tip, mostly within the first 20 eV, but extending out to roughly 100 eV from the high frequency limit, and generally including a strong peak in the first few eV. None of this structure is observed in experiments using NaI or Ge(Li) detectors, nor is it predicted by the simple potential model calculations with the final electron in a continuum state, as just mentioned. It is generally ascribed to transitions in which the initial electron emits a photon and falls into one of the unoccupied (usually d or f) bound states above the Fermi level. This structure was first observed in 1940 by Ohlin [75] and has been the subject of numerous experiments ever since [76-83]. It was originally of great interest [75,76,78,80] in connection with an accurate determination of h/e, as given by the high frequency limit of the bremsstrahlung spectrum, which limit was in turn obtained by extrapolating the spectrum near the end point. Any structure near the end point clearly modifies the limiting value thus obtained. More recently, this structure has been of interest in connection with a determination of the density of states above the Fermi level [78,81,82,83]. Although numerous theoretical explanations of this structure have appeared in the literature of the past 25 years [84-87], here too there is at present no truly satisfactory theoretical calculation.

To summarize: Experiments in which the detector has an energy resolution ΔE of more than a few hundred eV should be understandable in terms of a model in which an initial, continuum state, electron in the field of a screened potential makes a transition to a final continuum state in the field of the same potential, with the emission of a photon. Additional such experiments, as well as a theory in agreement with them, would be very helpful for an understanding of the bremsstrahlung process. On the other hand, for experiments in which the detector has a resolution ΔE of the order of a few eV, one must consider the details of the atomic structure of the target, including the density of states above the Fermi level and matrix elements for transitions to these states. This situation is inherently a more complicated one -- and much richer in its physical content.

One last point should be made with regard to the bremsstrahlung tip as calculated from a simple potential, with initial and final electrons in continuum states. As noted by Wigner [88] in his work on the behavior of cross sections near thresholds (and again, later, by Jabbur and Pratt [89] in connection with their calculation of the tip of the bremsstrahlung spectrum), the bremsstrahlung cross section for an unscreened Coulomb potential ($V = -Ze^2/r$) approaches a finite (non-zero) value at the high frequency limit, i.e., as the momentum, p, of the final electron goes to zero. This follows as a consequence of the form of the Coulomb wave function at the origin, which is inversely proportional to $p^{1/2}$ for small p, and thus cancels (in the cross section) a factor p coming from the density of final states. On the other hand, for a screened potential the wave function remains finite as $p \to 0$, and hence the bremsstrahlung cross section goes to zero at the high frequency limit. Nonetheless, one might, from some of the figures and tables in the published literature [90], get the contrary impression, viz., that the cross section goes to a finite, non-zero, limit for a screened potential. This result in these articles comes from the fact that the limiting value there is obtained by extrapolating from values close to the limit, as is stated explicitely on p. 1801 of [73]. A vanishing cross section at the high frequency limit is not necessarily in contradiction with the measurements of the bremsstrahlung tip by Starek, Aiginger and Unfried [72]. As mentioned, the energy resolution of the detector in that experiment was 3.34 keV (FWHM), so that a falling of the cross section to zero within an energy region smaller than, say, 1 keV, would not be observed as a vanishing cross section at the end point. The discontinuous drop of the cross section at the limit is solely a feature of the Coulomb potential (just one more of its many pathologies), and even this feature disappears if one consider an "average" cross section in the discrete region. This latter point has been made by Breit [91], and discussed in detail by Newton and Fonda [92] in their consideration of the energy dependence of cross sections in the neighborhood of the threshold for a process in which the two emerging particles are oppositely charged. More recently it has been discussed quite clearly and succinctly in a paper by C. Tzara [93] on the effect of the Coulomb potential on π^- photoproduction (see, in particular, the appendix in that paper). Since the Coulomb potential has an infinite number of bound states arbitrarily close to the high frequency limit, the final particle (here the π^-; in the bremsstrahlung tip, an electron) can occupy one of the bound levels rather than a continuum state. He constructs explicitely an average cross section in the discrete region and shows that the cross section is then continuous across the boundary between continuum and discrete states.

5. Virtual Photon Theory - The comparison of electron and photon induced reactions

The theoretical calculations which form the basis for most of the work in this field are contained in the articles of Thie, Mullin and Guth [94] and of Dalitz and Yennie [95]. Particularly to be recommended for its clarity is the later paper of Eisenberg [96]. All of these calculations were performed in Born approximation. Going beyond this, Gargaro and Onley [97] use distorted waves for the electron in a Coulomb field. Other theoretical papers that should be noted are those of Berman [98], who compares photoproduction and electroproduction by separating, in the cross sections for these processes, the kinematic and dynamic aspects; Gibson and Williams [99], who consider virtual photon theory in the long wavelength limit for two-body electrodisintegration, and, most recently, Dressler and Tomusiak [100], who examine in detail the validity of those assumptions of virtual photon theory which must be made in order to extract photodisintegration cross sections from electrodisintegration data.

Experiments using virtual photon theory in their analysis have been performed by several groups. Particularly to be noted are the measurements of the total cross section for the electrodisintegration of deuterium in the energy range 17 to 28 MeV by Skopik et al. in Saskatchewan [101], and the measurements of both the total electrodisintegration and photodisintegration cross sections for a number of nuclei (^{12}C, ^{19}F, ^{35}Cl, ^{63}Cu and ^{65}Cu) by Wolynec et al. in São Paulo [102]. The analysis of the latter group makes use of the distorted wave treatment of Gargaro and Onley [97].

Finally, with regard to the use of positron beams and a comparison of positron and electron cross sections, one should consult the fairly recent theoretical paper of Nascimento and Wolynec [103], who analyze the existing experiments, all of which measure the total cross sections for electrodisintegration by electrons and by positrons, on a number of nuclei. These have been performed by two groups: Herring *et al.* [104] at 27 MeV on ^{12}C, ^{63}Cu, ^{107}Ag and ^{181}Ta, and, more recently, Kuhl and Kneissl [105] in the energy range 20 to 30 MeV on ^{12}C, ^{63}Cu and ^{107}Ag and Kneissl, Kuhl and Weller [106] in the energy range 15 to 40 MeV on uranium.

Concluding Observations

We have concentrated our considerations in this report on the energy range 5 - 500 MeV. This range of values has been chosen principally because it comprises most of the experiments using electromagnetic probes for nuclear research. It also represents a significant range from the viewpoint of theoretical calculations. Below about 5 MeV, although Born approximation calculations may have questionable validity, it is often feasible to use a partial wave decomposition; for low energies a relatively small number of partial waves enter. On the other hand, above a few hundred MeV, high-energy approximations (eikonal or WKB, for example) can generally be applied. It is just the energy range 5 - 500 MeV that is the least amenable to the wellknown methods of mathematical physics, and hence the most lacking in reliable and useful theoretical expressions for the cross sections we have considered. Examples of this have been cited in the preceding sections, where it was noted that the question of the magnitude of the Coulomb corrections to both Delbrück scattering and pair production in the energy range 5 to 100 MeV is an open one; the expressions for Delbrück scattering including Coulomb corrections assume very high energies (of the order of 1 GeV); those for the total cross section for pair production are valid only above about 50 MeV. The most significant challenge to improve the calculations comes, however, as a result of the increased accuracy of many experimental measurements. When these become better than 1%, corrections to the main process of relative order α (and with them all the difficulties of an additional set of diagrams) must be calculated if comparison is to be made between theory and experiment.

Acknowledgments

In the production of this report I have benefited greatly from many discussions with colleagues, both prior to the formulation of each of the sections, and in the course of the several rewritings which the manuscript has undergone. I am first of all indebted to R. Bergère for having asked. It was his question concerning the possible importance of an accurate measurement of the difference between the bremsstrahlung spectrum from electrons and positrons that engendered in response a letter which grew and grew until it became this report. Several of those whose articles are listed in the references were very helpful in providing, in discussions held with each of them, an understanding of essential aspects of their work. For this I am grateful to J. Ahrens, T. Bar-Noy, B. Frois and C. Tzara. The section on dispersion corrections owes a great deal to several lengthy discussions with J. L. Friar, and the part of the section on the bremsstrahlung tip dealing with atomic physics would not have been formulated without several conversations with A. J. McAlister and with R. D. Deslattes whom I also thank for a very thoughtful reading of the manuscript resulting in important improvements. The manuscript also received careful and detailed readings by L. S. Cardman and E. G. Fuller, whose suggestions have been very useful. The section on electron scattering and its corrections owes much of its form and content to innumerable discussions with J. W. Lightbody, X. K. Maruyama and S. Penner. Their contribution to this section was very significant. And finally, a note of thanks is appreciatively given to E. V. Hayward, who has been a sounding board for almost every idea contained herein, who has given, throughout the entire writing, unstinting counsel on both technical and editorial matters, with patience and with humor.

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NBS-114A (REV. 7-73)

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4. TITLE AND SUBTITLE Electromagnetic Interactions from 5 to 500 MeV and Nuclear Research -- A Position Paper as of March 1977			5. Publication Date August 1977 6. Performing Organization Code
7. AUTHOR(S) Leonard C. Maximon			8. Performing Organ. Report No.
9. PERFORMING ORGANIZATION NAME AND ADDRESS NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			10. Project/Task/Work Unit No. 11. Contract/Grant No.
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* Same as 9.			13. Type of Report & Period Covered Final 14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

We present the current status of both experimental measurements and theoretical expressions for cross sections for the majority of the electromagnetic processes that are intimately connected with nuclear research using electromagnetic probes, emphasizing in particular those theoretical papers which are both reliable and useful for an analysis of the experiments, and indicating those regions in which the theoretical calculations are inadequate. Serving as a structure for this presentation, four areas of experimental research have been chosen, and we discuss in reasonable detail the status of the latest experiments in these areas: Total photoabsorption cross section measurements, Elastic Photon scattering and Delbrück scattering, Electron scattering and its corrections-radiative, recoil, dispersive and relativistic- and the bremsstrahlung spectrum tip. In addition, a guide to the more pertinent articles (experiment and theory) on the subject of virtual photons is presented.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Bremsstrahlung spectrum tip; Delbrück scattering; electromagnetic interactions; electron scattering; radiative corrections; total photon absorption cross sections; virtual photon theory.

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NOTE: At present the principal publication outlet for these data is the Journal of Physical and Chemical Reference Data (JPCRD) published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements available from ACS, 1155 Sixteenth St. N.W., Wash. D. C. 20056.

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