Simulation of Polarized Electron Interactions with Matter in the MeV Energy Range

Michał Drągowski

Marek Adamus Jacek Ciborowski Günter Weber Marta Włodarczyk

University of Warsaw, Faculty of Physics

National Centre for Nuclear Research, Świerk

Helmholtz Institut Jena

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Motivation

1. scarce experimental data
2. complexity of experiment optimization
3. beyond the scope of general purpose Monte Carlo codes

Interaction of electrons with matter

1. Mott scattering
   elastic scattering off target nuclei
2. Møller scattering
   elastic scattering off quasi-free target electrons
3. ionization
   scattering off bound target electrons
4. bremsstrahlung
   photon emission – negligible polarization change

Mott scattering

azimuthal asymmetry due to spin – orbit interaction

$$\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega}\right)_0 (1 + S(\theta)\vec{P}\cdot\vec{n})$$

$$\left(\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega}\right)_0 = \text{unpolarized cross section}$$

$$S(\theta) = \text{Sherman function}$$

$$\vec{P}\vec{n} = \frac{A_{LR}}{S_{\mathrm{eff}}}$$

the theoretical value of S is replaced with its effective value S_{eff}

N. F. Mott, *Proc. R. Soc.* A 124, 425 (1929)

Mott scattering

$$\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega} = \left(\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega}\right)_0 (1 + S(\theta)\vec{P}\cdot\vec{n})$$

$$\left(\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega}\right)_0 = |f(\theta)|^2 + |g(\theta)|^2$$

$$S(\theta) = i\frac{fg^* - f^*g}{|f(\theta)|^2 + |g(\theta)|^2}$$

$f(\theta) =$ spin–conserving amplitude

$g(\theta) =$ spin–flip amplitude

Mott scattering

$$\vec{P}' = \frac{(\vec{P}\cdot\vec{n} + S(\theta))\vec{n} + T(\theta)\vec{n}\times(\vec{n}\times\vec{P}) + U(\theta)(\vec{n}\times\vec{P})}{1 + S(\theta)\vec{P}\cdot\vec{n}}$$

$$S(\theta) = i\frac{fg^* - f^*g}{|f(\theta)|^2 + |g(\theta)|^2}$$

$$T(\theta) = \frac{|f(\theta)|^2 - |g(\theta)|^2}{|f(\theta)|^2 + |g(\theta)|^2}$$

$$U(\theta) = \frac{fg^* + f^*g}{|f(\theta)|^2 + |g(\theta)|^2}$$

J. Kessler, *Polarized Electrons*, Springer, Berlin (1985)

ELSEPA

- ELSEPA = ELastic Scattering of Electrons and Positrons by neutral Atoms and positive ions
- scattering amplitudes f and g determining $\left(\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega}\right)_0$, S, T and U
- relativistic (Dirac) partial–wave analysis in a central potential:

$$f(\theta) = \frac{1}{2\mathrm{i}k}\sum_{\ell=0}^{\infty}\left\{(\ell+1)\left[\exp(2\mathrm{i}\delta_{\kappa=-\ell-1})-1\right]+\ell\left[\exp(2\mathrm{i}\delta_{\kappa=\ell})-1\right]\right\}P_\ell(\cos\theta)$$

$$g(\theta) = \frac{1}{2\mathrm{i}k}\sum_{\ell=0}^{\infty}\left[\exp(2\mathrm{i}\delta_{\kappa=\ell})-\exp(2\mathrm{i}\delta_{\kappa=-\ell-1})\right]P_\ell^1(\cos\theta).$$

- assuming Fermi distribution for nuclear charge density
  + numerical description of atomic electrons density
  + approximate exchange correction

F. Salvat, A. Jablonski, C. J. Powell, *Comput. Phys. Commun.* 165, 157 (2005)

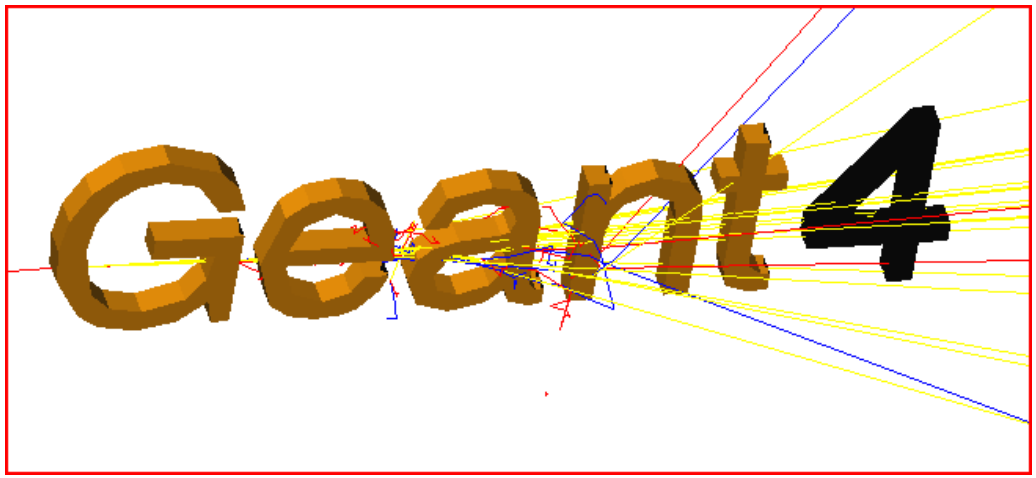
PEBSI Monte Carlo simulation

- PEBSI = Polarized Electron Bremsstrahlung SImulator
- simulation of bremsstrahlung emission from polarized electrons in thin solid state targets
- scattering amplitudes f and g determining $\left(\frac{\mathrm{d}\sigma_{\mathrm{Mott}}}{\mathrm{d}\Omega}\right)_0$, S, T and U from ELSEPA code
- analytical formulae for Møller scattering cross section and polarization transfer

G. Weber *et al.*, *Nucl. Instr. Meth. Phys. Res. B* 279, 155 (2012)
M. Drągowski *et al.*, *Nucl. Instr. Meth. Phys. Res. B* 389, 48 (2016)

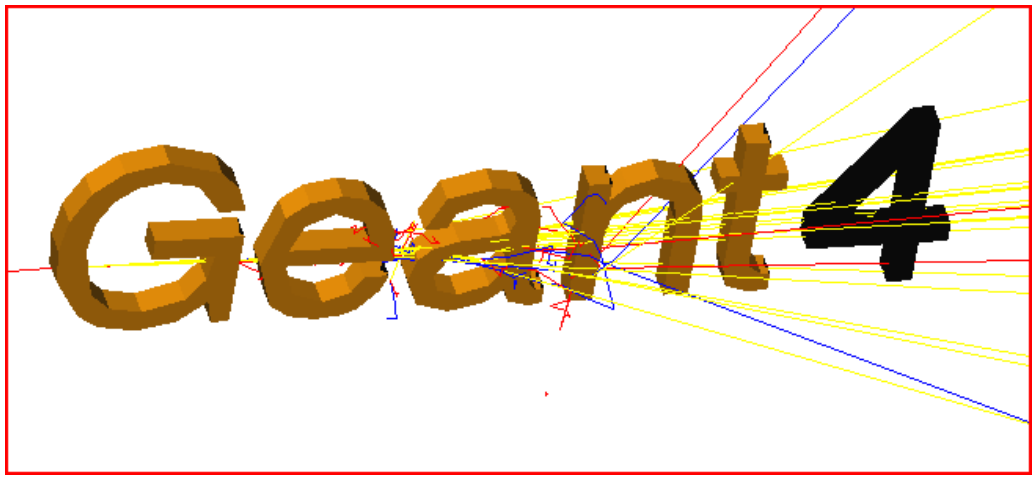
Geant4 Monte Carlo simulation

toolkit for the simulation of the passage of particles through matter



Geant4 Monte Carlo simulation

toolkit for the simulation of the passage of particles through matter

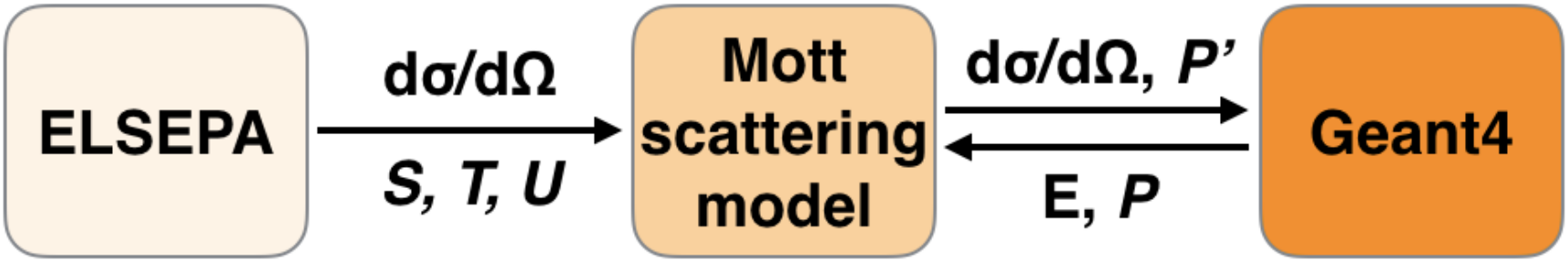


Coulomb Scattering:

- multiple and single scattering algorithms
- no dependence on polarization
- no polarization transfer

Sung Hun Kim *et al.*, *IEEE Trans. Nucl. Sci.* 62, 451 (2015)

Geant4 Extension

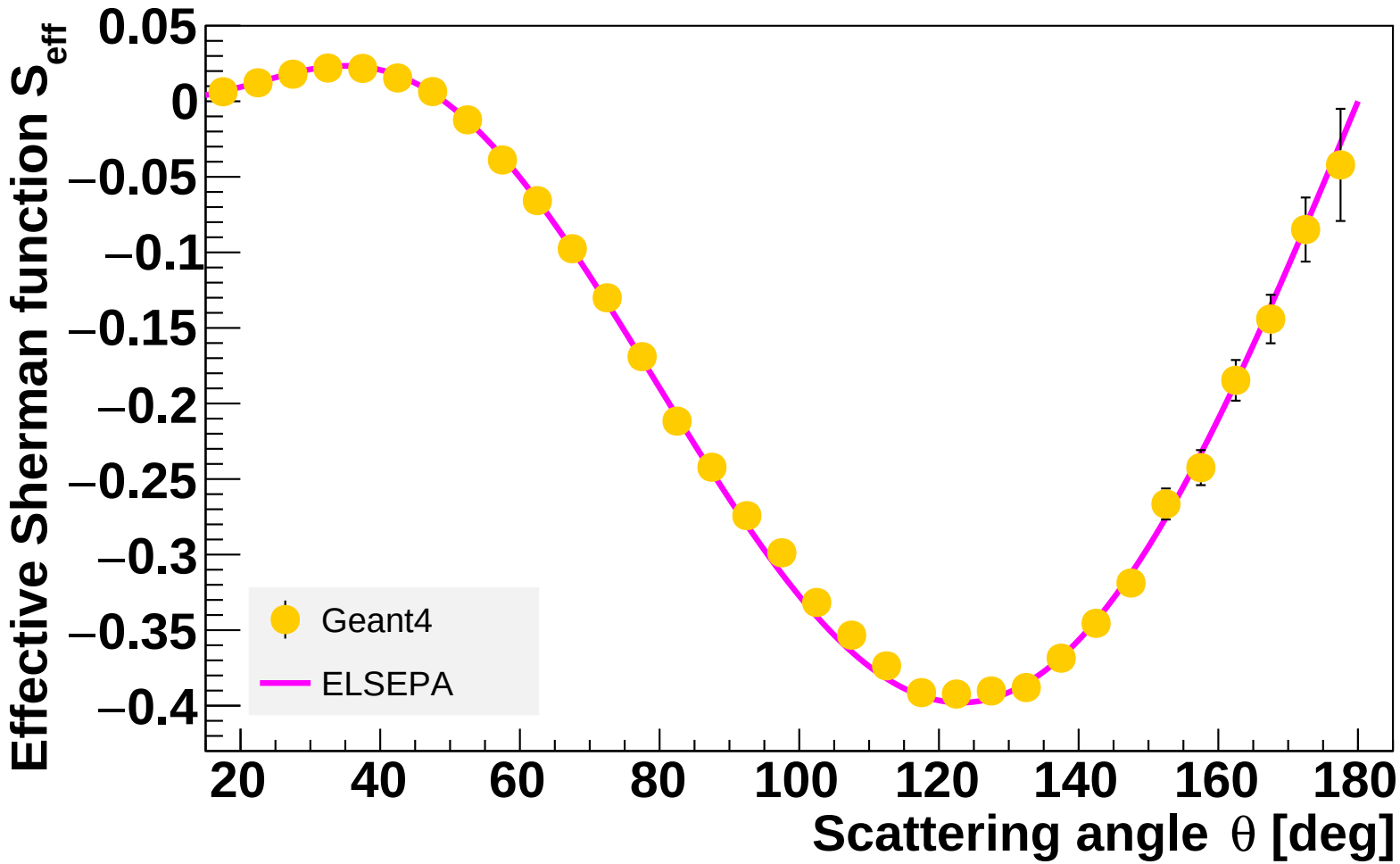


interaction model to replace the default Coulomb scattering model

cross section, momentum and polarization change calculated for given energy, momentum and polarization

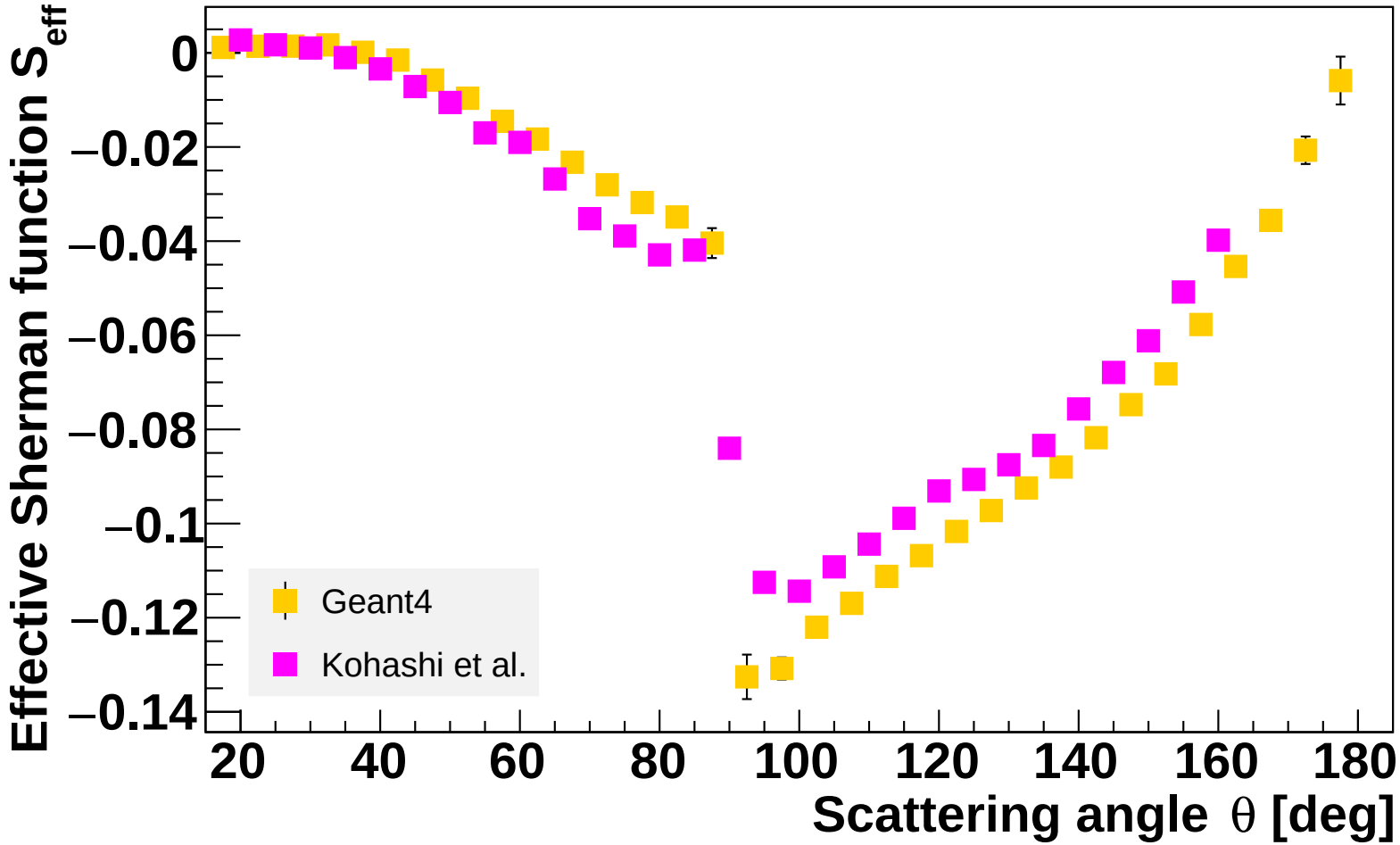
data from ELSEPA imported only at initialization

Simulated effective Sherman function
Comparison with theory



100 keV, 2 nm Au

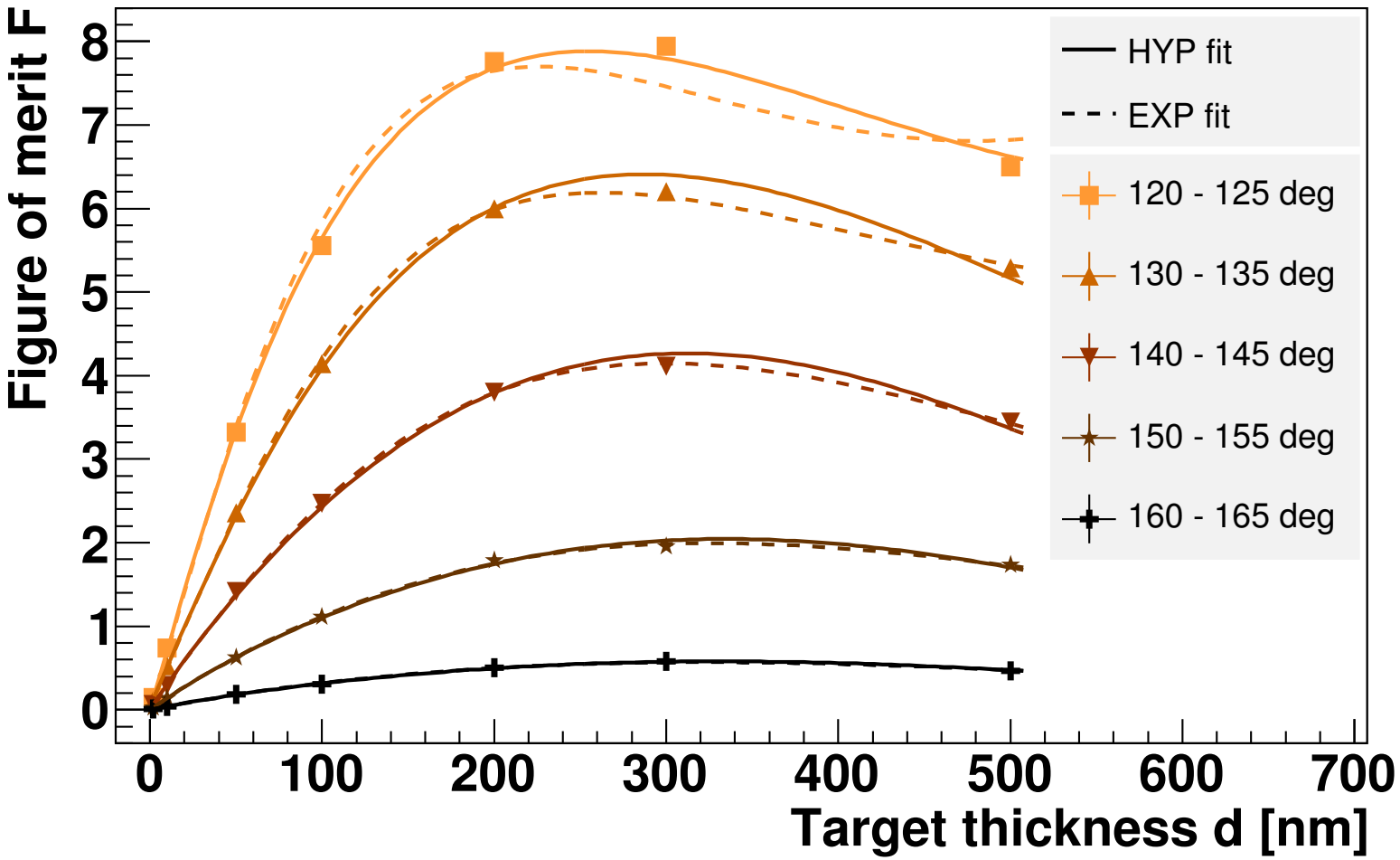
Simulated effective Sherman function
Comparison with measurement



100 keV, 500 nm Au

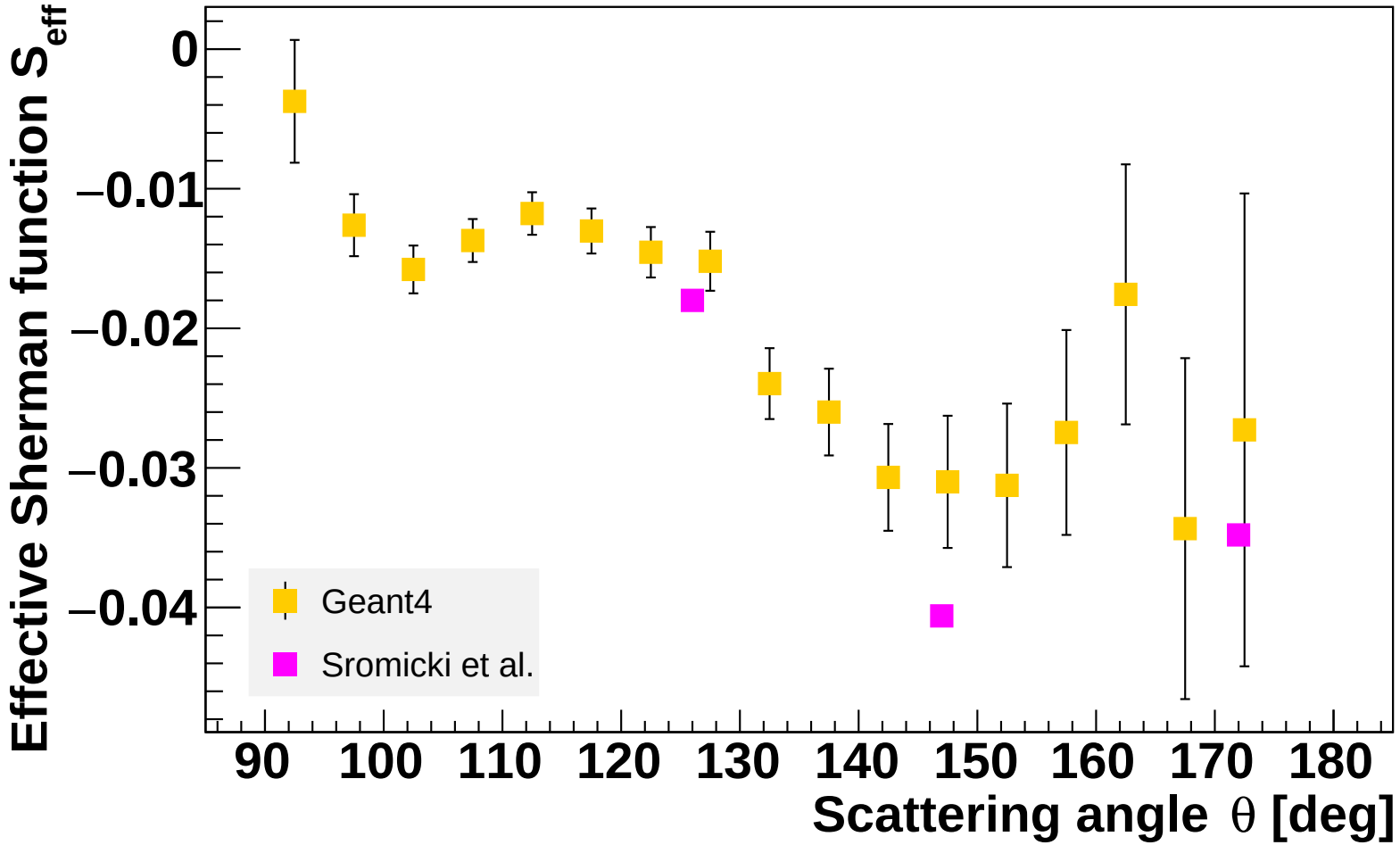
T. Kohashi, M. Konoto and K. Koike, Jpn. J. Appl. Phys. 45, 6468 (2006)

Figure-of-Merit $= S_{eff}^2 N$



100 keV, 2 – 500 nm Au

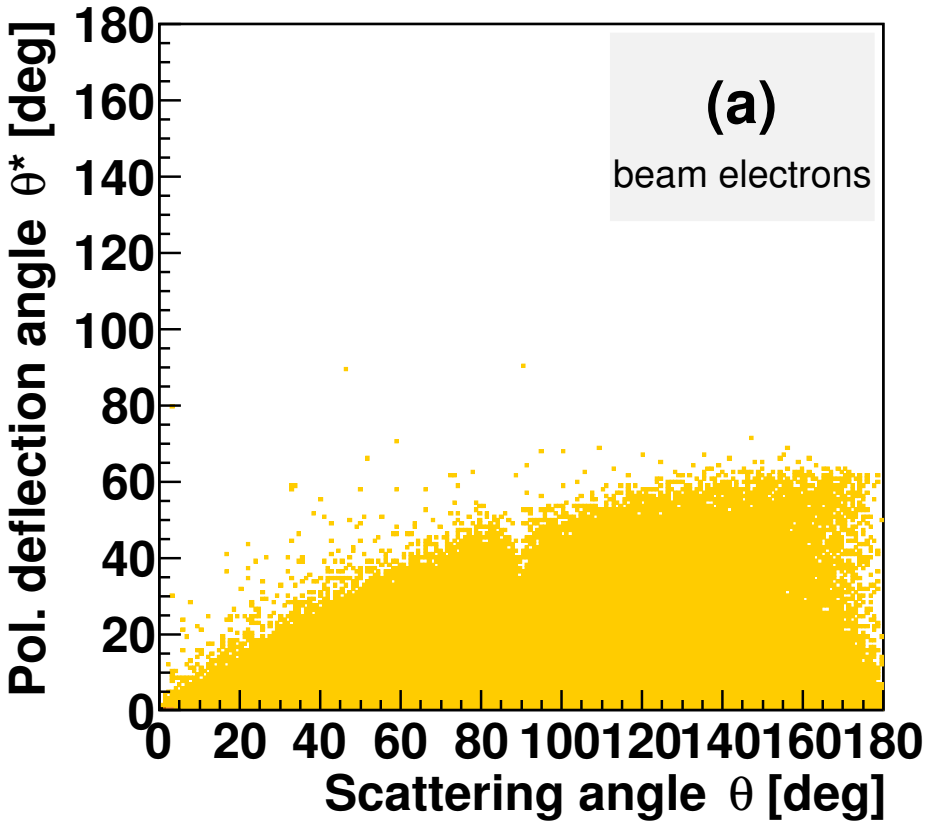
Simulated effective Sherman function
Comparison with measurement

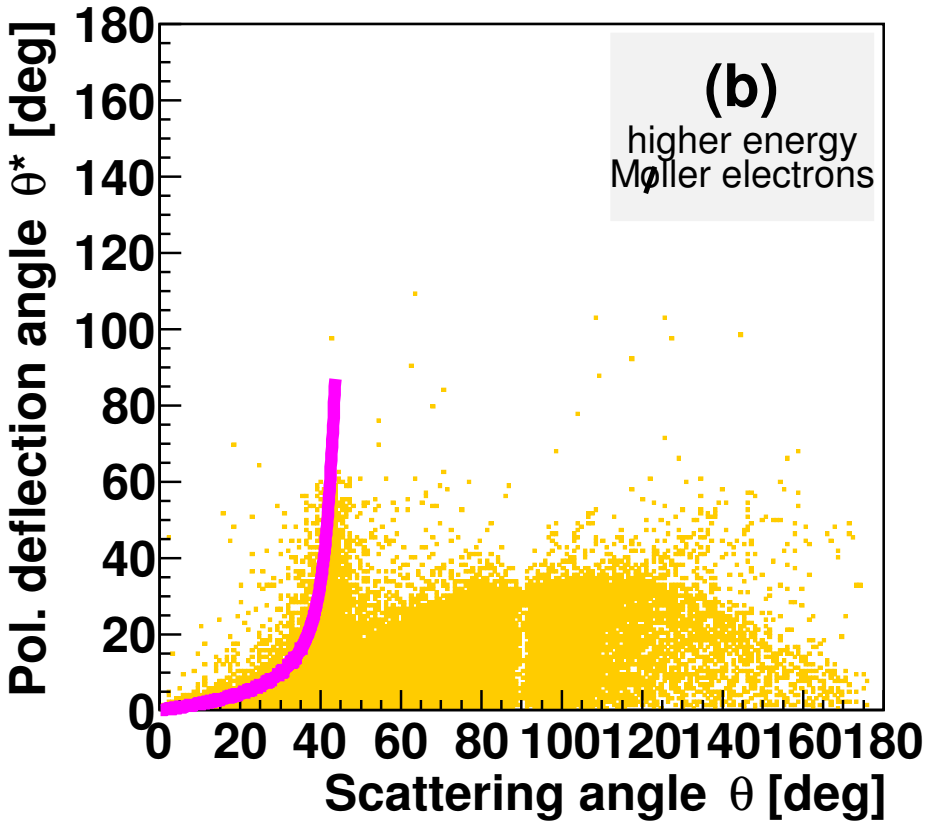


14 MeV, 210 μm Pb

J. Sromicki et al., Phys. Rev. Lett. 82, 57 (1999)

Depolarization





100 keV, 10 nm Au

Summary

1. encouraging results of comparison with experimental data
2. applications:
   - computation of the effective Sherman function
   - experiment optimization
   - depolarization of electron beams passing through matter
3. further validation ongoing (higher energies)

Acknowledgements

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