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Electron–positron pair production by photons: A historical overview☆

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Abstract

This account briefly traces the growth of our theoretical and experimental knowledge of electron–positron pair production by photons, from the prediction of the positron by Dirac [1928a. The quantum theory of the electron. Proc. R. Soc. (London) A 117, 610–624; 1928b. The quantum theory of the electron. Part II. Proc. R. Soc. (London) A 118, 1928b, 351–361] and subsequent cloud-chamber observations by Anderson [Energies of cosmic-ray particles. Phys. Rev. 43, 491–494], up to the present time. Photons of energies above $2m_ec^2$ (1.022 MeV) can interact with the Coulomb field of an atomic nucleus to be transformed into an electron–positron pair, the probability increasing with increasing photon energy, up to a plateau at high energies, and increasing with increasing atomic number approximately as the square of the nuclear charge (proton number). This interaction can also take place in the field of an atomic electron, for photons of energy in excess of $4m_ec^2$ (2.044 MeV), in which case the process is called triplet production due to the track of the recoiling atomic electron adding to the tracks of the created electron–positron pair. The last systematic computations and tabulations of pair and triplet cross sections, which are the predominant contributions to the photon mass attenuation coefficient for photon energies 10 MeV and higher, were those of Hubbell et al. [Pair, triplet, and total atomic cross sections (and mass attenuation coefficients) for 1 MeV–100 GeV photons in elements $Z = 1$–100. J. Phys. Chem. Ref. Data 9, 1023–1147], from threshold (1.022 MeV) up to 100 GeV, for all elements $Z = 1$–100. These computations required some ad hoc bridging functions between the available low-energy and high-energy theoretical models. Recently (1979–2001), Sud and collaborators have developed some new approaches including using distorted wave Born approximation (DWBA) theory to compute pair production cross sections in the intermediate energy region (5.0–10.0 MeV) on a firmer theoretical basis. These and other recent developments, and their possible implications for improved computations of pair and triplet cross sections, are discussed.
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1. Introduction

The safe and efficient use of (and protection against) high-energy photon radiation (e.g., gamma rays and bremsstrahlung) for medical diagnosis and treatment, industrial irradiation and gauging, nuclear power plant shielding, security surveillance and diverse other applications, requires quantitative and accurate knowledge of the mechanisms by which the photons interact with the atoms of the target materials. The dominant interaction mechanisms include the atomic photoeffect, coherent (Rayleigh) and incoherent (Compton) scattering, and, in the photon energy region above 1 MeV,

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electron–positron pair (and triplet) production. Systematic tabulations of the probabilities, or cross sections, for these processes, and their totals in the form of mass attenuation coefficients μ/ρ, extending to photon energies above 1 MeV, have been developed at NBS/NIST and elsewhere and revised from time to time, for example by White [Grodstein] (1952), Grodstein (1957), Hubbell and Berger (1965, 1968), Plechaty and Terrall (1968), Storm and Israel (1970), Hubbell (1969, 1982), Berger and Hubbell (1987), and Cullen et al. (1997). A compilation by Hubbell and Seltzer (1995) including both μ/ρ and the mass energy-absorption coefficient μ_{en}/ρ, utilizing the theoretical work of Seltzer (1993) for the μ_{en}/ρ computations, should also be mentioned. This report is intended to summarize historical and current information on pair and triplet production, the dominant processes above a few MeV.

The photon energy threshold for the disappearance of a photon in the field of a bare nucleus and creation of an electron–positron pair is $2m_ec^2$ in which m_e is the mass of an electron e^- or positron e^+ and c is the speed of light in a vacuum, giving a threshold value of 1.022 MeV. This threshold applies in the case where both positron and electron are created in the continuum. If the electron is created in a bound state of an atom, the threshold is lowered by the binding energy of the orbital into which the electron is created. For pair production in the field of an atomic electron, called "triplet production" due to the visualization in a cloud chamber of the recoil of the struck electron along with the tracks of the created electron and positron, the kinematics require a higher threshold of $4m_ec^2$, or 2.044 MeV.

The probability, or cross section, for the pair creation process, is approximately proportional to the square of the target-particle charge. Hence, for pair production in the field of a nucleus, the cross section κ_n per atom is

$$\kappa_n \propto Z^2$$

in which Z is the atomic number, or proton number, of the target nucleus. For triplet production, for which the target electron has unit charge, the cross section κ_e for a neutral atom with Z electrons is

$$\kappa_e \propto Z$$

and thus

$$\kappa_e/\kappa_n \simeq 1/Z$$

for incident photon energies well above the differing thresholds.

For detailed descriptions and information on pair and triplet production, beyond what will be included in this brief report, reference can be made to the various major review articles on these processes, for example by Motz et al. (1969), Tsai (1974), Hubbell et al. (1980), hereafter referred to as "HGØ", and Eichler (1990).

2. Pair and triplet measurements: a brief history and survey

The experimental investigations of these processes started soon after a theoretical observation by Dirac (1928a, b), who noted a "difficulty" in the relativistic wave equation for a free electron (e^-), in that its solutions yielded negative energy states as well as positive energy states, thus suggesting the existence of electrons with the opposite charge sign e^+, the same charge as for a proton. This theoretical observation was soon followed by Anderson's (1932, 1933) experimental observation in his cosmic ray studies using a cloud chamber in which a strong magnetic field was imposed, of symmetrical tracks curving in opposite directions, the signature of the creation of an electron–positron pair, e^- and e^+, by a photon generated in the shower induced by the cosmic ray particle. Also, Perrin (1933) pointed out the possibility of pairs being produced in the field of atomic electrons.

Further cloud chamber photographic experiments followed, for example by Blackett and Occhialini (1933), Chadwick et al. (1934), and Simons and Zuber (1937) with some quantitative interpretation by Zuber (1938). I. Curie and Joliot (1933a, b) described and interpreted their observations, but did not publish any photos. Later, striking photos of the trident signature of triplet production were obtained using photographic emulsions, for example by Mohanty et al. (1961) and Castor et al. (1970), also using a streamer chamber by Jousset et al. (1970) and Augerat et al. (1971, 1977).

In addition to the two- and three-pronged track signatures of the pair production process, another signature results from the ultimate fatal encounter of the positron with an ordinary electron, in which the two particles annihilate and their combined mass-energy of $2m_ec^2$ is de-materialized into two photons. Single-photon annihilation can also occur; see, e.g., Cahn (2000). If the positron has effectively come to rest in the target before annihilating, the most probable result is a pair of $1m_ec^2$ (0.511 MeV) photons departing the annihilation site in opposite directions, providing a measurable signature using detectors paired in coincidence on either side of the target material. For high-energy incident photons, and annihilation in flight at high positron velocities, the two photons will be emitted at forward angles, and at higher energies.

The introduction by Hofstadter and McIntyre (1950) of the NaI(Tl) scintillation detector spectrometer provided the necessary tool for such coincidence measurements. However, the first scintillator material used in a pair production cross section measurement, by Hahn et al. (1952), seems to be the organic crystal anthracene. The many such coincidence pair production cross section measurements, up to a few MeV above threshold using radionuclide photon sources include, for example, the works by Dayton (1953), Staub and Winkler (1954), Schmid and Huber (1955), West (1956), Titus and Levy (1966), Henry and Kennett (1972), Avignone and Khalil (1981), Khalil and Avignone (1982) and Avignone et al. (1985).

At higher photon energies the pair and triplet cross sections dominate the total attenuation coefficient, which can in turn be used to obtain experimental values for pair and triplet by subtracting the relatively small scattering (coherent and incoherent) and atomic photoeffect theoretical cross sections. A complicating factor in the intermediate energy region 5–40 MeV is the presence of the isotopically dependent photonuclear giant resonance cross section, peaking in a low-Z target for example ^{12}C at 23 MeV and for a high-Z target such as ^{235}U at 12.2 MeV, amounting at peak to 5.9% and 2.4% of the total "electronic" cross section for these two nuclides, respectively. This photonuclear cross section information was taken from Hubbell (1969), Table 2.-16 supplied by E.G. Fuller. More detailed and exhaustive photonuclear cross section data can be obtained from Dietrich and Berman (1988).

This complicating factor, however, stimulated a number of high-accuracy total attenuation coefficient measurements in regions from a few MeV up to a few tens of MeV, for example the works Ahrens et al. (1971), Gimm and Hubbell (1978), Gurevich et al. (1980) and Sherman et al. (1980, 1985, 1987), Sherman and Ewart (1981, 1983), Sherman and DelBianco (1988). The primary objective of these measurements was to isolate and evaluate the photonuclear giant resonance cross sections. However, as a secondary objective, the available pair and triplet theoretical cross sections in this intermediate energy region could also be tested. For example, these measurements, treating the electronic cross sections as a baseline under the photonuclear cross section resonance peak, suggested that the pair and triplet cross sections tabulated by Hubbell (1969) and used also by Storm and Israel (1970) were 1%, 2% and 5% too low for Cu, Sn and Pb, respectively, for 10 MeV incident photons. On the other hand, these measurements were found to be in excellent agreement with the Hubbell et al. (1980) calculated and tabulated total electronic cross sections above, below and underlying the photonuclear resonance peaks.

A notable set of total attenuation coefficient measurements between the pair threshold and photonuclear main peak was that of Henry and Kennett (1971) who used (n,γ) photons from reactor neutrons to deduce pair production cross sections in W, Pb and U from 1.778 to 10.827 MeV, obtaining good agreement with a semi-empirical formula of Øverbø et al. (1968). Other total attenuation coefficients, extending well above the photonuclear peak region, are indexed and graphed in comparison with theory in Hubbell (1971). Most notable of these, supporting the high-energy theory then already available, are the 1-GeV measurements by Malamud (1959) at Cornell for 12 elements from H to U, and the 10 GeV measurements in C and 13.5 GeV in Li, C, Cu and Pb by Fidecaro et al. (1962) at CERN. Additional total attenuation coefficient measurements in the pair production region, beyond the sampling mentioned in this brief report, are cited and indexed in the surveys by Sud (1987) and Hubbell (1994).

Some wide-angle electron–positron pair production measurements in C in the region 1 to 2 GeV were made at DESY by Blumenthal et al. (1966), Asbury et al. (1967) and Alvenslaben et al. (1968). More recently, some other measurements have been made at intermediate and extreme high photon energies for pair production aspects other than cross section data. Examples of these are the 50 and 100 MeV measurements by Asai and Skopik (1999) of asymmetry ratios in pair production and degree of linearly polarized photons, and the measurements by Moore et al. (1996) and Kirsebom et al. (1998) of the enhancement of pair production by 5–150 GeV photons in the strong crystalline fields of tungsten and other targets.

Most recently, Dauvergne et al. (2003) have measured photon impact ionization of the K shells of Ag ($Z = 47$) and Au ($Z = 79$) in the 1-GeV photon energy range, to demonstrate that the triplet cross section is dominated by a new channel called vacuum-assisted photoionization (Ionescu et al. 1999). For their source, Dauvergne et al. (2003) used high-energy photons generated by Compton backscattering of laser photons from the 6 GeV electron beam from the European Synchrotron Radiation Facility (ESRF) at Grenoble. As a check on their experimental technique they also measured absolute e^+–e^- total ($\kappa_n + \kappa_e$) pair production probabilities as a function of target foil thickness. They considered their measured atomic cross sections, 14.2b and 35.1b for Ag and Au, respectively, to be in good agreement with the HGØ (1980) tabulated theoretical values of 14.70b and 36.90b at 1 GeV.

3. Pair and triplet theory: from Dirac (1928a, b) to HGØ (1980)

Soon after Dirac's (1928a, b) positron prediction and its experimental confirmation by Anderson (1932, 1933) and others, the theoretical probability for the electron–positron pair production process was quickly established by Oppenheimer and Plesset (1933) to have a Z^2 dependence on the atomic number Z for a given photon energy. This Z^2 dependence was independently confirmed in quantitative cross section calculations by Nishina et al. (1934) in which $(\alpha Z)^2$ was neglected in comparison with l^2, where α is the fine structure constant and l is the quantum number for the azimuthal wavefunction of the hydrogen-like atom, also by Heitler and

Sauter (1933) using a similar approach. For a full treatment they encountered integrals which in general cannot be evaluated analytically. For the total pair cross section, Racah (1934, 1936) derived expressions in terms of elliptic integrals which involved no high-energy approximation.

Bethe and Heitler (1934) and Bethe (1934) then developed more-detailed theory, using the Born (1926) approximation [see also Schiff (1949)], which is still the starting point for modern pair and triplet production cross section computations, and by Jaeger and Hulme (1935, 1936) who explored the validity of the Born approximation and concluded that it led to good results at extreme high energies. For intermediate photon energies the effects of screening of the nuclear charge by the atomic electrons requires substantial corrections. For these corrections, Wheeler and Lamb (1939) developed expressions into which atomic models, such as the statistical model of Thomas (1927) and Fermi (1928) could be inserted. Following a lull in theoretical activity during World War II, the work by Jost et al. (1950), examining the recoil of the nucleus in pair production, renewed the chain of evolving refinements.

White (Grodstein) (1952), in her ground-breaking systematic 10 keV to 100 MeV compilation of photon cross sections and attenuation coefficients for 17 elements H to U plus air, NaI, water and concrete, drew on the above available pair production theoretical models, with some adjustments based on the measurement data base up to that time. From threshold (1.022 MeV) to 2.5 MeV White used the non-Born calculations of Jaeger and Hulme (1936) and Jaeger (1936), guided also by Hough (1948a, b), and above 10 MeV she used the Bethe–Heitler (1934) Born-approximation with (Thomas, 1927; Fermi, 1928) screening included according to the Wheeler–Lamb (1939) formulation. The gap from 2.5 to 10 MeV was filled in using graphical interpolation. For the triplet (electron field pair production) cross section she used the Borsellino (1947a, b) results from threshold (2.044 MeV) up to 50 MeV, beyond which she extrapolated to 100 MeV guided by the Wheeler–Lamb results. These pair and triplet cross sections were incorporated in the Davisson (1955) review article.

A further advance in pair production theory was the work of Davies and Bethe (1952), Bethe and Maximon (1954) and Davies et al. (1954) in which integrations were successfully performed without the Born approximation and its limitations. These advances were then incorporated in the revised cross section and attenuation coefficient compilation by G. White Grodstein (Grodstein, 1957) [now using her married name] for 24 elements H to U plus water, NaI, calcium phosphate (for bone), air and concrete. Of interest in cosmic ray physics also was the work of Migdal (1957) at extreme high photon energies, of the order of 10^{13} eV.

The pair production review article by Motz et al. (1969) drew together and presented all of the above pair and triplet cross section theoretical models and expressions for computations, plus subsequent high-energy results such as by Suh and Bethe (1959), and Kopylov et al. (1964). An additional work by Kudryavtsev et al. (1968) explored the effect of a condensed medium on angular distributions, in limiting cases reproducing the Bethe–Heitler (1934) spectrum and the Migdal (1957) condensed-medium result. Another notable theoretical effort at this time was the work of Deck et al. (1969) who derived compact and simple correction terms of the order αZ, where α is the fine structure constant $\approx 1/137$, to the Bethe–Heitler formulae for the pair production cross section in an unscreened point Coulomb field.

Incorporating the above theoretical information where applicable, plus using the simple, rapidly converging Born-approximation expressions by Maximon (1968) for low and high energies, respectively, derived from the Racah (1934, 1936) results, Hubbell and Berger (1965) and Hubbell (1969) [NSRDS-NBS 29] updated the White-Grodstein (1957) compilation, extending the energy range up to 100 GeV. Other refinements in the Hubbell (1969) nuclear-field pair production theoretical evaluations, beyond the Grodstein work, were the use of screening corrections calculated by Sørenssen (1965, 1966) using Hartree–Fock–Slater wave functions for $0 \leqslant q \leqslant 0.3$, and the Thomas–Fermi model of the atom for $0 \leqslant q \leqslant 8.0$ where q is momentum transfer in mc units. Also used was the radiative correction of Mork and Olsen (1965) in the Hubbell (1969) evaluation which was also interpolated and used by Storm and Israel (1970) in their all-Z (1–100) widely used compilation.

For the triplet cross section computations for the above compilation, Hubbell and Berger (1965) and Hubbell (1969) [NSRDS-NBS 29] followed Grodstein (1957) using the Ghizzetti (1947) and Borsellino (1947a, b) expressions, with screening from the Wheeler–Lamb (1939) formulation, but now modified by a correction obtained by Mork (1967) by integrating the Votruba (1948a, b) expressions numerically.

In the decade following NSRDS-NBS 29, up to 1980, the group at Clermont–Ferrand examined various aspects of pair production theory including the Coulomb correction by Roche et al. (1968a, b), Proriol and Roche (1974) and Roche and Jousset (1975), angular cross sections by Dugne and Proriol (1970), molecular coherence effects by Proriol and Roche (1972), screening by Proriol (1972) and Dugne (1976), and an analytic continuation to the tip of the positron spectrum in a point Coulomb calculation by Dugne and Meunier (1977). Other important work in this decade included screening calculations by Tseng and Pratt (1971), the application by Fink and Pratt (1973) of Furry–Sommerfeld–Maue wave functions to obtain differential pair production cross sections, and an examination of polarization correlations by Tseng and Pratt (1974) in which they concluded that such correlations are practically independent of atomic-electron screening.

Also in this decade up to 1980, the group at Trondheim provided major pair production formulations and sample computations including exact unscreened calculations by Øverbø et al. (1973), evaluation of the Coulomb correction at intermediate energy by Øverbø (1977), screening corrections for intermediate and high-energy photons by Øverbø (1978) and for intermediate and low-energy photons by Øverbø (1979). Other works in this decade to be mentioned are the screening effect calculations at intermediate and high energies by Borie and Arenhövel (1972), and Tseng and Pratt (1972, 1980) at low energies. Also, Borie (1981) used Furry–Somerfeld–Maue wave functions to compute Coulomb corrections at medium and high energies.

From the point of view of the evaluator and table-maker for scientific, medical and technological practical applications, the next major milestone in this pair and triplet cross section evolutionary process was the 1 MeV to 100 GeV, $Z = 1-100$ computation and tabulation by Hubbell et al. (1980) in HGØ. As described in detail in HGØ, in these computations, the above various effects and corrections to the nuclear-field pair production cross section κ_n, and to the electron-field (triplet) pair production cross section κ_e, were considered semi-independent.

For κ_n from threshold to 5 MeV, the relevant theoretical models and modifications were pieced together according to

$$\kappa_n = \kappa_n^{BH}\left[\kappa_n^{ØMO}/\kappa_n^{BH}\right]\left\{\left[\kappa_n^{BH} - \Delta\kappa_n^{B}(\mathrm{scr}) + \Delta\kappa_n^{TPØ} - (\mathrm{scr, h.o.})\right]/\kappa_n^{BH}\right\} \quad (1)$$

in which κ_n^{BH} is the Bethe–Heitler unscreened Born-approximation cross section computed using the Maximon (1968) expansions, $\kappa_n^{ØMO}$ are the Coulomb-corrected results of Øverbø et al. (1968), $\Delta\kappa_n^{B}(\mathrm{scr})$ is the exact-Born screening correction from an elaborate computation involving the atomic form factor $F(x,Z)$ taken from the relativistic Hartree–Fock compilation of Hubbell and Øverbø (1979), and $\Delta\kappa_n^{TP\text{-}Ø}$(scr, h.o.) are the near-threshold Tseng-Pratt (1980) screening corrections including higher-order effects pointed out by Øverbø (1979).

Above 5 MeV, up to 100 GeV, the HGØ results were computed according to

$$\kappa_n = \left[\kappa_n^{BH}\left\{\left[\kappa_n^{BH} - \Delta\kappa_n^{nB}(\mathrm{scr}) + \Delta\kappa_n^{TP\text{-}Ø}(\mathrm{scr, h.o.})\right]/\kappa_n^{BH}\right\} \times\Delta\kappa_n^{Ø}(\mathrm{Coul})\right][1+\Delta(\mathrm{rad.corr.})] \quad (2)$$

in which $\Delta\kappa_n^{Ø}$(Coul) is the Coulomb correction computed from the expressions given by Øverbø (1977), and Δ(rad. corr.) is the Mork–Olsen radiative correction arbitrarily turned off in HGØ using a sine function below 10 MeV (outside its range of validity) to avoid unphysical results near threshold.

In a somewhat analagous fashion the HGØ electron-field (triplet) pair production cross sections were computed according to

$$\kappa_e = \kappa_e^{BG}\left[\kappa_e^{H}/\kappa_e^{BG}\right]\left\{\left[\kappa_e^{H} - \Delta\kappa_e^{BH}(\mathrm{scr})\right]/\kappa_e^{H}\right\}1.01 \quad (3)$$

in which κ_e^{BG} is the Borsellino (1947a, b)-Ghizzetti (1947) unscreened triplet cross section including retardation, the ratio $\kappa_e^{H}/\kappa_e^{BG}$ uses the Haug (1975, 1981, 1985) results to include the γ–e interaction and exchange effects, and the $\Delta\kappa_e^{BH}$(scr) screening and electron-binding effects were computed according to the Bethe–Heitler (Wheeler–Lamb) expression, using the non-relativistic incoherent scattering functions $S(x,Z)$ compiled by Hubbell et al. (1975) from various available sources, and the triplet radiative correction factor 1.01, as advised by Mork (1967), is taken as this constant value over the entire energy range.

The HGØ computed tabulation of κ_n and κ_e, summed together with the incoherent and coherent scattering cross sections and the atomic photo effect, have been shown to be in close agreement with measurements in the photonuclear region by Gurevich et al. (1980) and Sherman et al. (1980, 1985, 1987) Sherman and Ewart (1981, 1983), Sherman and DelBianco (1988), and a considerable improvement, for high-Z materials, over the 1969 values by Hubbell (1969) and Storm and Israel (1970) which appear to be as much as 4% low for the highest Zs in this energy region.

4. Some further theoretical work, beyond HGØ (1980)

The formulations used by Hubbell et al. [HGØ] (1980) might yield more accurate values of the pair and triplet cross sections if the screening effects calculations for κ_n were repeated using the relativistic Hartree–Fock–Slater modified atomic form factors $F(x,Z)$ computed and tabulated by Schaupp et al. (1983), and for κ_e using the relativistic Dirac–Hartree–Fock incoherent scattering functions $S(x,Z)$ computed and tabulated by Kahane (1998).

Maximon and Gimm (1981) provided new and simplified expressions for the recoil distribution in triplet production, from which Gimm (1982), using the same Hubbell et al. non-relativistic $S(x,Z)$ values as used in HGØ (1980), recomputed κ_e for all elements $Z = 1-100$ and all energies above 10 MeV, presenting his results compactly in the form of 7-parameter polynomial fits. Also, Haug (1985) re-examined the energy and angular distributions of electrons in triplet production, refining and simplifying the expressions of Jarp and Mork (1973). More recently, Haug (2004) has investigated the production of electron–positron pairs in a hot

Maxwellian plasma at semirelativistc and relativistic temperatures, in the fields of positrons and electrons (triplet, κ_e) and nuclei (κ_n), of interest in astrophysics in the study of stellar black-hole binaries and Seyfert galaxies (see, e.g., Zdziarski, 1982; Lightman, 1982; Lightman and Zdziarski, 1987; Zdziarski et al., 1990; Mastichiadis et al., 1994).

For κ_n, Tseng (1990, 1994b) re-examined screening effects at intermediate photon energies, and also near threshold (Tseng, 1994a). Tseng (1995a, b) also performed relativistic calculations of the positron energy-angle distributions for low and for intermediate photon energies, and more recently (Tseng, 1997) used a relativistic partial-wave method to examine pair production polarization correlations for intermediate-energy incident photons.

Vacuum polarization of arbitrary spin particles in pair production has also been studied by Kruglov (2001a, b). A bound-electron pair production treatment by Bergstrom et al. (1996) could have some impact on future HGØ (Hubbell et al., 1980) updates, as well as the extreme high-energy study by Mil'shtein and Strakhovenko (1993).

Other work to be considered in any update and recomputation of the κ_n values in HGØ (1980) should include the work of Sud and his collaborators, beginning with the Sud et al. (1979) novel expressions for the radial integrals for pair production in a point-Coulomb potential, then applied in the tip region of the positron spectrum by Sud and Sharma (1984). Then, following three studies of intermediate-energy pair cross sections for selected heavy elements using distorted wave Born approximation (DWBA) by Sud and Sharma (1987), Wright et al. (1987) and Sud and Soto Vargas (1991, 1994), Selvaraju et al. (2001) used DWBA to compute and tabulate differential (in positron energy) and total κ_n values for six elements H to U over the intermediate photon energy range 5.0–10.0 MeV. Attention is called also to the work of Lee et al. (2004) in this same energy region, in which screening effects on the Coulomb correction are examined using a next-order expansion in inverse energy, and some results presented.

Finally, there is a wealth of theory and measurements of the pair production process occurring in ion collisions with nuclei. This kind of pair production is also related to the possible photon bound-pair production process (produced electron of the pair bound to the atom), which can occur below the $2m_ec^2$ (1.022 MeV) threshold under some circumstances (see Bergstrom et al. 1996 and the references therein). See also, for example, Vane et al. (1994), Agger and Sørensen (1997), Eichler (1995), Belkacem et al. (1998), Belkacem and Sørensen (1998), Ionescu et al. (1999) and Wells et al. (1999) which also have the potential to apply also to computations of pair production by photons on nuclei with bound electrons.

5. Summary and conclusions

Preliminary examination and evaluation of the available old and new treatments, experimental (e.g., Sherman et al., 1980, 1985, 1987; Sherman and Ewart, 1981, 1983; Sherman and DelBianco, 1988; Gurevich et al., 1980; Dauvergne et al., 2003) and theoretical, suggests that new calculations are advisable, but no dramatic changes in recommended cross sections are anticipated, likely 2–3% at most. However, it is obvious that new computations, beyond HGØ (1980), will again be a "witch's brew," combining interdependent theoretical models, effects and corrections, a worthy challenge for the next table-maker of high-energy photon cross sections and attenuation coefficients to serve the medical, industrial and other user communities who require such data.

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