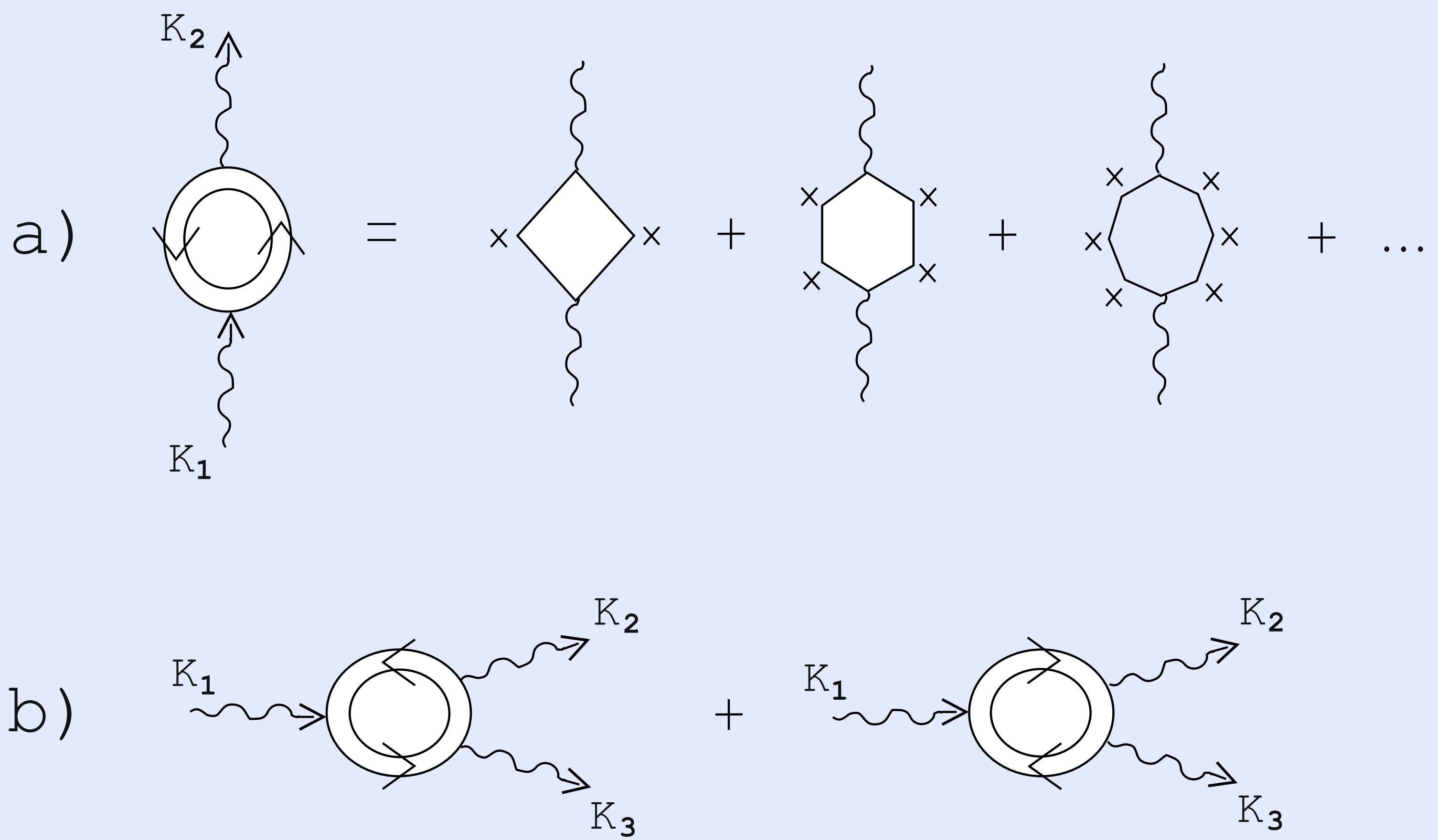
Delbrück scattering and photon splitting in atomic fields, theory and experiments

A.I. Milstein

G.I. Budker Institute of Nuclear Physics, Novosibirsk, Russia



(a) Feynman diagrams for Delbrück scattering: the Farry representation and the representation via the usual diagrams of the perturbation theory. The double line denotes the electron Green function in the Coulomb field, crosses denote the Coulomb field. (b) Feynman diagrams in the Farry representation for photon splitting.

Delbrück scattering

L. Meitner, H. Kösters (and M. Delbrück), Z.Phys. **84**, 137 (1933)

- The amplitudes were calculated in the lowest in $Z\alpha$ order, but for an arbitrary photon energy ω and scattering angle θ. These results are applicable only at small Z.
- At $\omega \gg m$ (m is the electron mass) and $\theta \ll 1$ the amplitudes were obtained exactly in $Z\alpha$ by summing in a definite approximation of Feynman diagrams.
- At $\omega \gg m$ and $\theta \ll 1$ the amplitudes were calculated exactly in $Z\alpha$ using the quasiclassical approximation.
- At $\omega \gg m$ and $\theta \sim 1$ the amplitude were calculated exactly in $Z\alpha$ but neglecting the electron mass as compared to ω and momentum transfer Δ.

There are two independent helical amplitudes, $M_{++} = M_{--}$ and $M_{+-} = M_{-+}$. For unpolarized photons, the differential cross section is given by

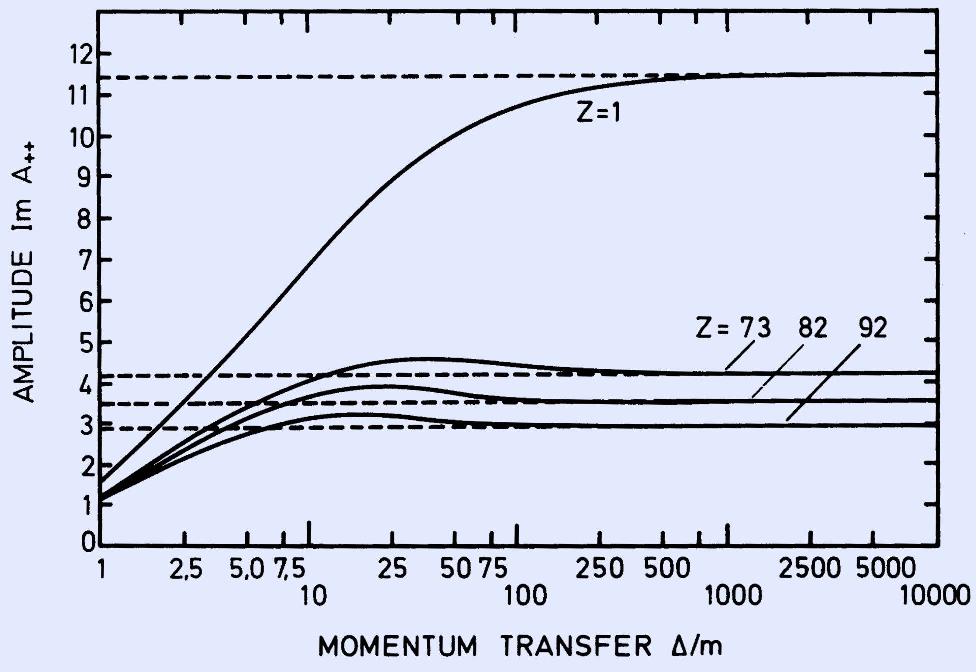
$$\frac{d\sigma}{d\Omega} = \frac{1}{16\pi^2}\left(|M_{++}|^2 + |M_{+-}|^2\right) . \qquad (1)$$

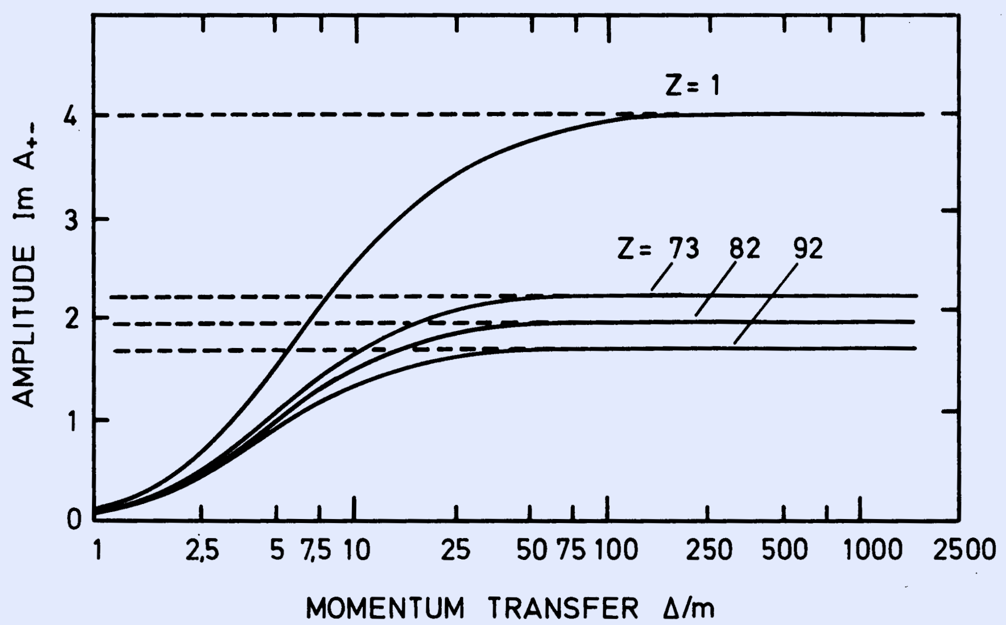
If the initial photon is not polarized, partial polarization of the final photon in the scattering plane is produced. The corresponding Stokes parameters are

$$\xi_3 = 2\,Re\,\left(M_{++}M^*_{+-}\right) / \left(|M_{++}|^2 + |M_{+-}|^2\right) , \xi_1 = \xi_2 = 0 . \qquad (2)$$

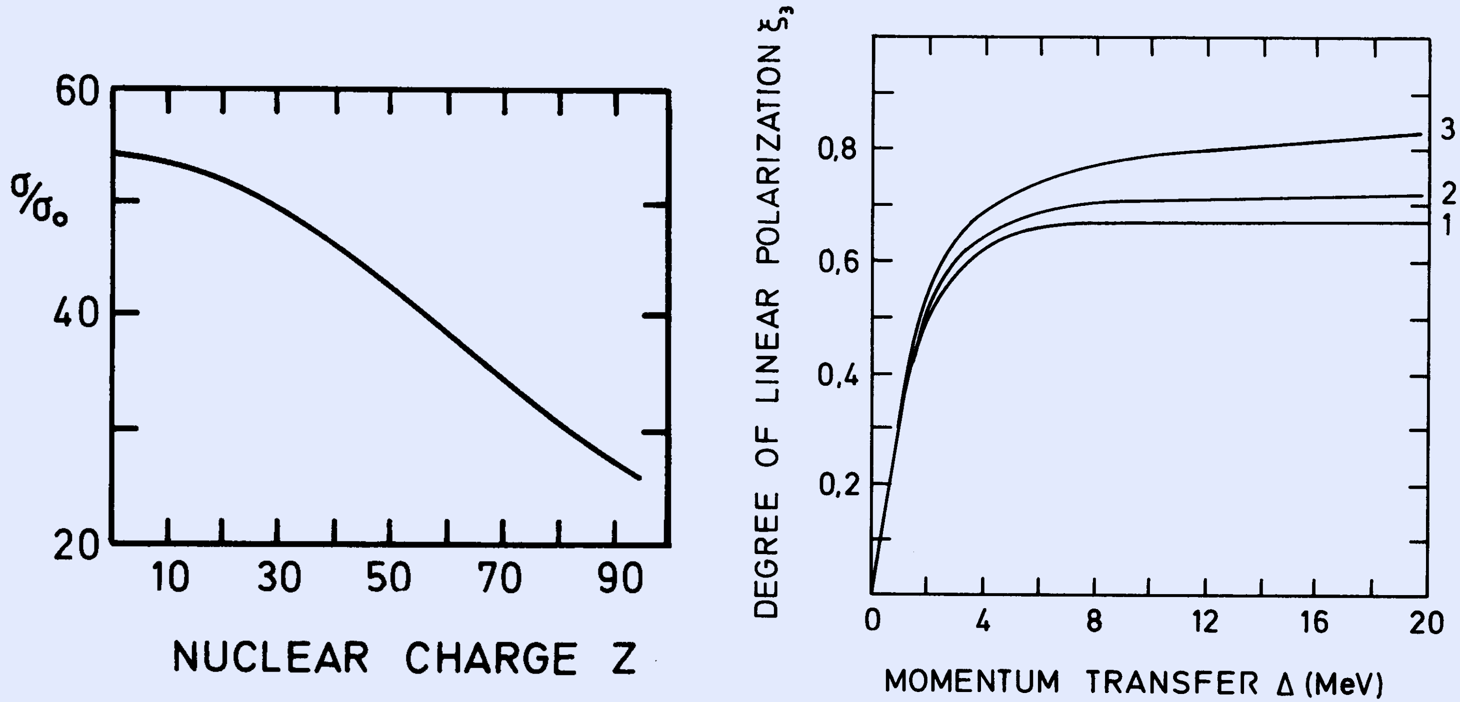
It is convenient to represent he amplitudes in the following form:

$$M_{++,+-} = \frac{2\alpha\omega}{\Delta^2}(Z\alpha)^2 A_{++,+-} \qquad (3)$$

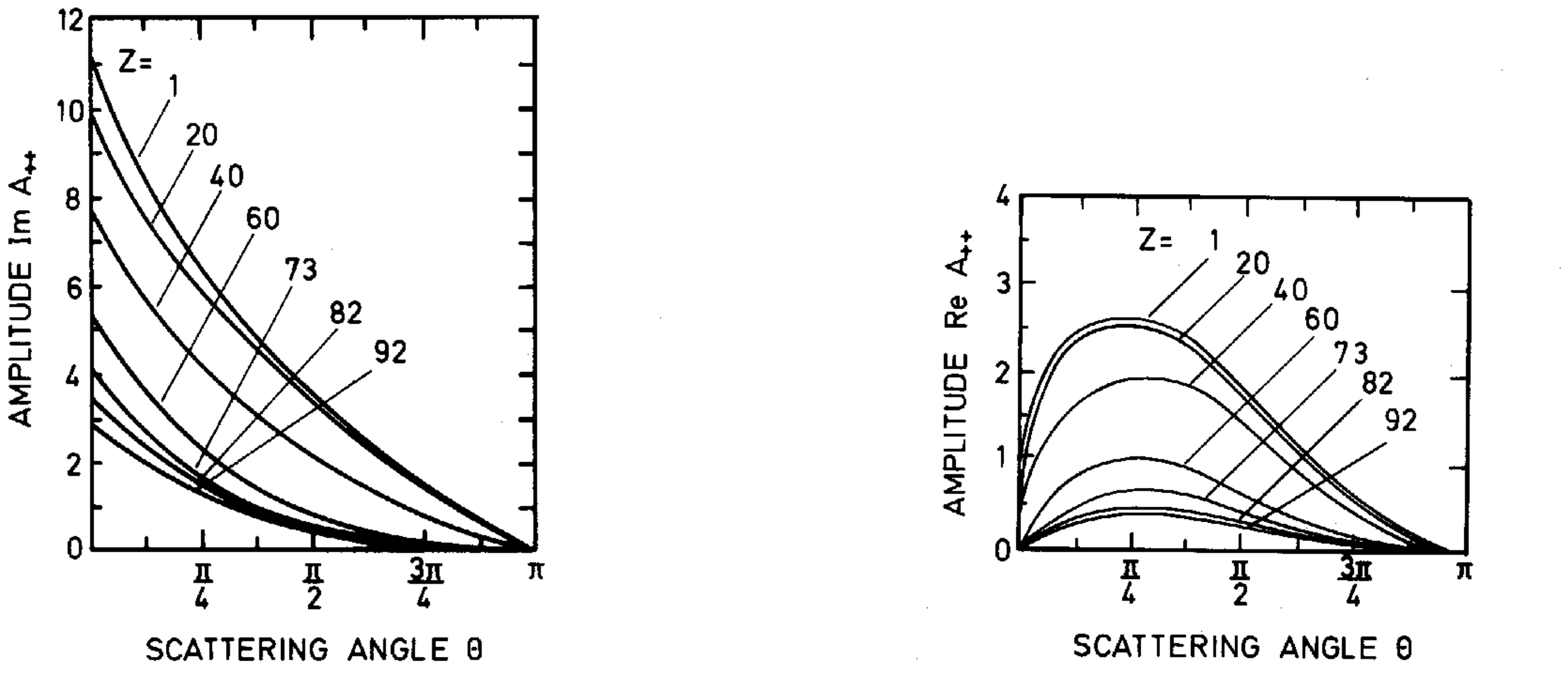




Imaginary parts of the Delbrück scattering amplitudes calculated in the small-angle high-energy approximation for different charge numbers Z.



Left: Total cross section for Delbrück scattering in units of $\sigma_\circ = (Z\alpha)^4 r_\circ^2/16\pi$.
Right: The degree of linear polarization ξ_3 at $Z = 1$ (1), $Z = 47$ (2), and $Z = 92$ (3).

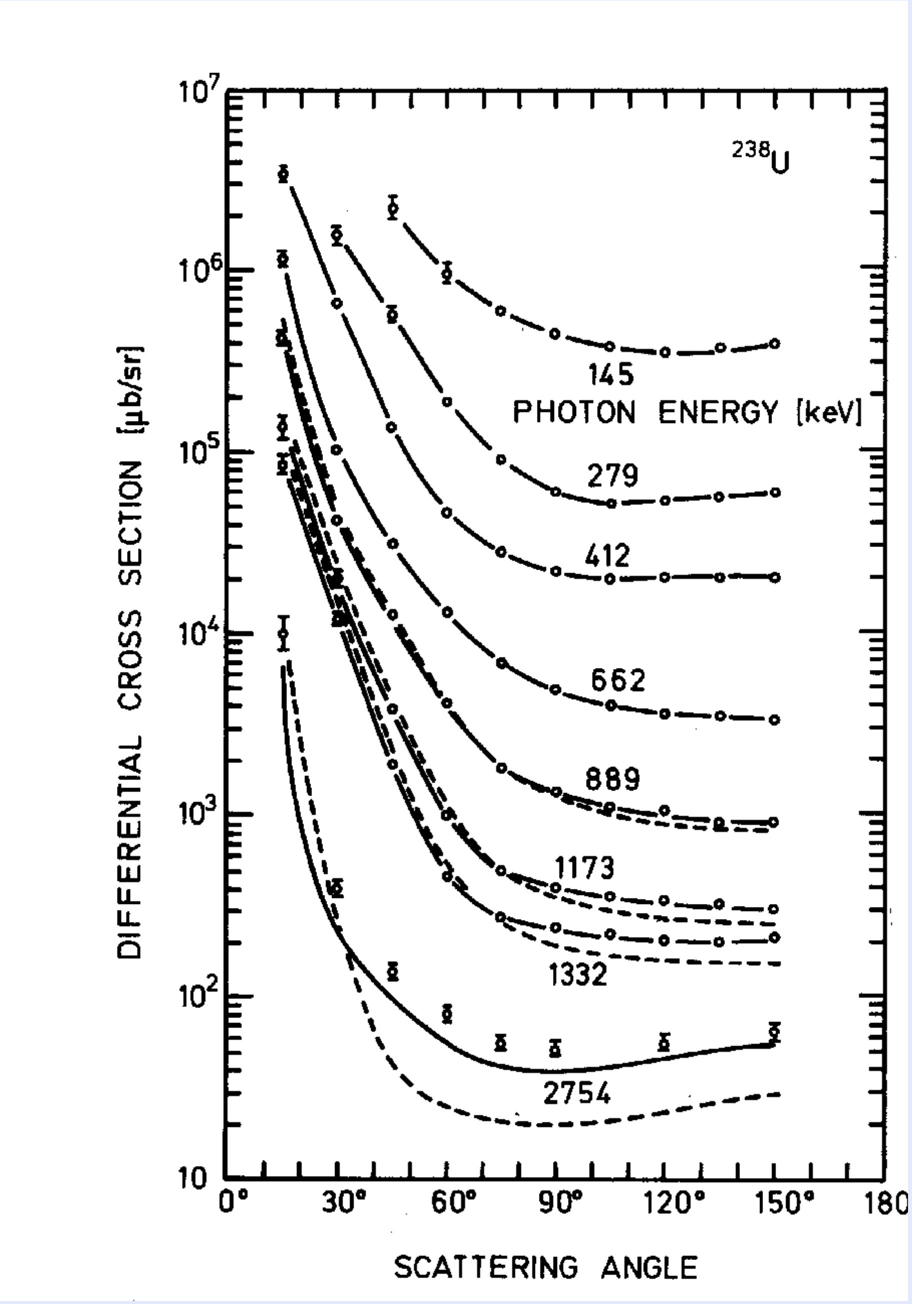


Imaginary (left) and real (right) parts of the no-helicity-flip Delbrück scattering amplitude calculated for the scaling limit at different Z.

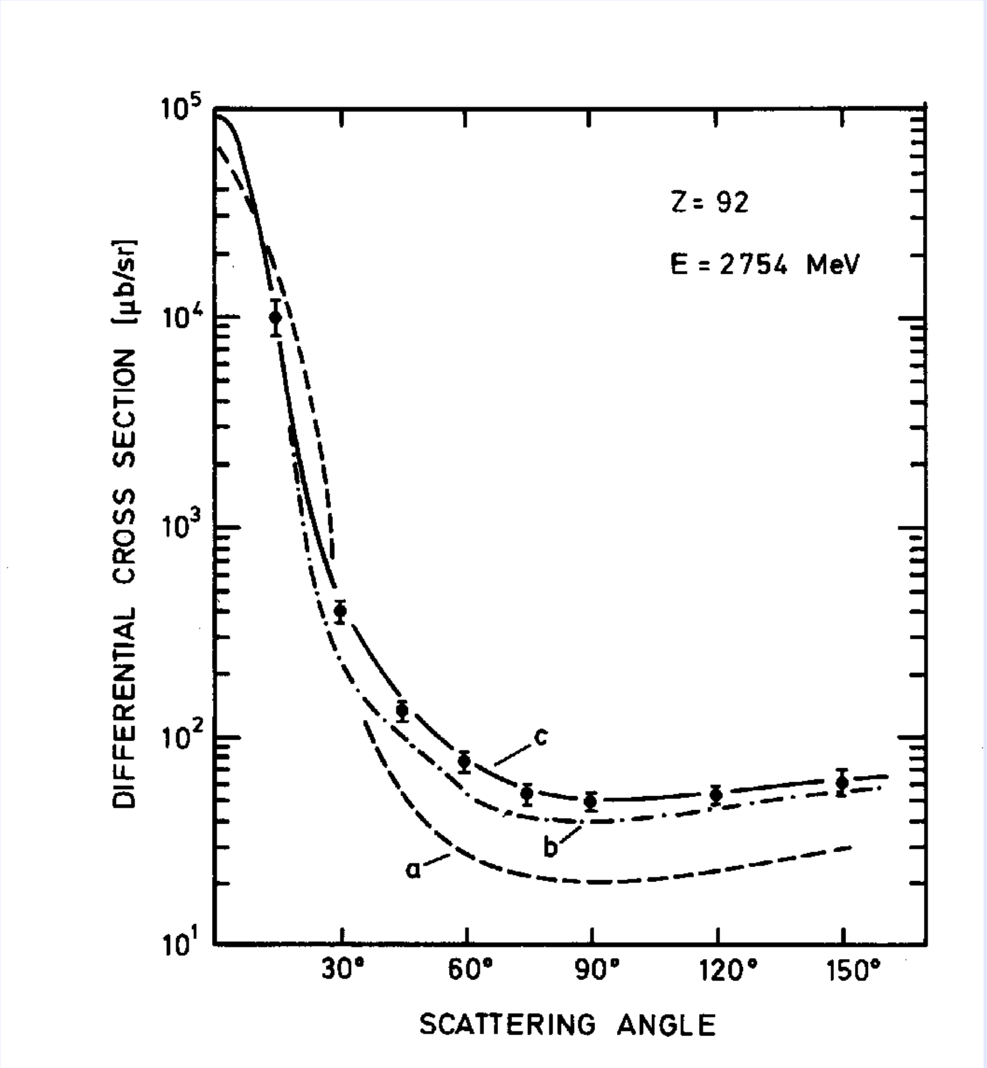
Experimental investigation of Delbrück scattering

Four different photon sources have been used :

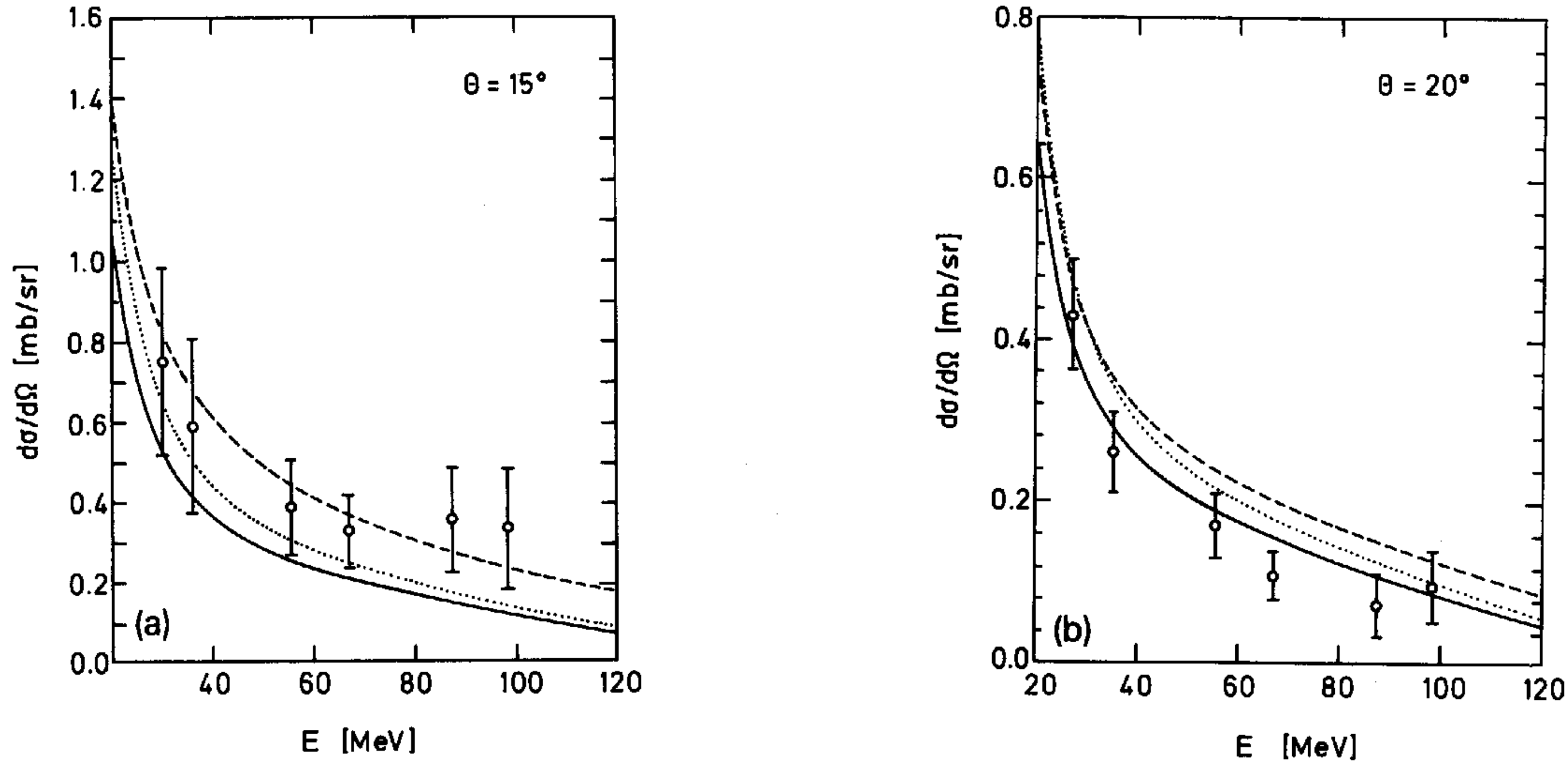
- Photons from the radioactive sources, for instance $^{24}\mathrm{Mg}$ ($\omega = 2.75$ MeV).
- Photons from the nuclear-reactions-like capture of thermal neutrons in the energy range $\omega = 4 - 12$ MeV.
- In the energy range $20 - 100$ MeV the experiment has been carried out with tagged bremsstrahlung photons. Delbrück scattering above 1 GeV has been investigated using bremsstrahlung photons without tagging.
- In the recent experiment at BINP, tagged backscattered Compton photons of energies $140 - 450$ MeV were used.



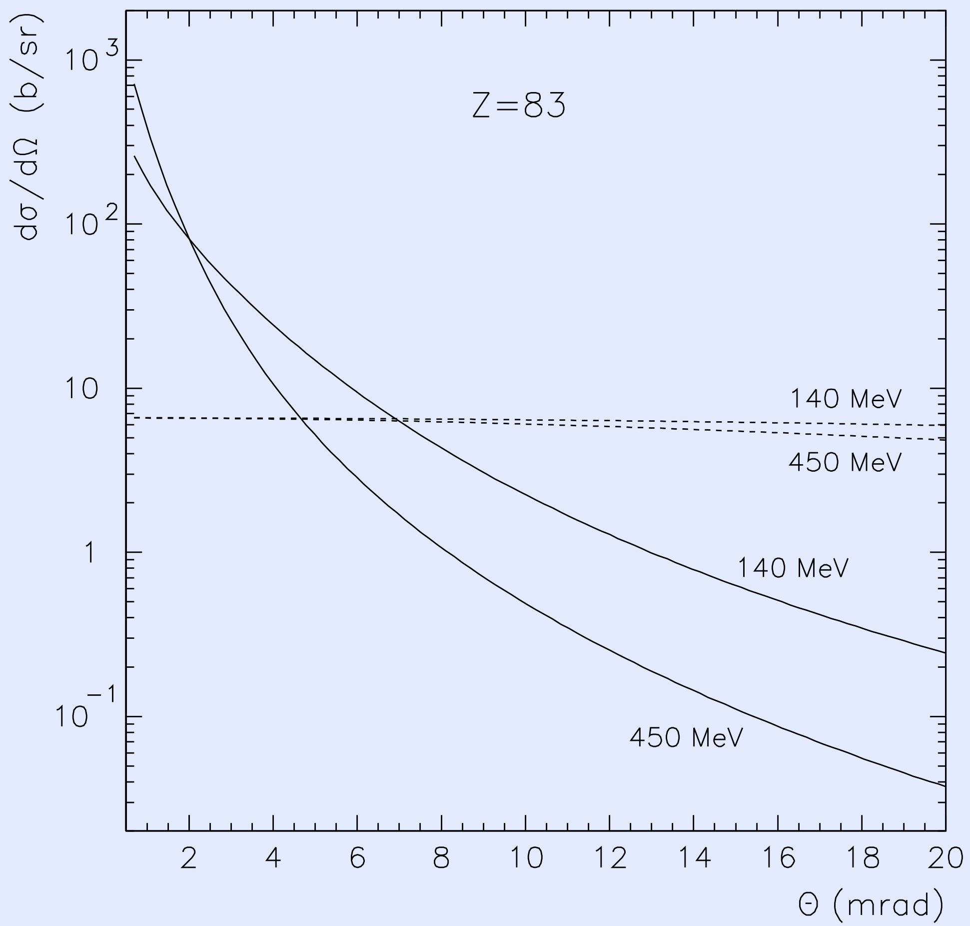
Elastic differential cross sections versus scattering angle with the photon energy as a parameter. The scattering target was uranium (Z=92). The solid lines contain the contributions from atomic Rayleigh scattering, nuclear scattering and Delbrück scattering, the latter calculated in the lowest-order Born approximation. For the dashed curves Delbrück scattering was omitted.



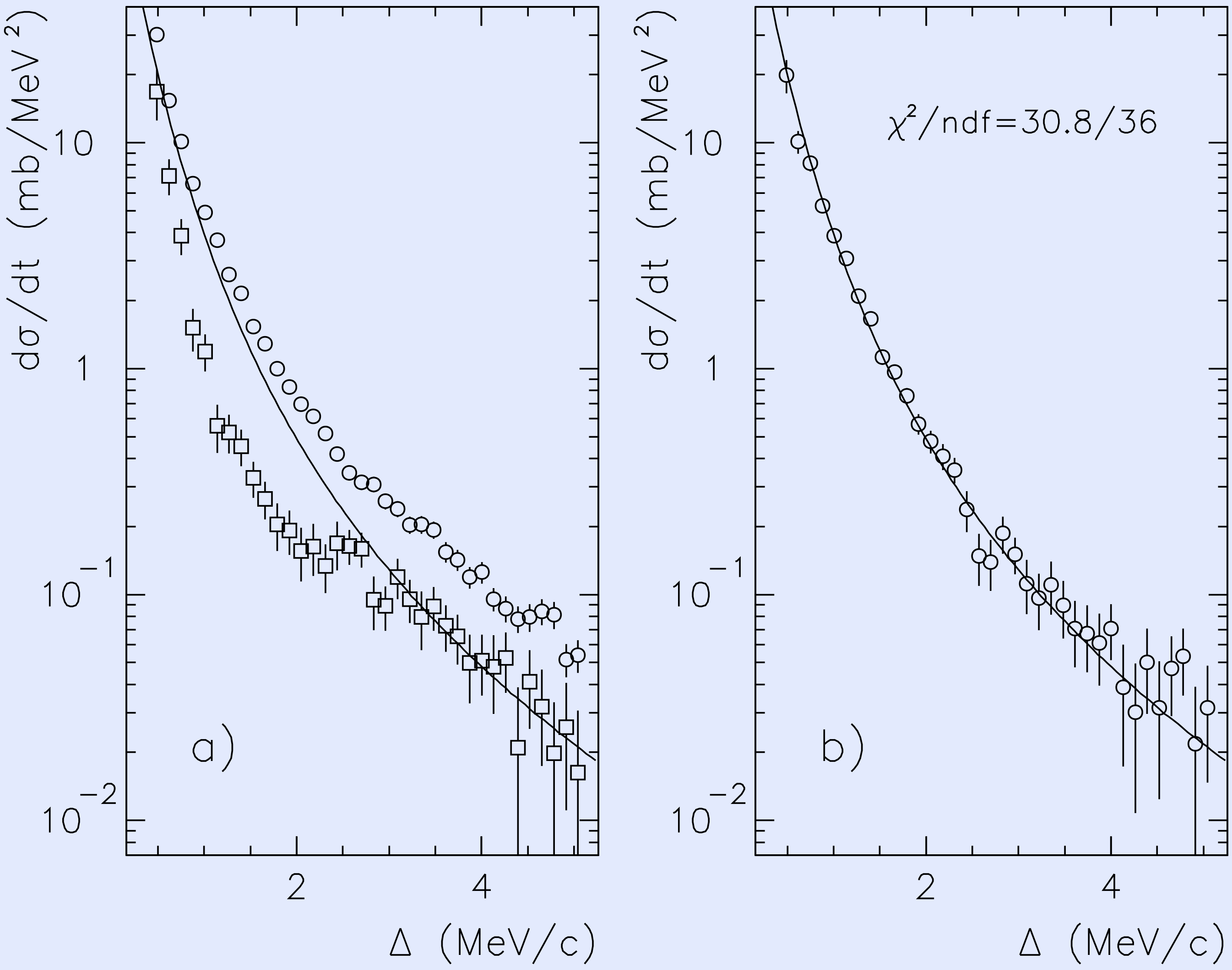
Experimental elastic differential cross sections versus scattering angle for Z=92 and E=2.754 MeV compared with predictions: (a) including atomic Rayleigh and nuclear scattering, (b) same as (a) but including also Delbrück scattering in the lowest-order Born approximation, (c) same as (b) but including also the empirical Coulomb correction term.



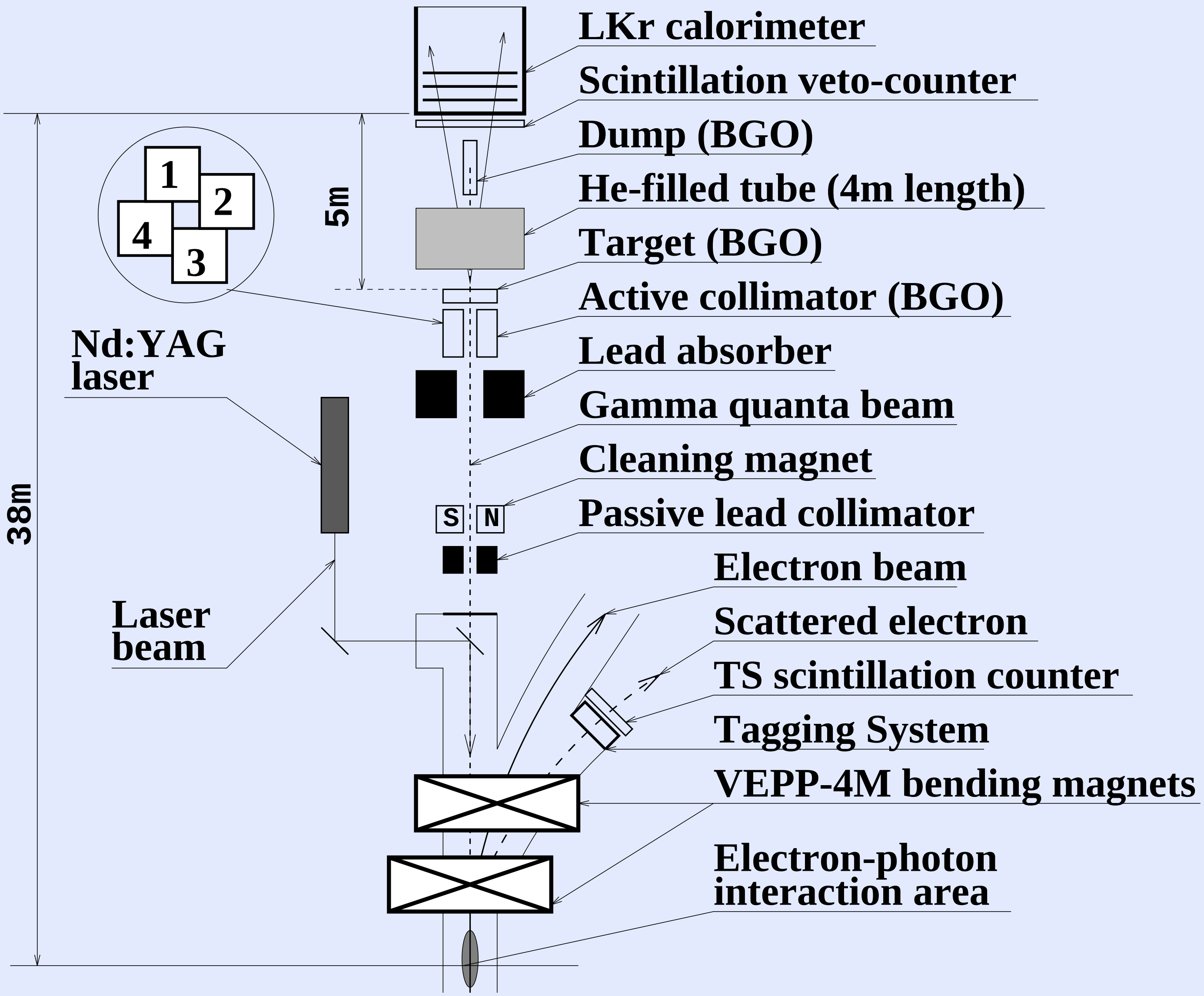
Experimental differential cross section for elastic photon scattering through $\theta = 15^\circ$ and $\theta = 20^\circ$ versus photon energy measured for Pb (Z=82) compared with predictions. Solid curve: including nuclear scattering and Delbrück scattering calculated in the large-angle high-energy approximation, dashed curve: same as solid curve but calculating Delbrück scattering in the lowest-order Born approximation, dotted curve: same as solid curve but calculating Delbrück scattering in the small-angle high-energy approximation.



The differential cross section for Delbrück (solid lines) and Compton (dashed lines) scattering on bismuth.



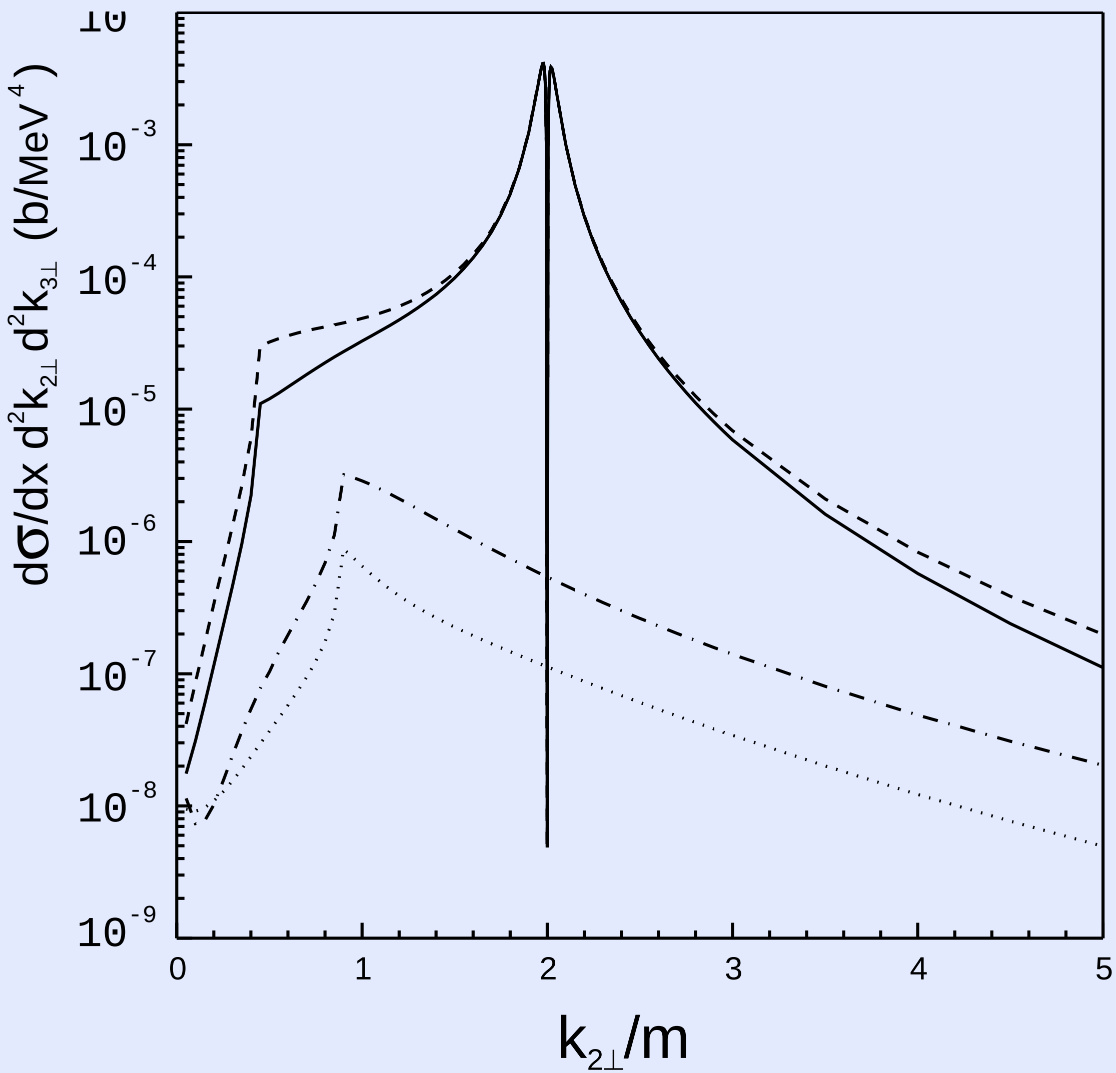
The differential cross section of photon scattering $d\sigma/dt$ as a function of the momentum transfer Δ for a molecule of bismuth germanate. (a) Experimental data (circles) and background (squares). (b) Experimental data after subtraction of background (circles). Solid line is the result of calculation.



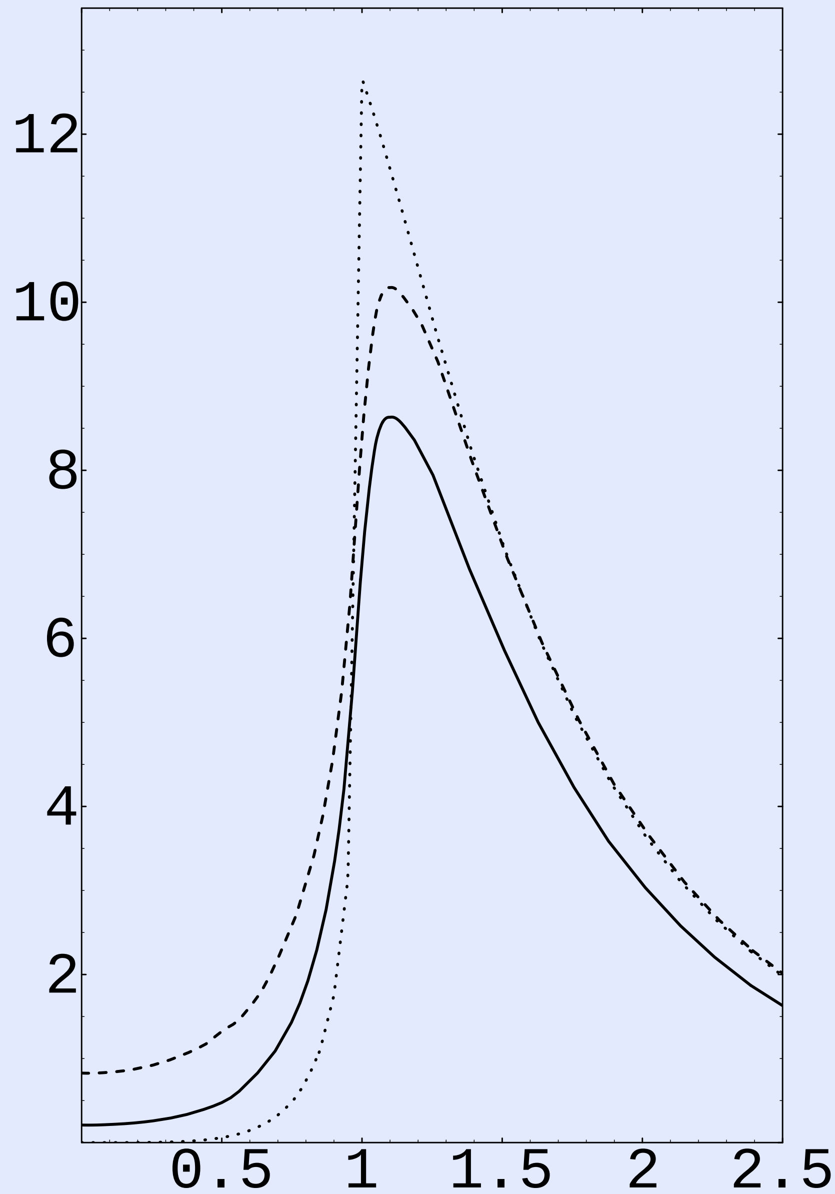
The experimental setup.

Photon splitting

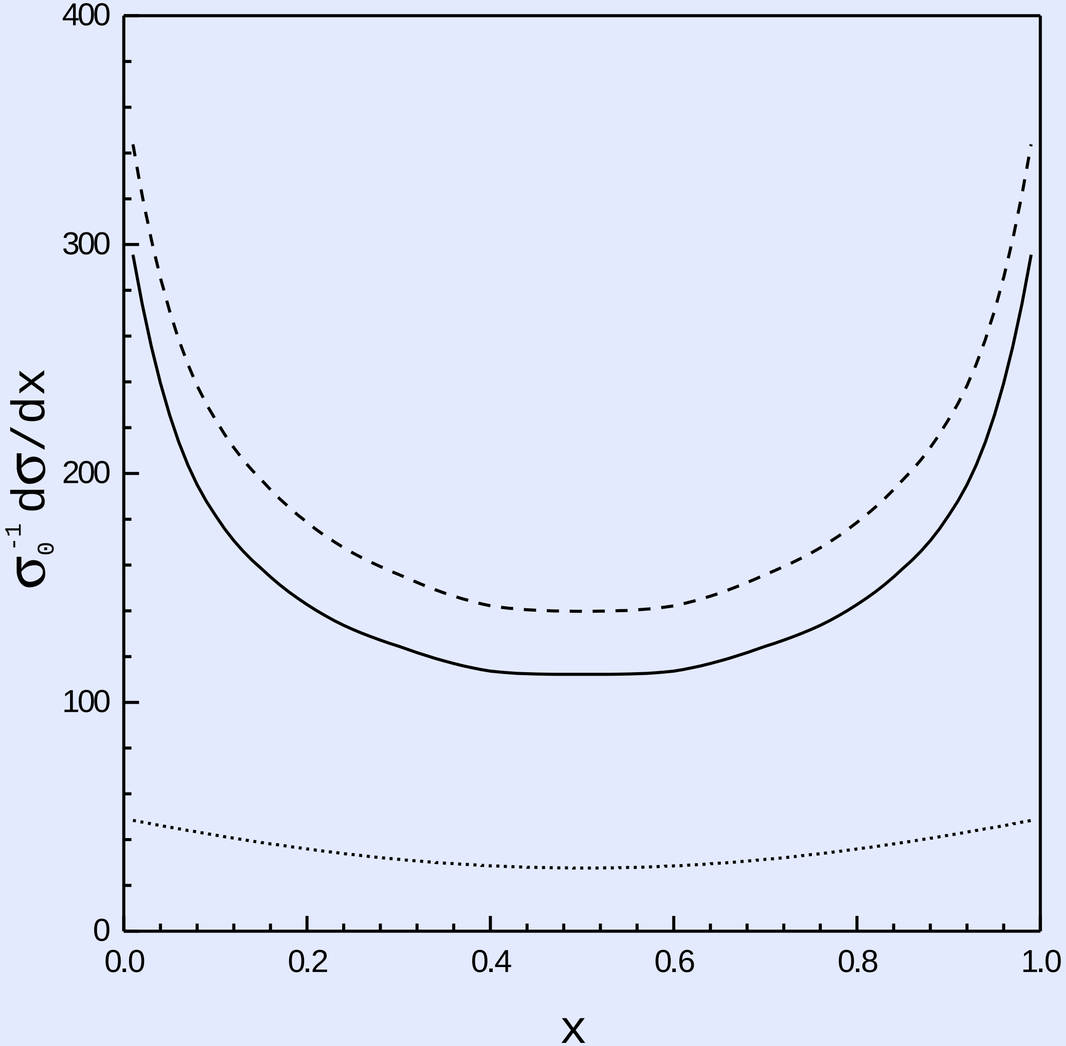
- The amplitudes were calculated in the lowest in $Z\alpha$ order, but for an arbitrary photon energy ω and scattering angle θ. These results are applicable only at small Z.
- In the same approximation, an essentially simpler form of the cross section was obtained using the Weizsäcker-Williams method providing the logarithmic accuracy.
- At $\omega \gg m$ and $\theta \ll 1$ the amplitudes were calculated exactly in $Z\alpha$ using the quasiclassical approximation.



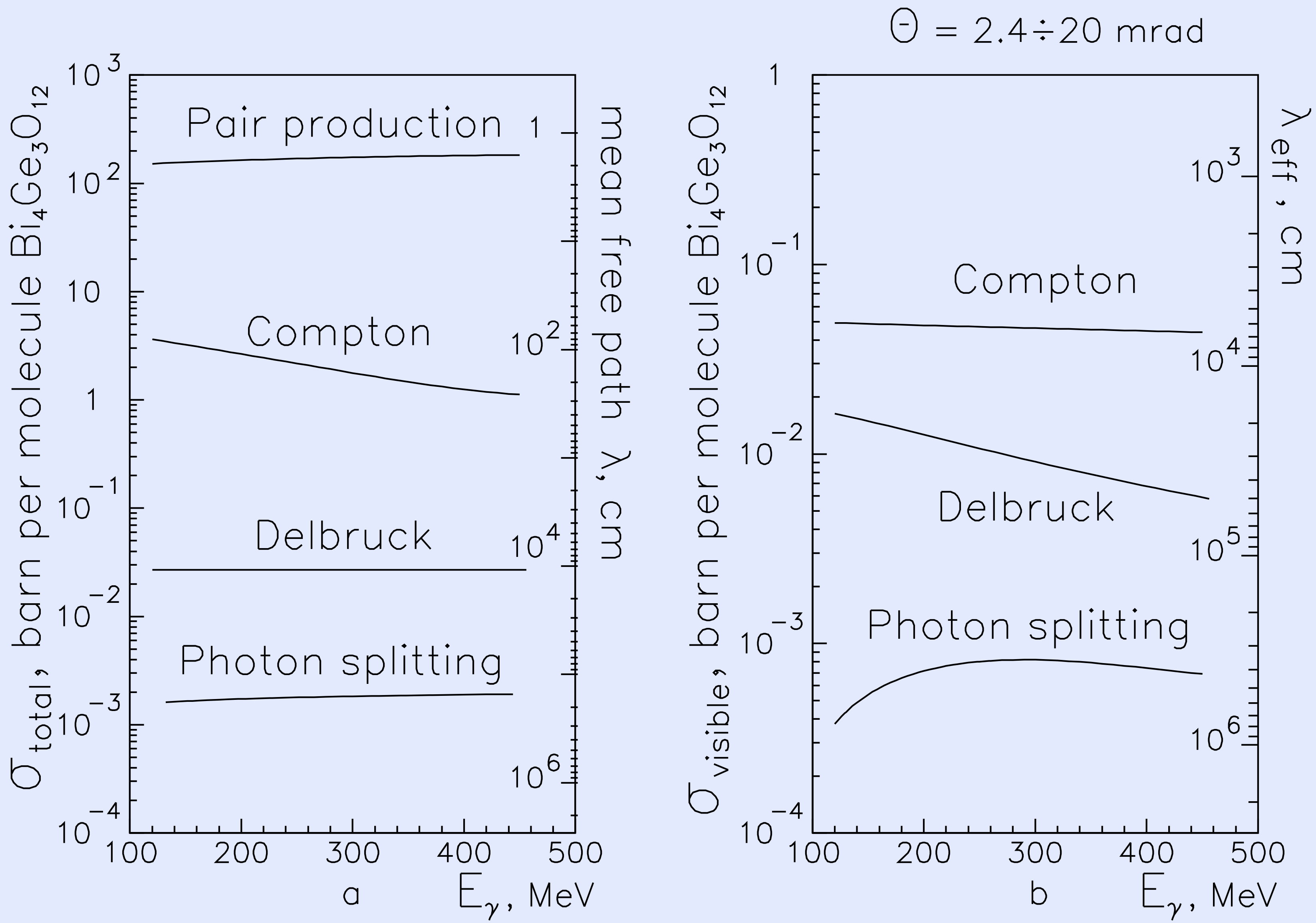
Differential cross section $d\sigma/dxd\boldsymbol{k}_{2\perp}d\boldsymbol{k}_{3\perp}$ vs $|\boldsymbol{k}_{2\perp}|/m$ in a screened Coulomb potential for different azimuth angle ϕ between vectors $\boldsymbol{k}_{2\perp}$ and $\boldsymbol{k}_{3\perp}$; $Z = 83$, $x = 0.1$, $\omega_1 = 1$GeV, $k_{3\perp} = 2m$. The dashed curve (Born approximation) and the solid curve (exact cross section) correspond to $\phi = \pi$. The dash-dotted curve (Born approximation) and the dotted curve (exact cross section) correspond to $\phi = 0$.



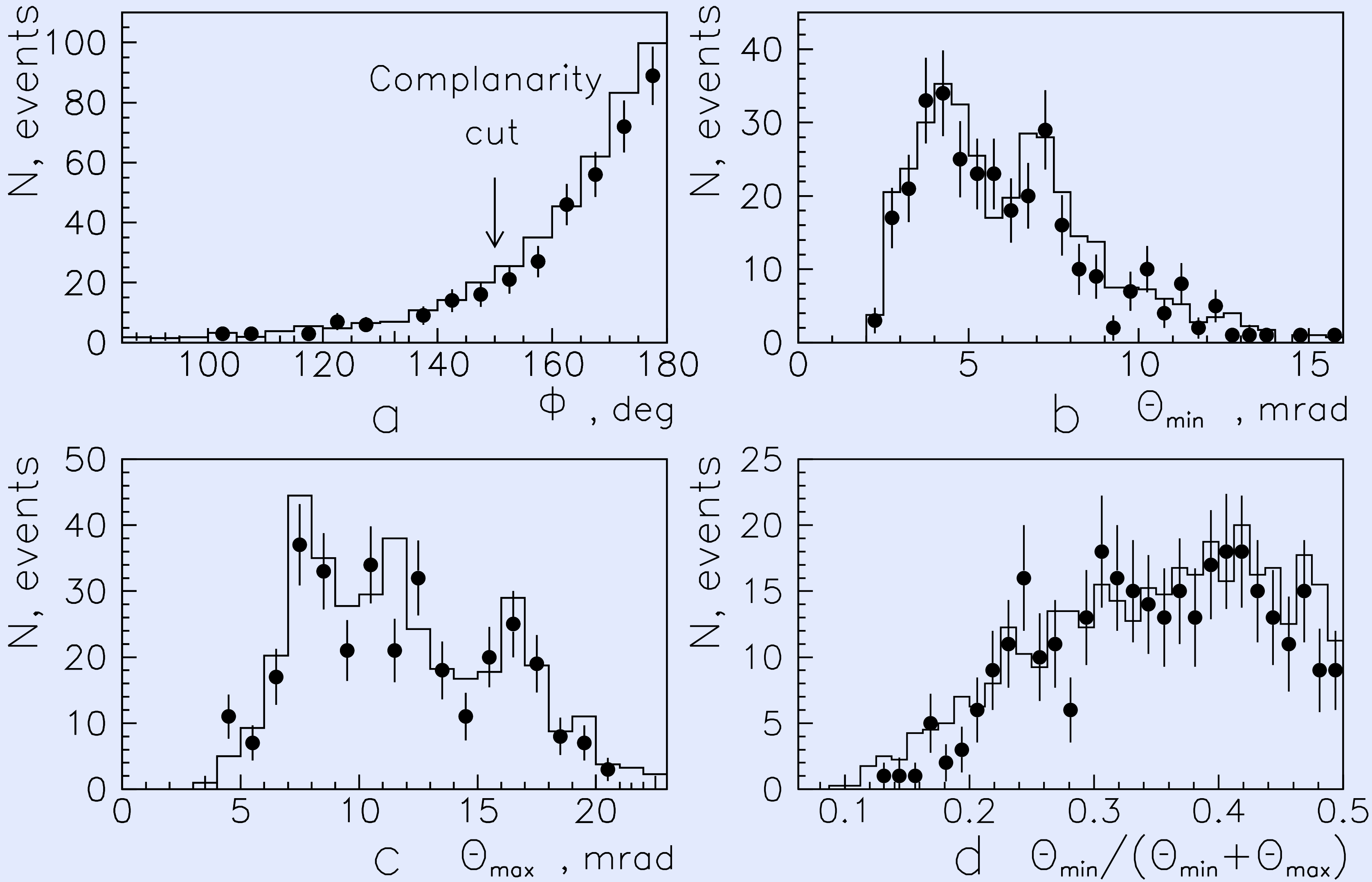
$m^2\sigma_0^{-1} d\sigma/dxd\boldsymbol{k}_{2\perp}$ vs $|\boldsymbol{k}_{2\perp}|/m$ for a screened Coulomb potential, $\omega_1/m = 1000$, $x = 0.5$, $Z = 83$, $\sigma_0 = \alpha^3(Z\alpha)^2/(4\pi^2 m^2) = 0.782 \cdot 10^{-9}\, Z^2$ b . The dashed curve corresponds to the Born approximation, the solid curve gives the exact result, and the dotted curve shows the result of the WW approximation.



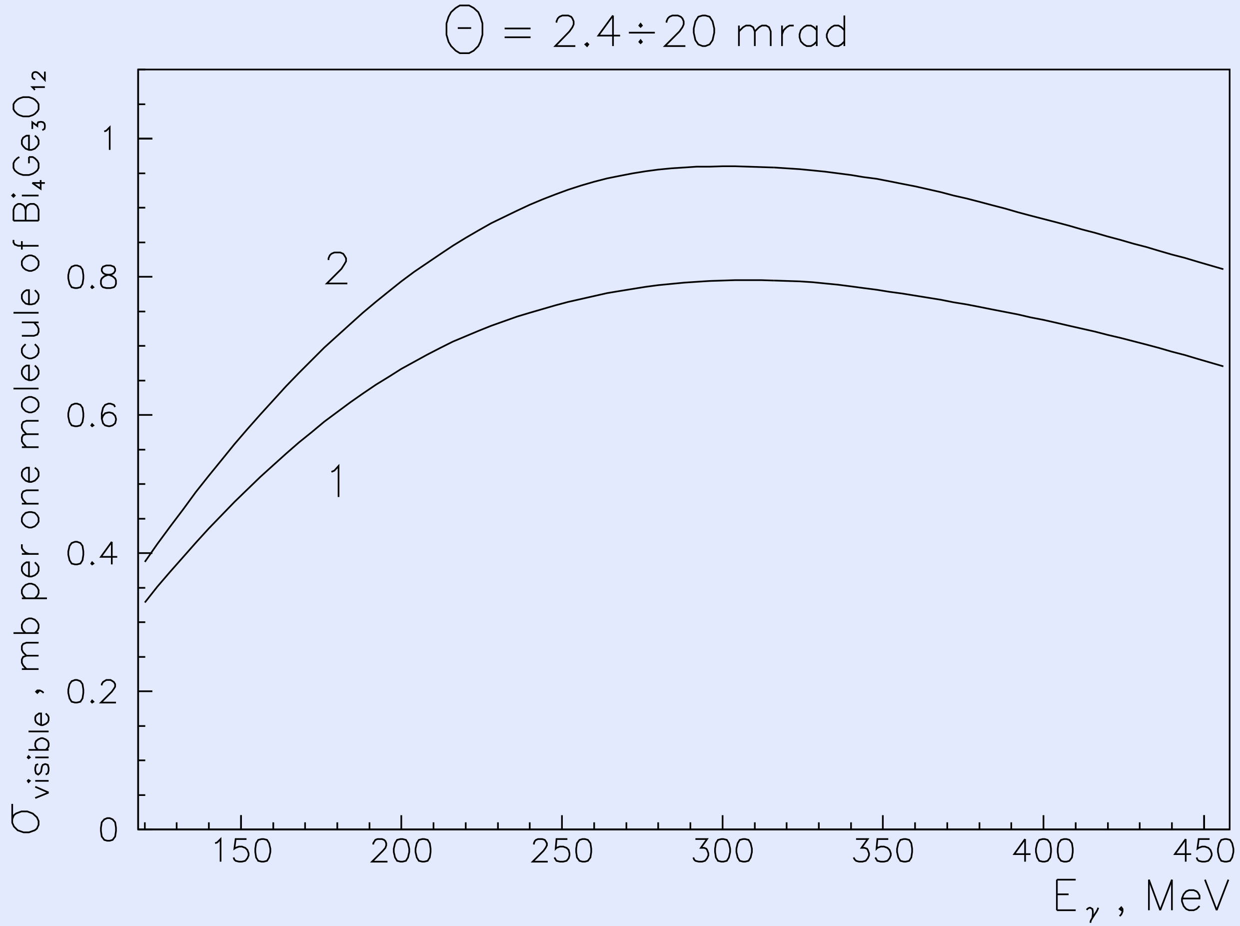
The dependence of $\sigma_0^{-1} d\sigma/dx$ on x for a screened Coulomb potential, $\omega_1/m = 1000$, $Z = 83$. The dashed curve corresponds to the Born approximation, the solid one gives the exact result, and the dotted curve shows the difference between the Born cross section and the exact one.



The calculated energy dependence of the total (a) and the visible (b) cross sections of various processes initiated by photons in BGO target (in units of barn per one molecule of $Bi_4Ge_3O_{12}$).



The number of the selected photon splitting events as a function of the azimuth angle between momenta of the outgoing photons (a); the polar angle $\theta_{min} = \min\{\theta_2, \theta_3\}$ (b); the polar angle $\theta_{max} = \max\{\theta_2, \theta_3\}$ (c); the variable $\tilde{x} = \theta_{min}/(\theta_{min} + \theta_{max})$ (d). In figures (b), (c), and (d) only events satisfying the complanarity cut $\phi \geq 150^\circ$ (see plot (a)) are included. Black circles present the experimental results, histograms are the results of Monte-Carlo simulation based on the exact in $Z\alpha$ photon splitting cross section.



The visible photon splitting cross section calculated exactly in $Z\alpha$ (1) and in the Born approximation(2) as a function of the initial photon energy.

Conclusion

- The high-energy photon splitting and Delbrück scattering in the atomic fields are reliably observed and well investigated experimentally.
- These nonlinear QED process are also studied in detail theoretically.
- The processes of photon splitting and Delbrück scattering can be adequately described only with the Coulomb corrections taken into account.
- At present, the experiment and the theory are consistent within the achieved experimental accuracy.