Coincidence Studies of Fragmentation Processes at FAIR

MTA atomki DEBRECEN

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(e,2e) on ions

Use neutral atom, eg, He, as source of quasi-free electrons

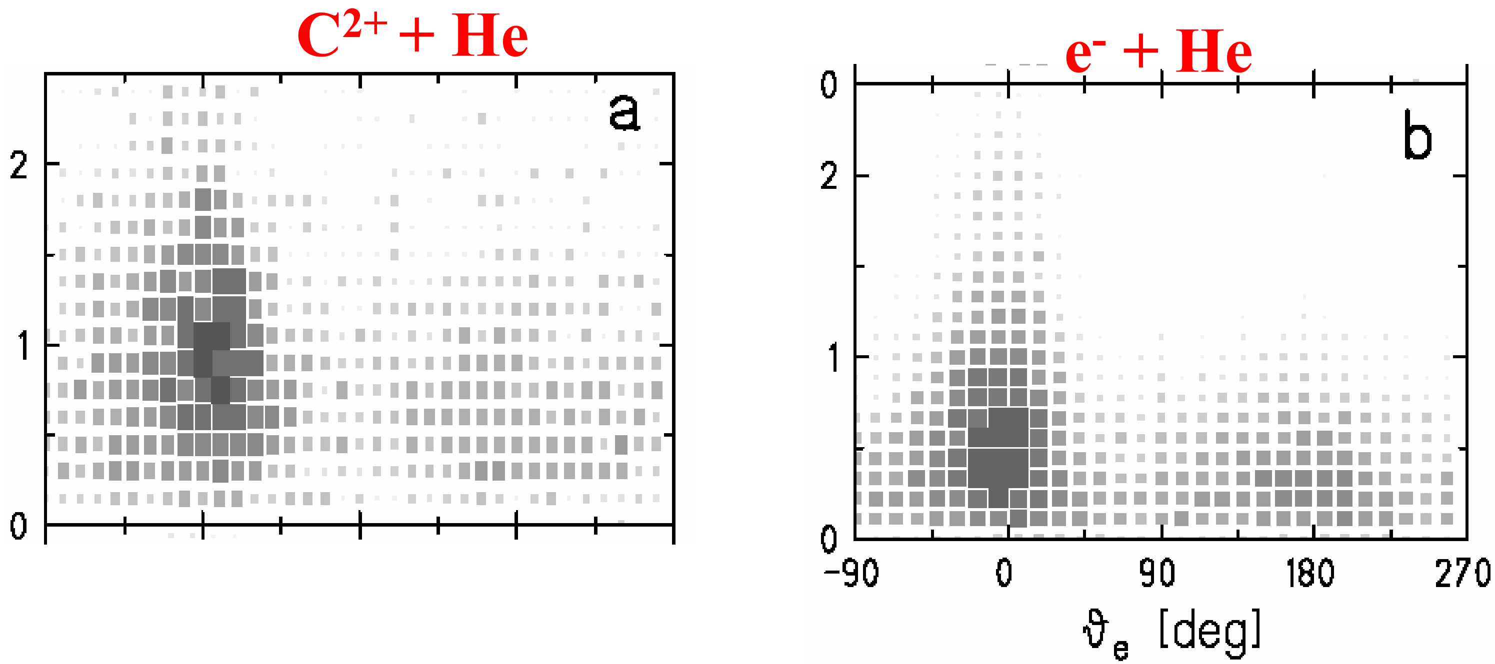


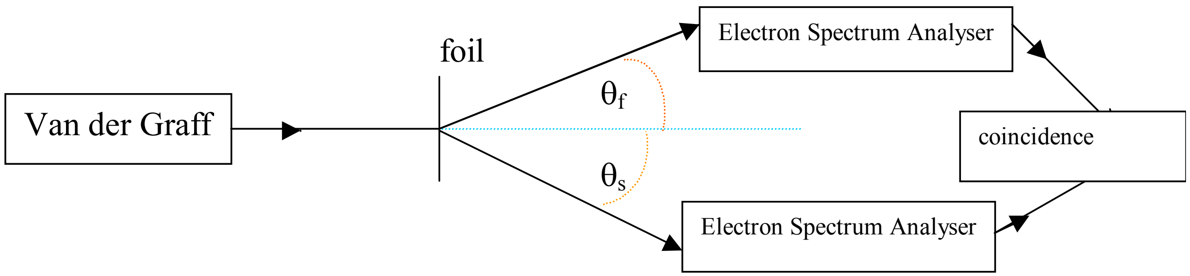
FIG. 3. Amount of the scaled momentum transfer q^* (see text) versus angle ϑ_e between $\vec{q}$ and the emitted electron in coplanar geometry for C^{2+} ionization (a) in inverse kinematics for simultaneous projectile and target ionization with $|\vec{P}_{\mathrm{Te}}| \geq |\vec{P}_T|$ and He ionization (b) by 2 keV electron impact (see text). The Z scale is logarithmic with ten steps from the minimum to the maximum cross section in each column represented by different sizes of the symbols.

What Physics would we expect to see in an electron impact ionization processes on a multi-charged ion?

(e,2e) on deep inner shells already performed at relativistic energies

Inner Shell Ionization of Heavy Metal Targets by Electron Impact at Relativistic Energies

Tübingen Experiments: (15% absolute error)- Nakel and collaborators



L and K shell ionization of copper, silver, gold and uranium targets in coplanar symmetric, coplanar asymmetric, coplanar constant Θ_{12} geometries with impact energies of 300 and 500 keV

Everything in sight is relativistic

- the incident and scattered electrons are fast
- the target electron is in the inner most shell of a heavy atom

A number of attempts were made to calculate TDCS notably Bell (1989), Das and Konar (1974) and Jakubaßa-Amudsen (1989,1992)

Some assumptions made

- Plane Wave Born Approximation factorises

false see Keller & Whelan (1994)

- Spin flip terms unimportant

false see Walters et al (1992)

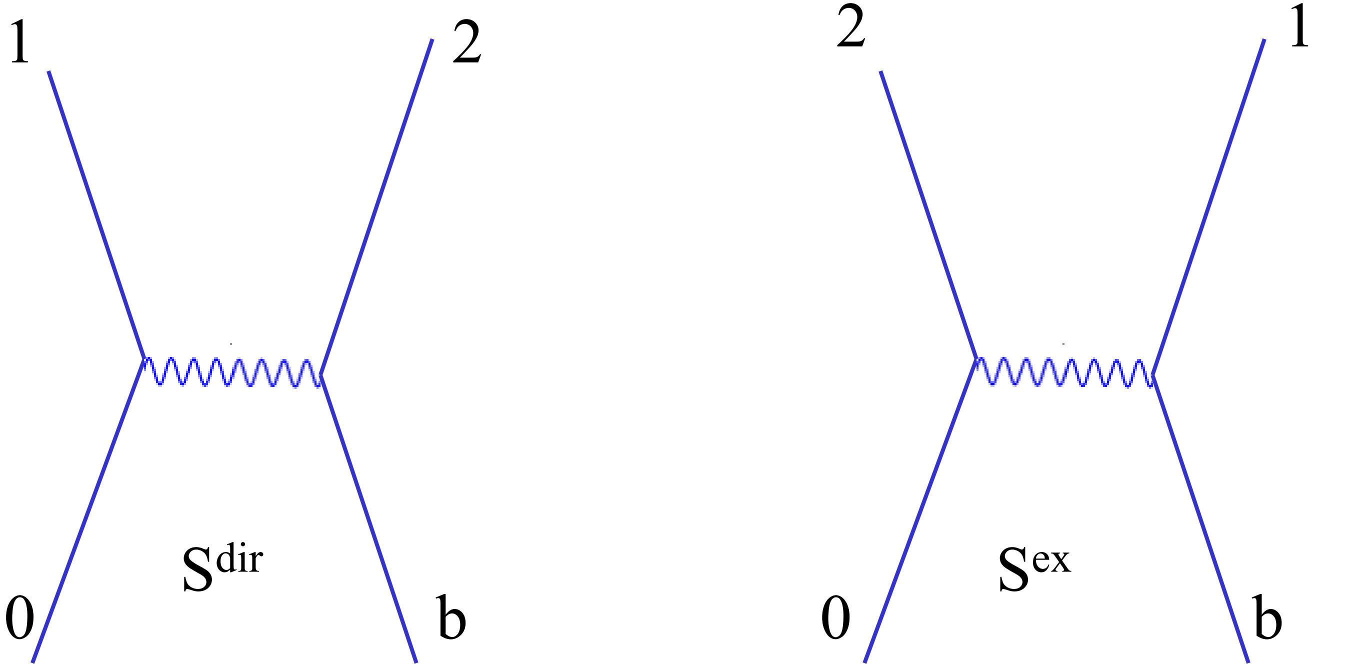
- Could use semi-relativistic wave functions

false

Theory

Relativistic Distorted-Wave Born Approximation

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE_2} = \frac{(2\pi)^2}{c^6}\frac{k_1 k_2}{k_0} E_0 E_1 E_2 \frac{N_\kappa}{2N_m} \sum_{\varepsilon_1\varepsilon_0\varepsilon_2\varepsilon_b} |\langle k_1\varepsilon_1, k_2\varepsilon_2|\hat{S}|k_0\varepsilon_0, \kappa\varepsilon_b\rangle|^2$$



$$S^{\mathrm{dir}} = -\,\mathrm{i}\int \mathrm{d}^4x\, \bar{\psi}_1(x)\gamma_\mu A^\mu(x)\psi_0(x)\,,$$

where the four potential $A^\mu(x)$ is given by

$$A^\mu(x) = \int \mathrm{d}^4y\, D^0_{\mu\nu}(x-y)J^\nu(y)$$

$$\langle k_1\varepsilon_1\, k_2\varepsilon_2 |\, S \,| k_0\varepsilon_0\ \kappa\varepsilon_b \rangle = S^{\mathrm{dir}} - S^{\mathrm{ex}}$$

$D^0_{\mu\nu}(x-y)$ is our free photon propagator which we can write as

$$D^0_{\mu\nu}(x-y) = \frac{-\,4\pi}{c}\,\mathrm{i}g_{\mu\nu}\int \frac{\mathrm{d}^4k}{(2\pi)^4}\,\frac{\mathrm{e}^{\mathrm{i}k(x-y)}}{k^2+\mathrm{i}\varepsilon}$$

and $J^\nu(y)$ is the fermion current

$$J^\nu = \bar{\psi}_2(y)\gamma^\nu\psi_{\mathrm{b}}(y)$$

$$\Longrightarrow$$

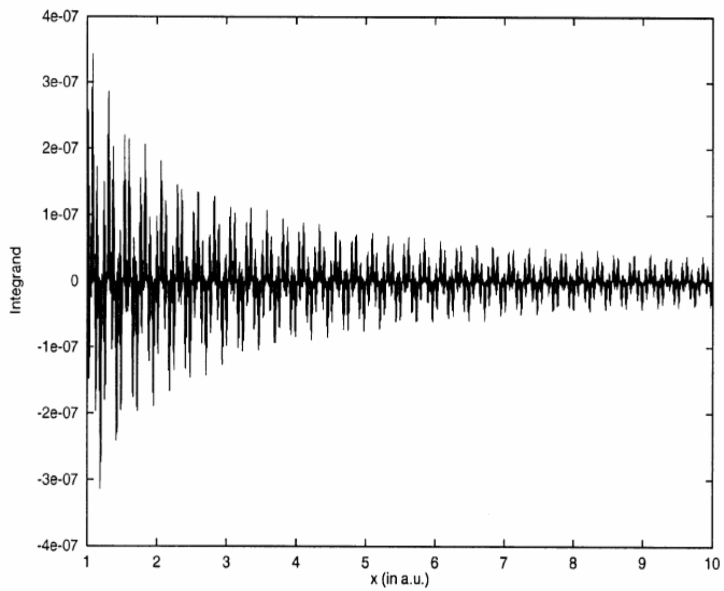
$$S^{\mathrm{dir}} = \mathrm{i}\int \mathrm{d}^4x \int \mathrm{d}^4y\, \psi^\dagger_{k1,\varepsilon 1}(x)\gamma^0\gamma^\mu\psi_{k0,\varepsilon 0}(x)D^0_{\mu\nu}(x-y)\psi^\dagger_{k2,\varepsilon 2}(y)\gamma^0\gamma^\nu\psi_{\kappa,\varepsilon\mathrm{b}}(y)\,,$$

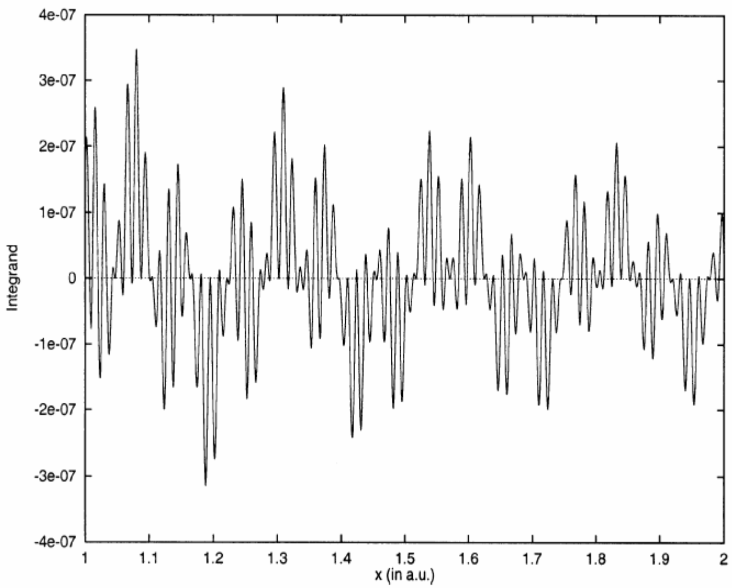
Technicalities

Millions of vector coupling coefficients

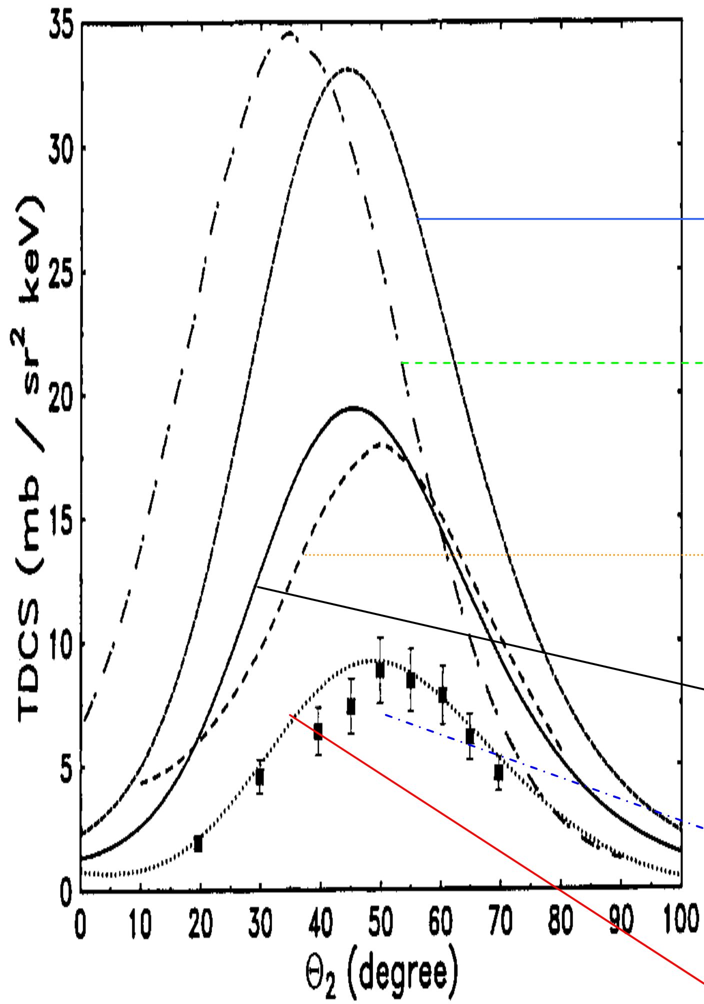
Thousands of highly osscillatory integrals

$$\int_0^\infty \mathrm{d}r_x\, r_x^2\, j_n(\rho r_x)\, j_{l_1}(k_1 r_x)\, j_{l_0}(k_0 r_x)\,. \qquad (3.9)$$





Plot of the integrand of term Eq. (3.9) for a typical set of parameters.



Semi Relativistic 1st Born - Walters et al

Semi Relativistic 1st Born-Das & Konar

Semi Relativistic Coulomb Born

Relativistic 1st Born

rDWBA

Experimental data is absolute

K-shell Gold, E_0=500keV, E_s=100keV, θ_f=-15^0

Crucially there is little difference between a fully relativistic Coulomb Born calculation and the equivalent rDWBA Asymmetric geometries:

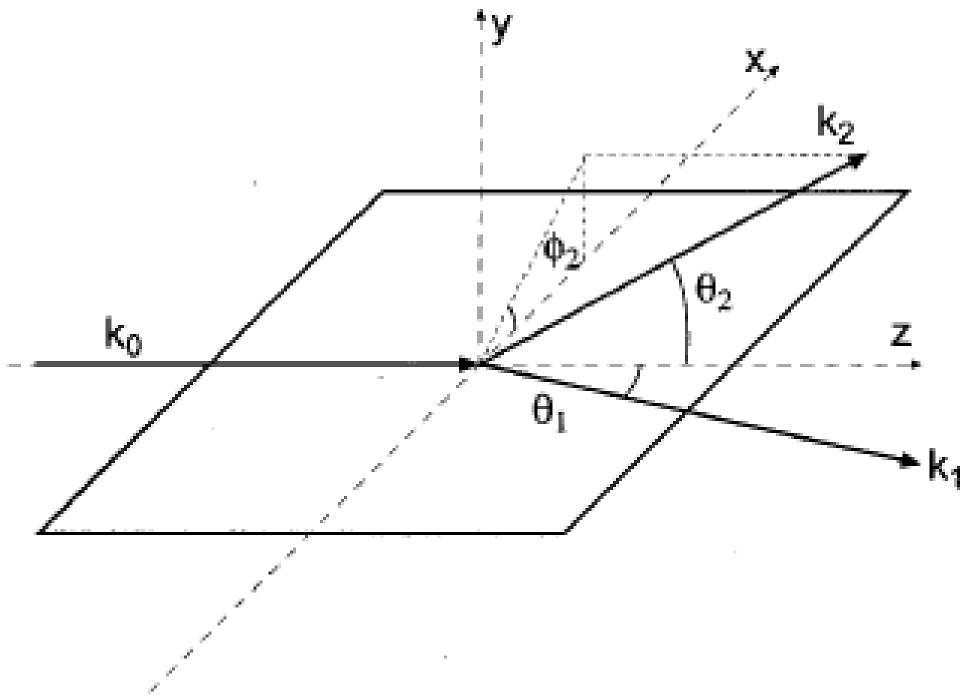


FIG. 1. The scattering geometry and the definition of the momenta for the incoming fast scattered and slow ejected electrons.

If

$$\frac{d^3\sigma}{d\Omega_s d\Omega_f dE} = \rho(\theta_s,\phi_s)$$

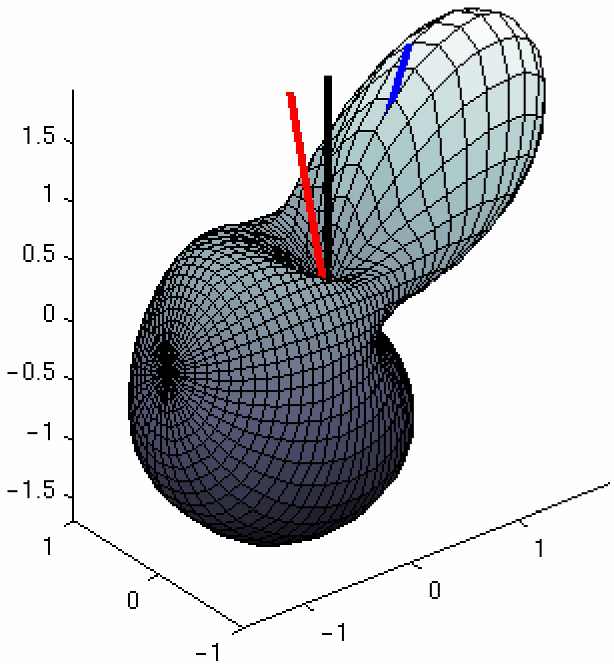
then define

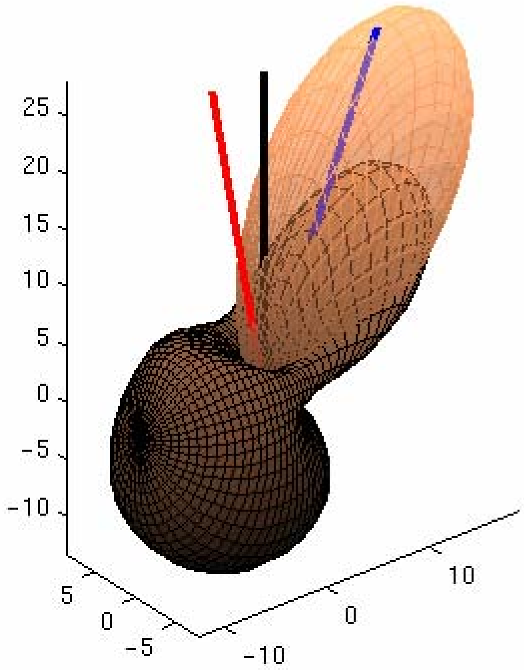
$x = \rho(\theta_s,\phi_s)\ \mathrm{Sin}(\theta_s)\ \mathrm{Cos}(\phi_s)$

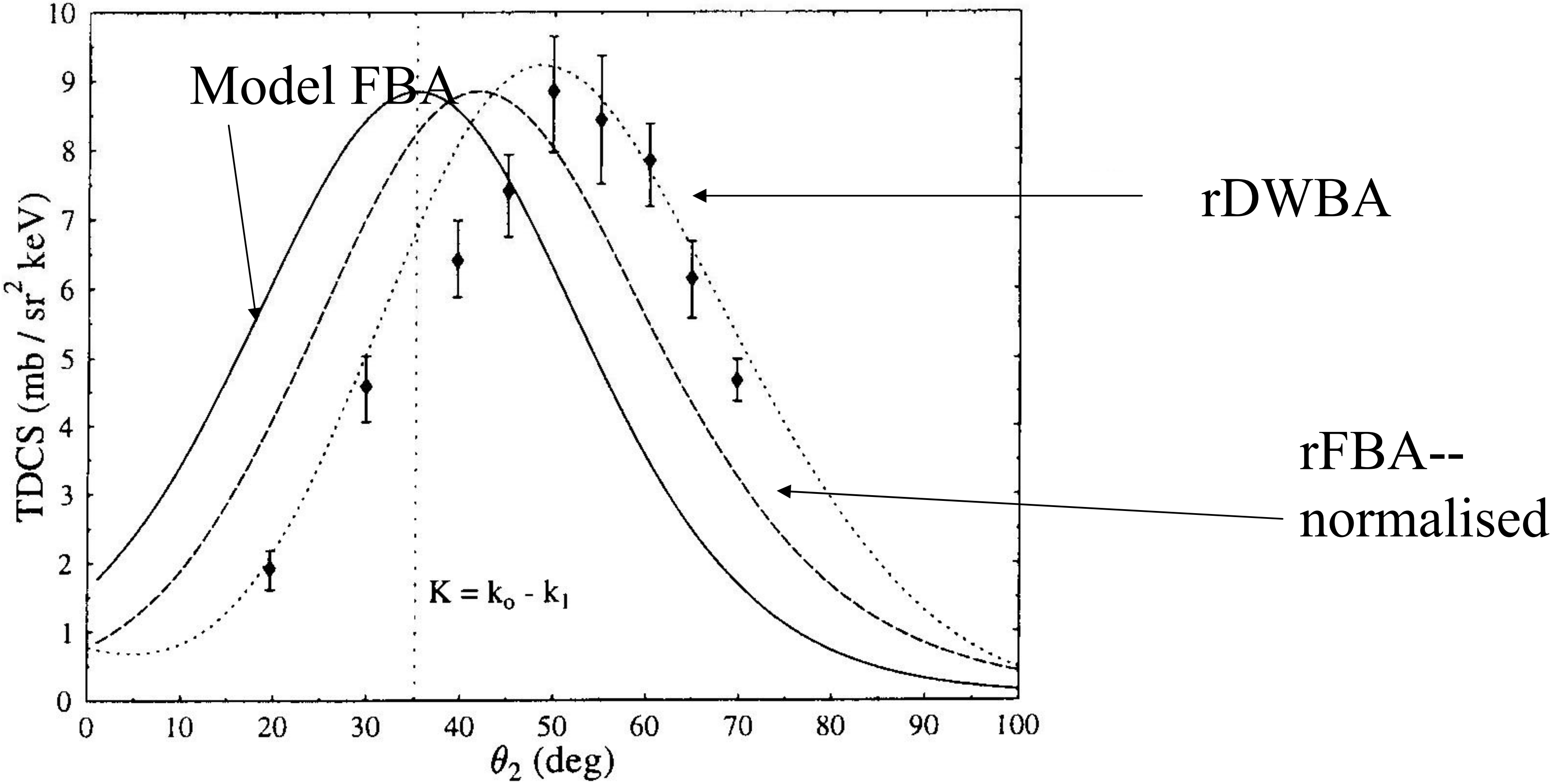
$y = \rho(\theta_s,\phi_s)\ \mathrm{Sin}(\theta_s)\ \mathrm{Sin}(\phi_s)$

$z = \rho(\theta_s,\phi_s)\ \mathrm{Cos}(\theta_s)$

(e,2e) calculations on hydrogen like Uranium, E_0=300keV, E_2=100keV $\Theta_1=10^0$





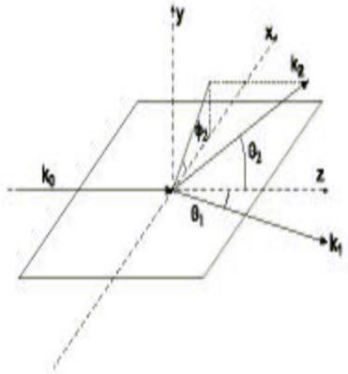


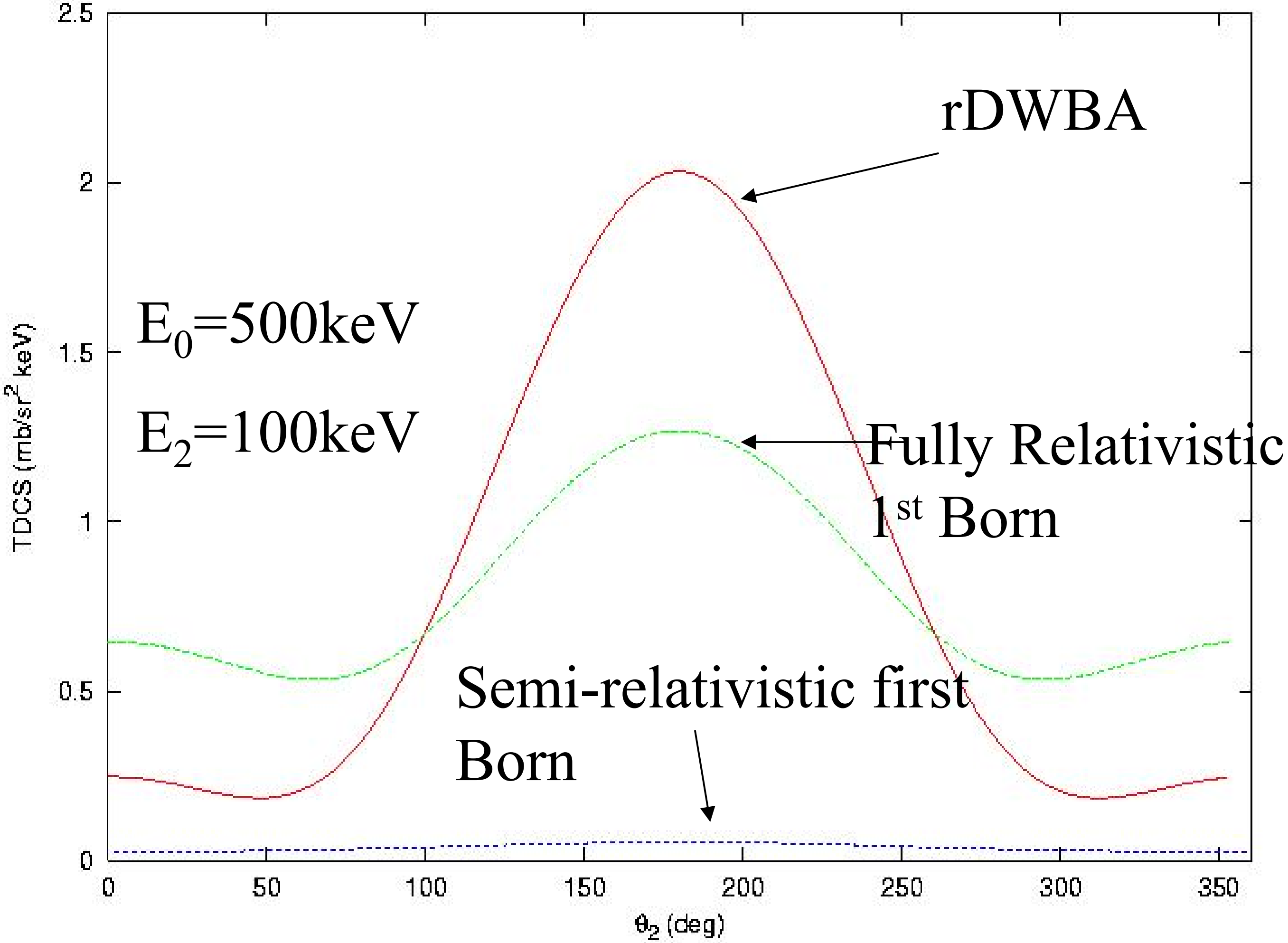
TDCS for the electron-impact K-shell ionization of gold, E_0 = 500 keV, E_2 =100 keV, fixed $\theta_1 = -15$.

Cross Section no longer symmetric about direction of momentum transfer---this break in symmetry is due to using the full qed Photon propogataor rather than the Coulomb interaction

The predicted shift is due to magnetic and retardation effects in the propogator-not present in the non-relativistic limit

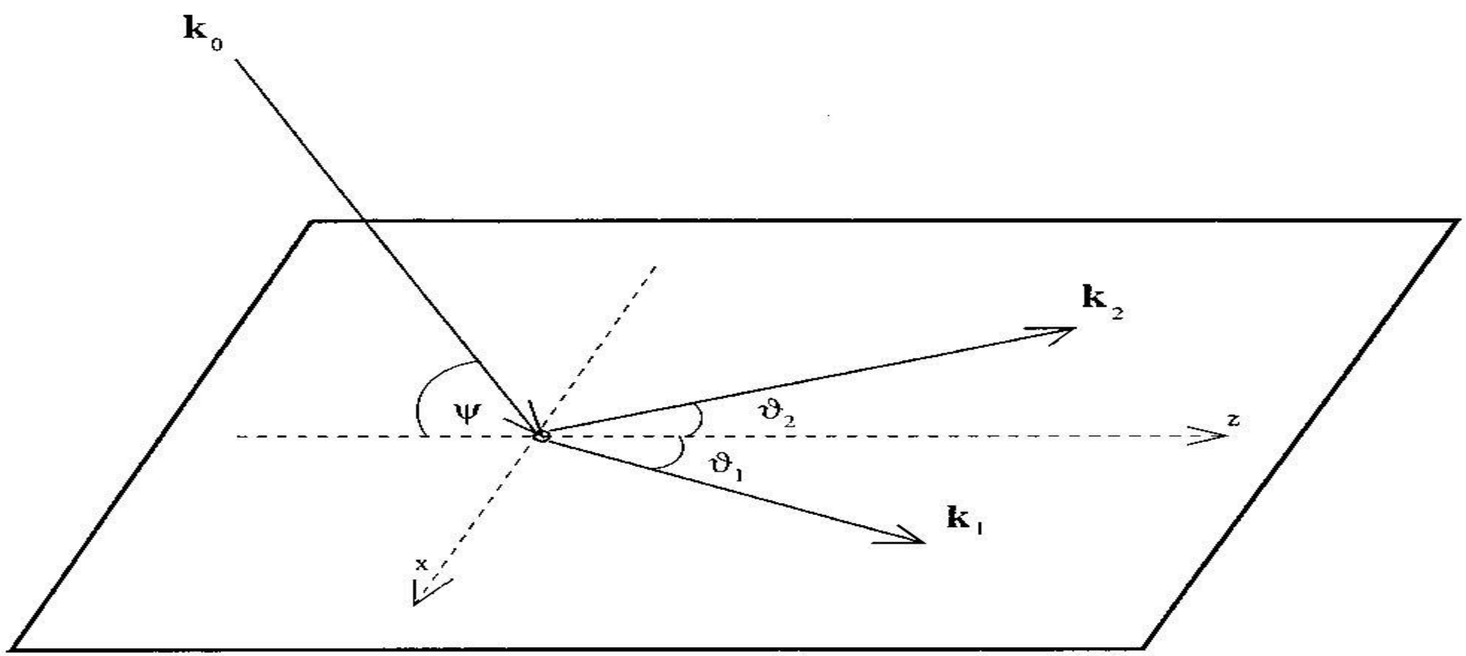
Hydrogen like Uranium in the plane perpendicular to **K**

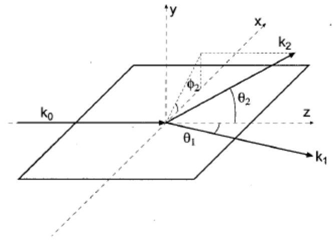




Symmetric Geometries

- $E_1 = E_2$





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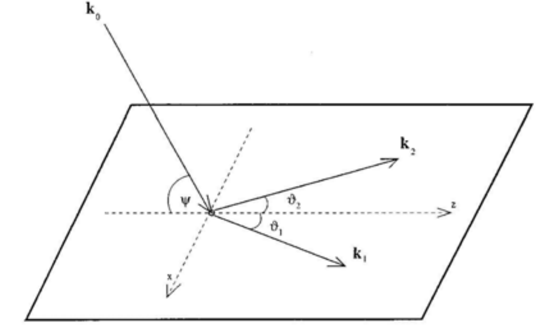
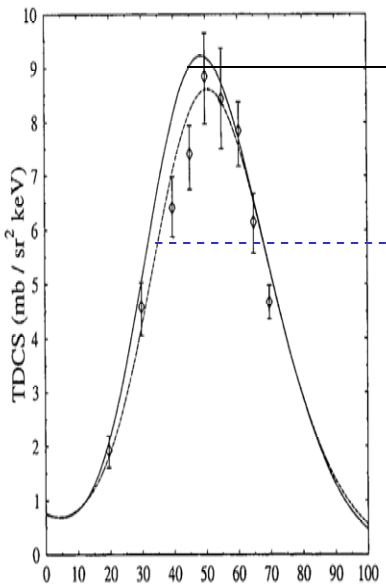
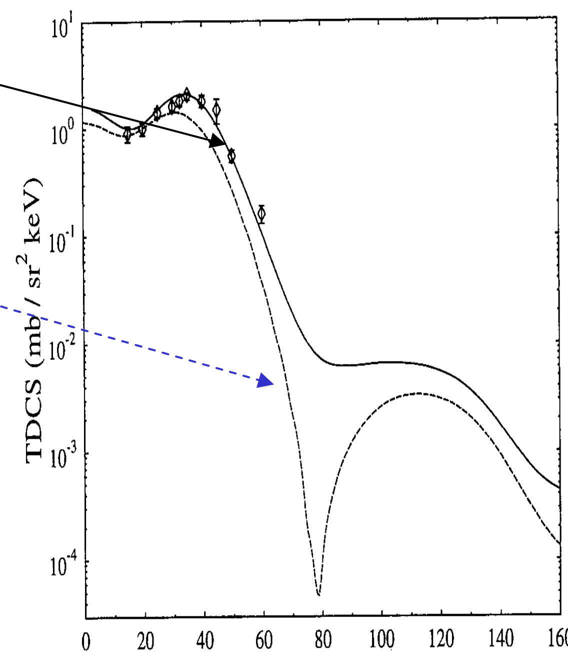


FIG. 1. Shown is the general setup for an $(e,2e)$ experiment. $\mathbf{k}_0$, $\mathbf{k}_1$, and $\mathbf{k}_2$ denote the incident and two outgoing electrons. ψ denotes the angle by which the incident electron gun is raised out of plane.



With spin flip

Without spin flip



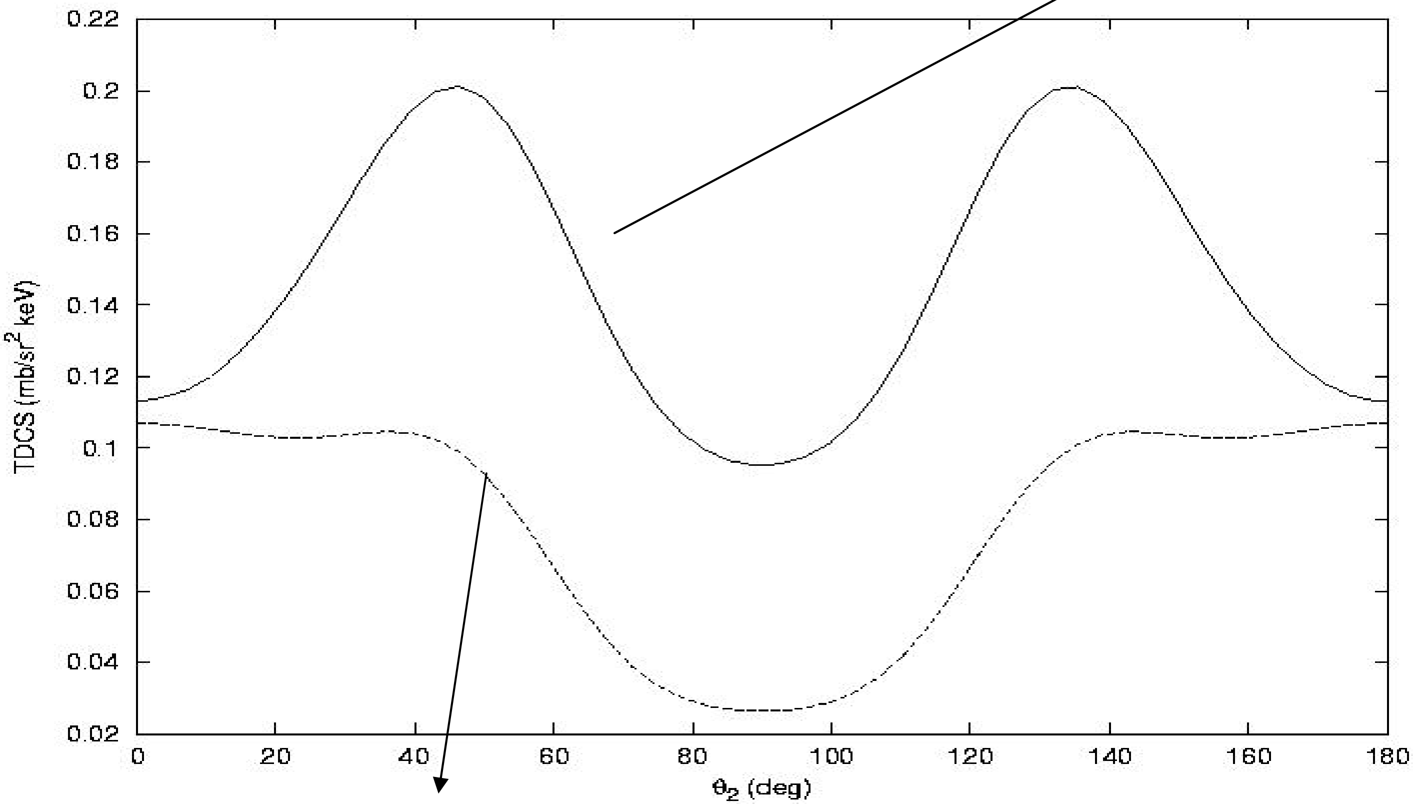
θ_2

Coplanar asymmetric geometry, $\phi_2=0$

Coplanar symmetric geometry, $\psi=0$

Consider Uranium with an electron impact of 200 keV and suppose we chose to work in a plane perpendicular to the beam direction($\psi=90^0$)

Including Spin-flip

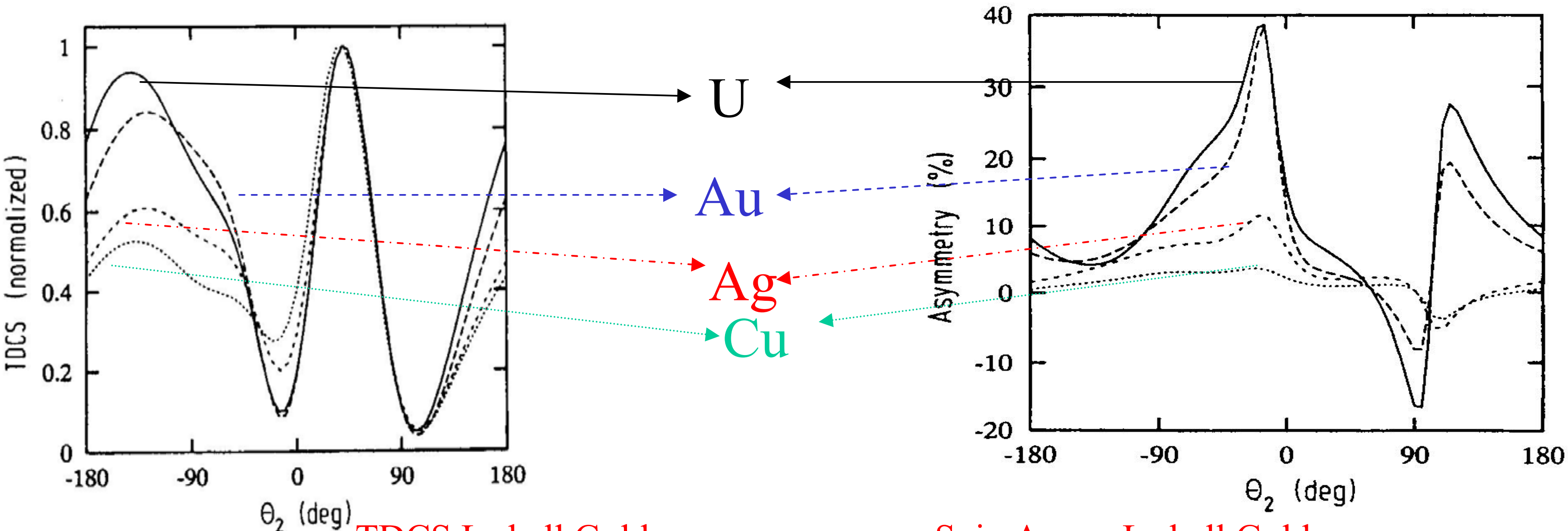


Without Spin Flip

K shell ionization

TDCS

Spin Asymmetry



TDCS L shell Gold

Spin Asym. L shell Gold

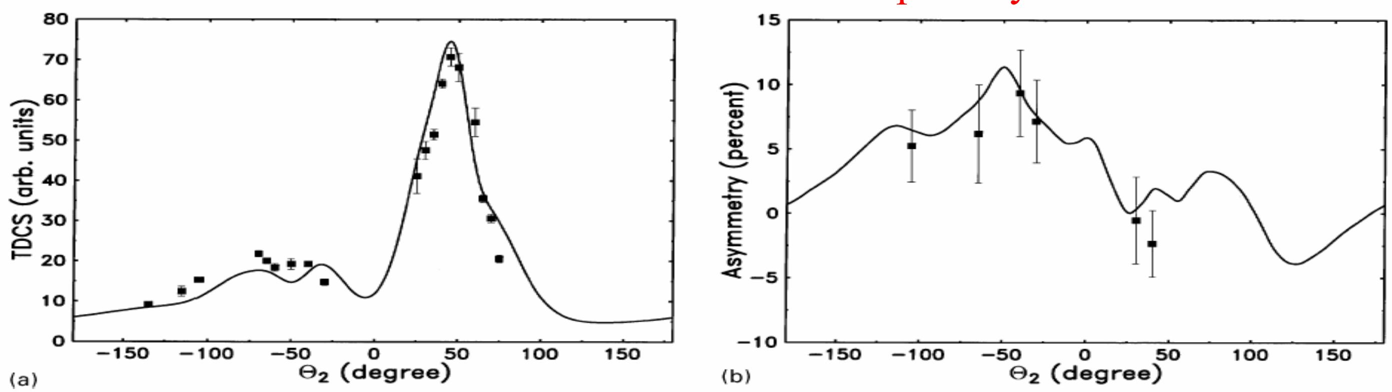


Fig. 37. (a) Relative TDCS for electron impact ionization of the L shell of gold, as a function of the observation angle θ_2 of the slow outgoing electron. Impact energy 300 keV, fast outgoing electron energy 200 keV, $\theta_1 = -10°$. Symbols: experiment (error bars indicate statistical error), full curve: rDWBA calculation, normalized to give best visual fit to the experimental data (from Prinz and Keller [78]). (b) Spin-up–down asymmetry (as given by Eq. (4.3)) of the TDCS for the kinematics of (a). Symbols: experiment (error bars indicate statistical error); full curve: results of rDWBA calculation, averaged over subshells (from Prinz and Keller [78]).

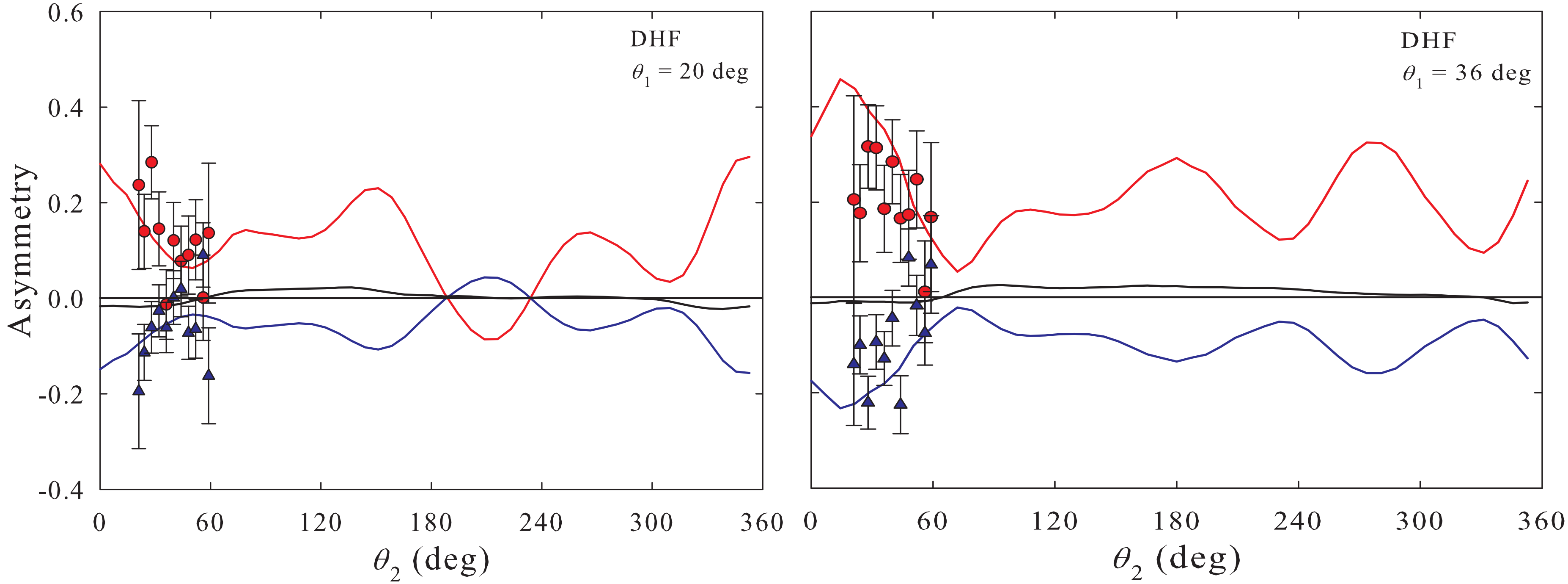
For L-shell one should also see a significant spin asymmetry due to the fine structure of the target(Hanne, Madison et al)

In the absence of Mott Scattering we should get

$$A_{1/2}=-2A_{3/2}$$

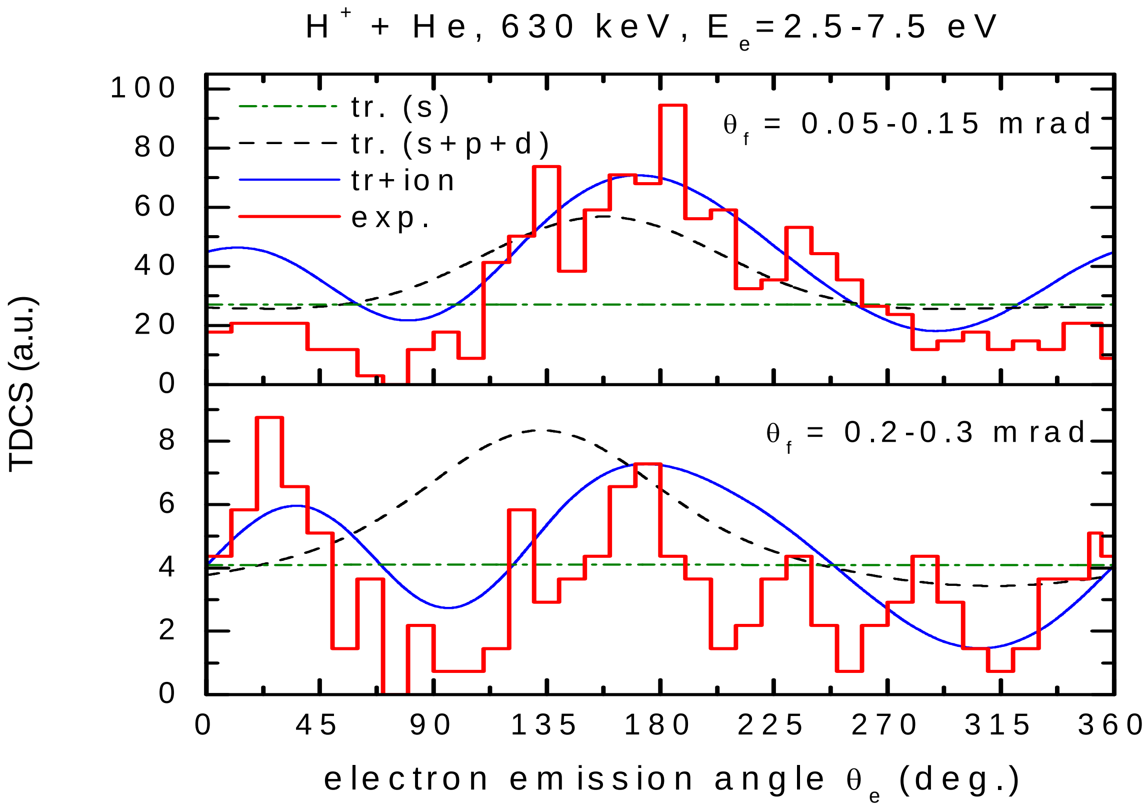
At low energies this effect is swamped by exchange in the elastic channels (see Mazevet, Madison)

At high energies it is difficult to distinguish it from the Mott scattering



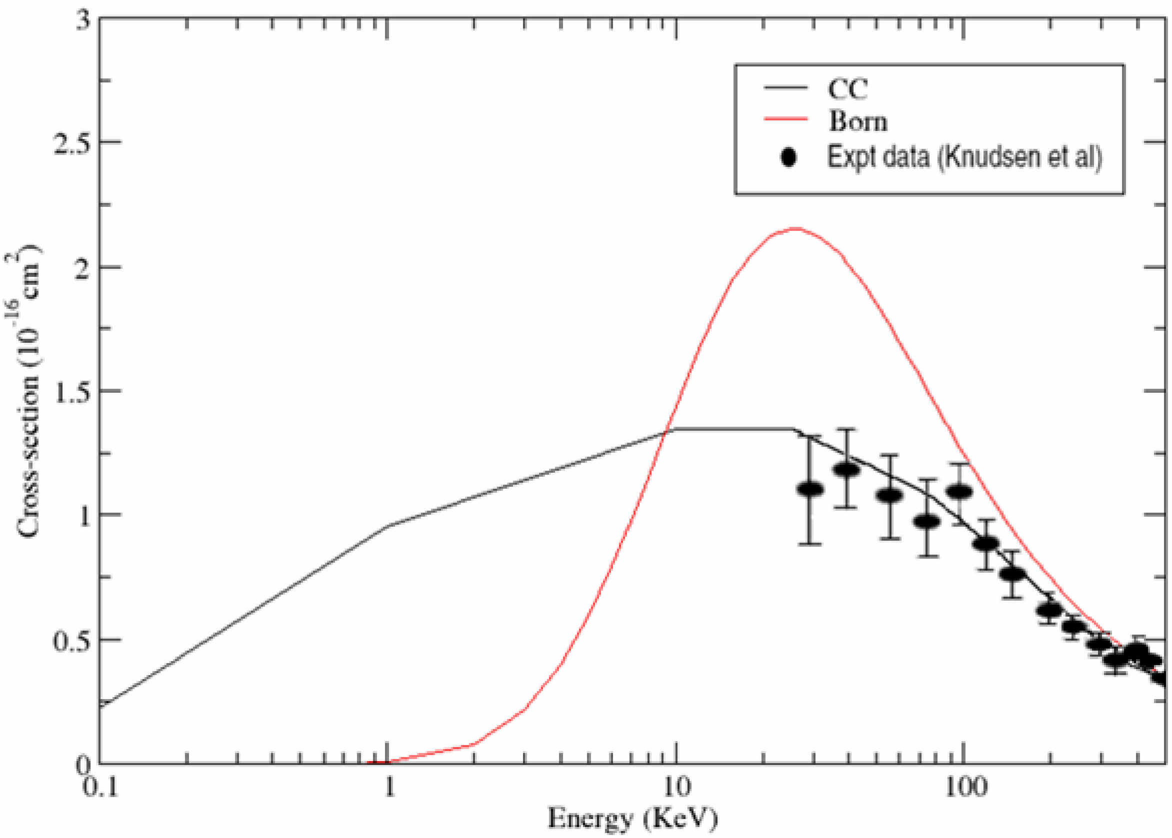
Spin asymmetry measurement for the ionization of Ar(2p). The upper set of experimental points corresponds to $^2P_{1/2}$ ion states and the lower to $^2P_{3/2}$ ion states. The incoming electron has an energy of E_0 = 910eV and the slow electron is detected with an energy of E_2 = 60eV. The fast scattered electron is detected at angles θ_1 between -20 and -60 with respect to the direction of the incoming electron beam. Asymmetries are presented as a function of the slow-electron scattering-angle θ_2, for fixed values of scattering angles θ_1. Shown are theoretical calculations for both spin asymmetries using the rDWBA approximation as described in the text. Also shown (black line) is the rDWBA calculation of the quantity $A_{1/2}+2A_{3/2}$. The upper red line and experimental points, ●, correspond to $A_{1/2}$, the lower blue line and experimental points, ▲, correspond to $A_{3/2}$.

Transfer Ionization



$\bar{p}$+H

75-state calculations of $\bar{p}^-$ ionization of H(1s)



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