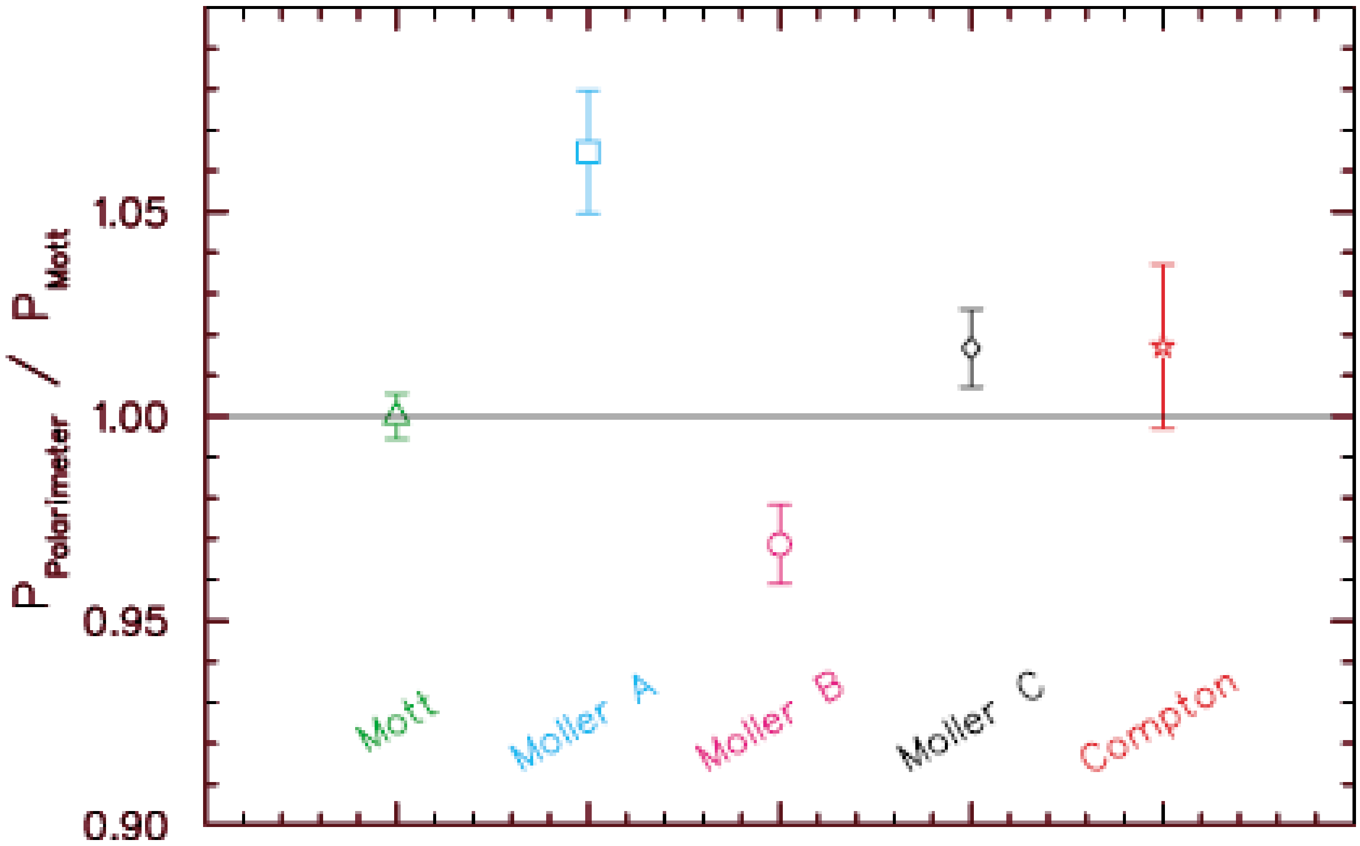
¿e?

Optical Electron Polarimetry

T.J. Gay
University of Nebraska

The Problem: the CEBAF Spin Dance

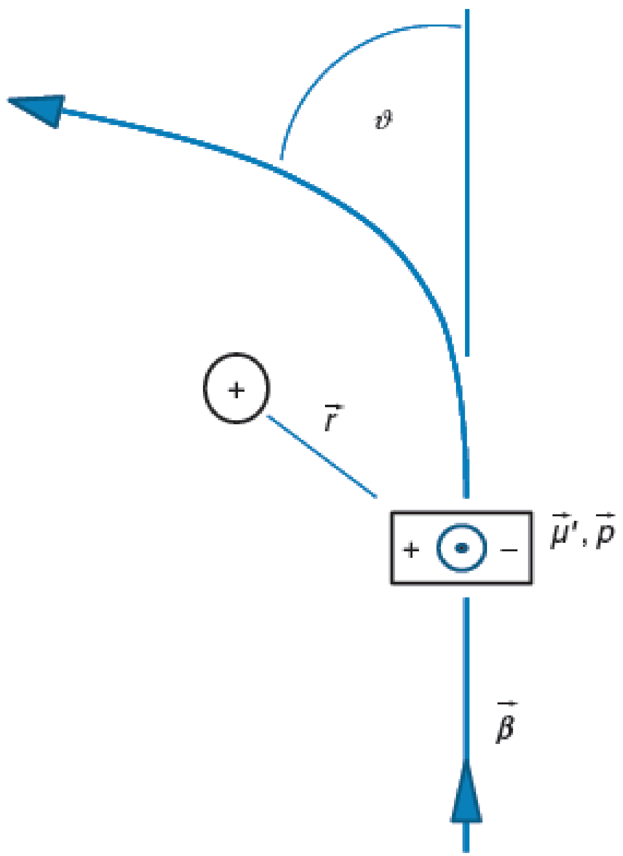


SYSTEMATICS

- Mott: 1%
- Möller A: 4%
- Möller B: 1%
- Möller C: 1%
- Compton: 3%

J.M.Grames *et al.*, Phys. Rev. Spec. Top. Acc. Beams **7**, 042802 (2004)

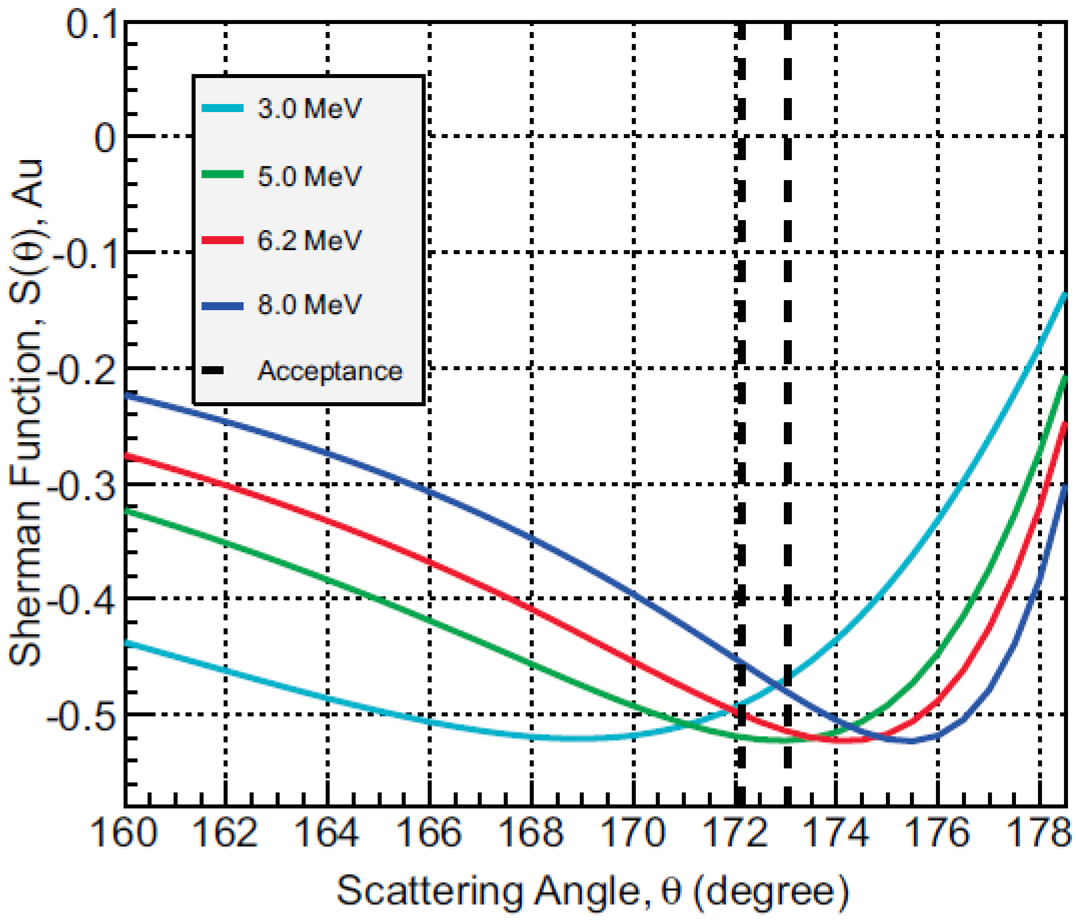
Mott Scattering



$$\vec{p} = \vec{\beta} \times \vec{\mu}\,'$$

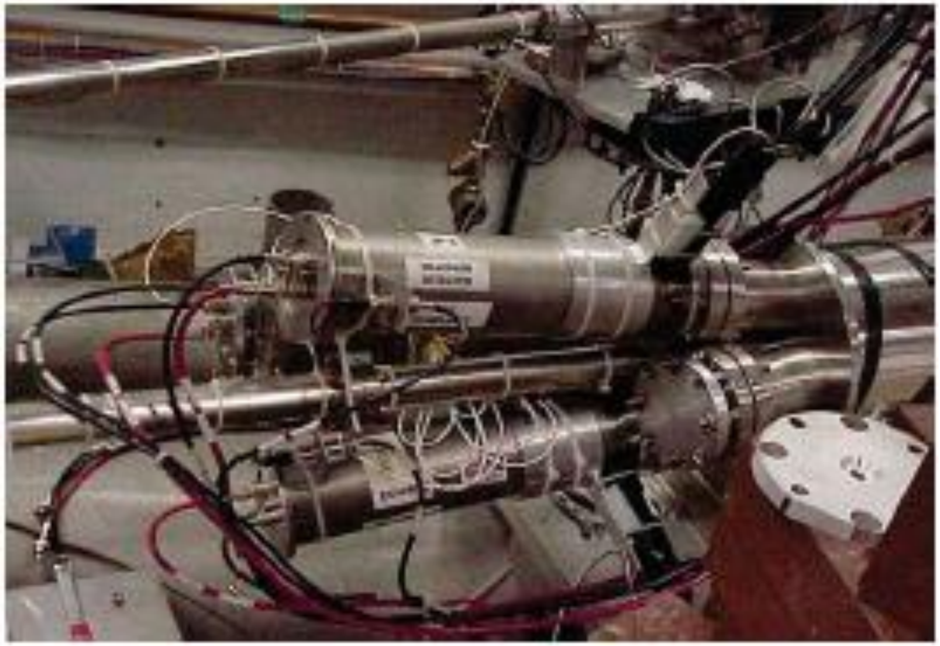
$$A \equiv \frac{I(+\vartheta) - I(-\vartheta)}{I(+\vartheta) + I(-\vartheta)} = S_A P_e$$

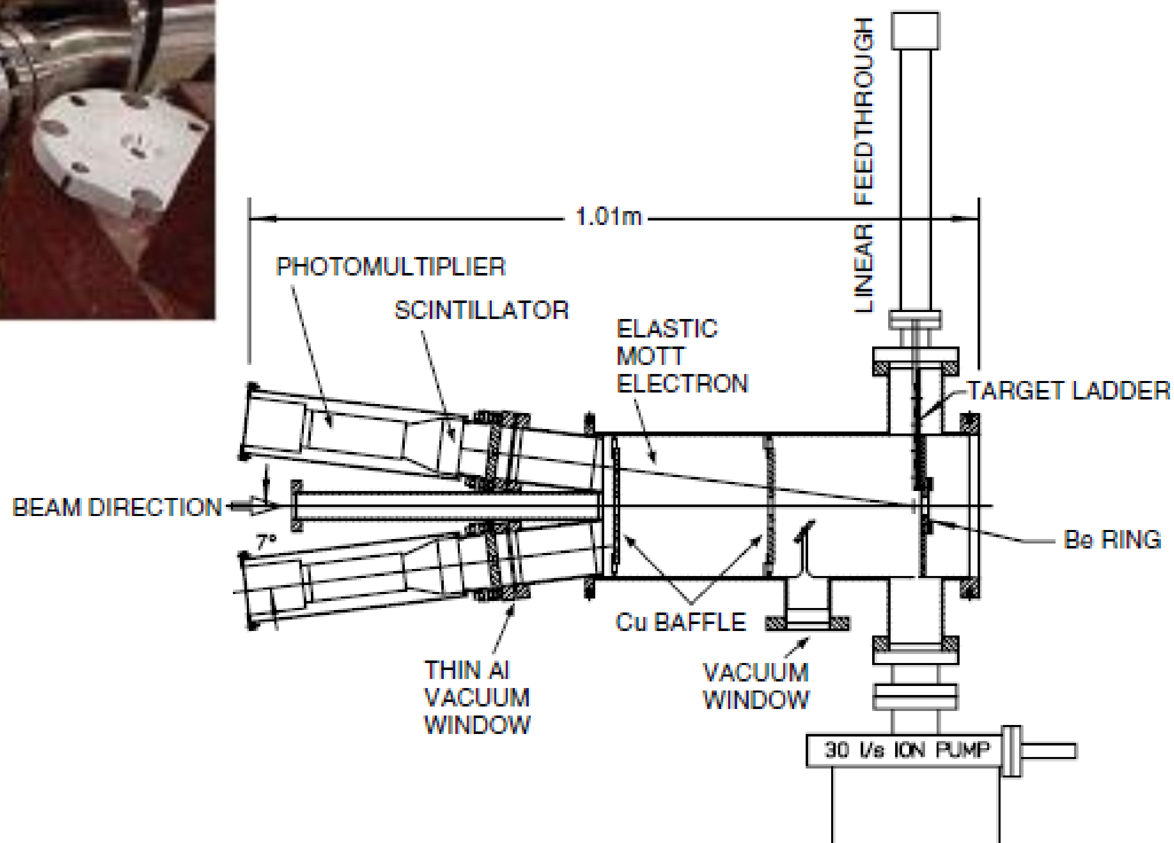
The 5 MeV Sherman Function



N. Sherman, Phys. Rev. **103,**
1601 (1956!)

The CEBAF 5 MeV Mott Polarimeter

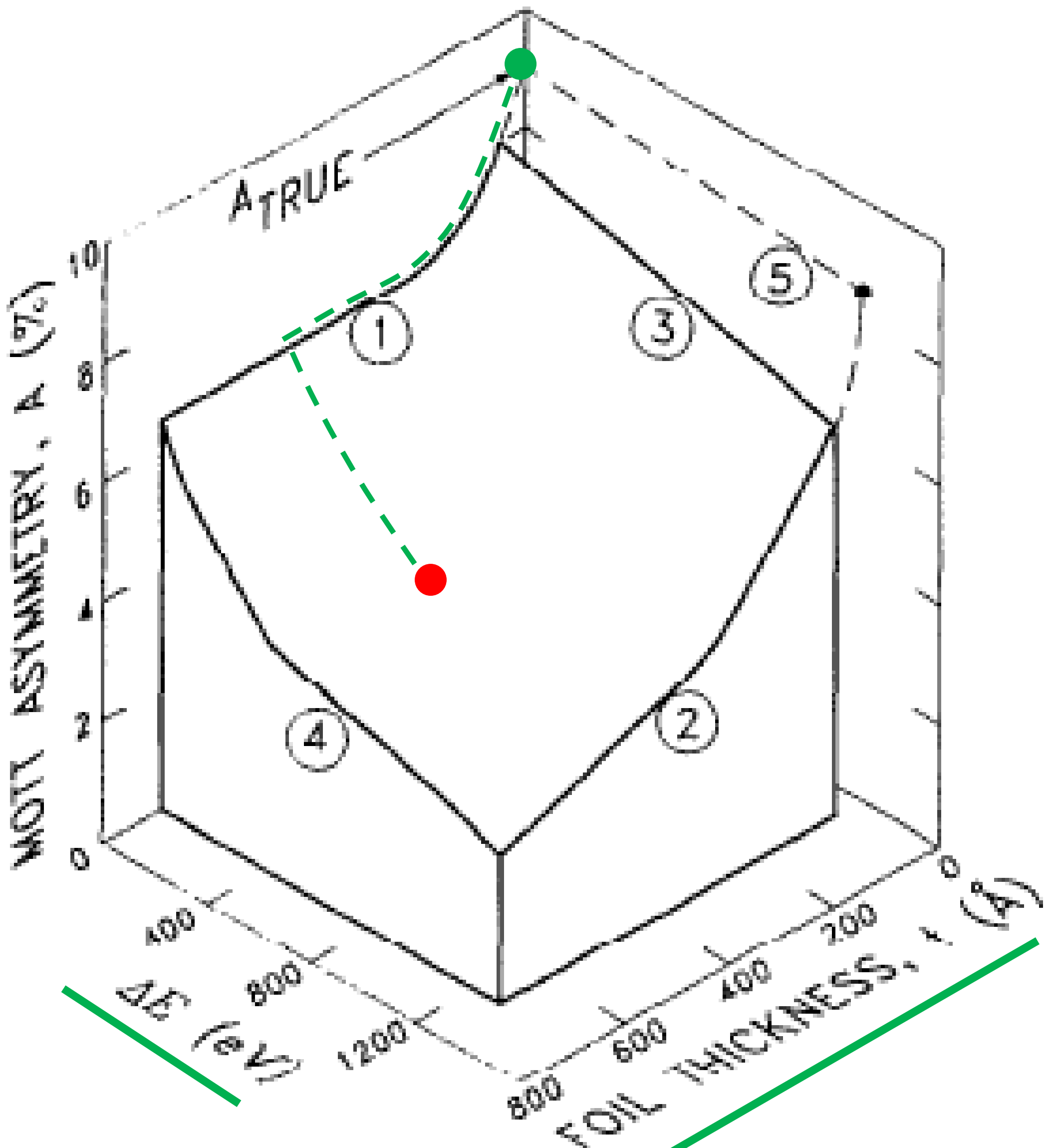




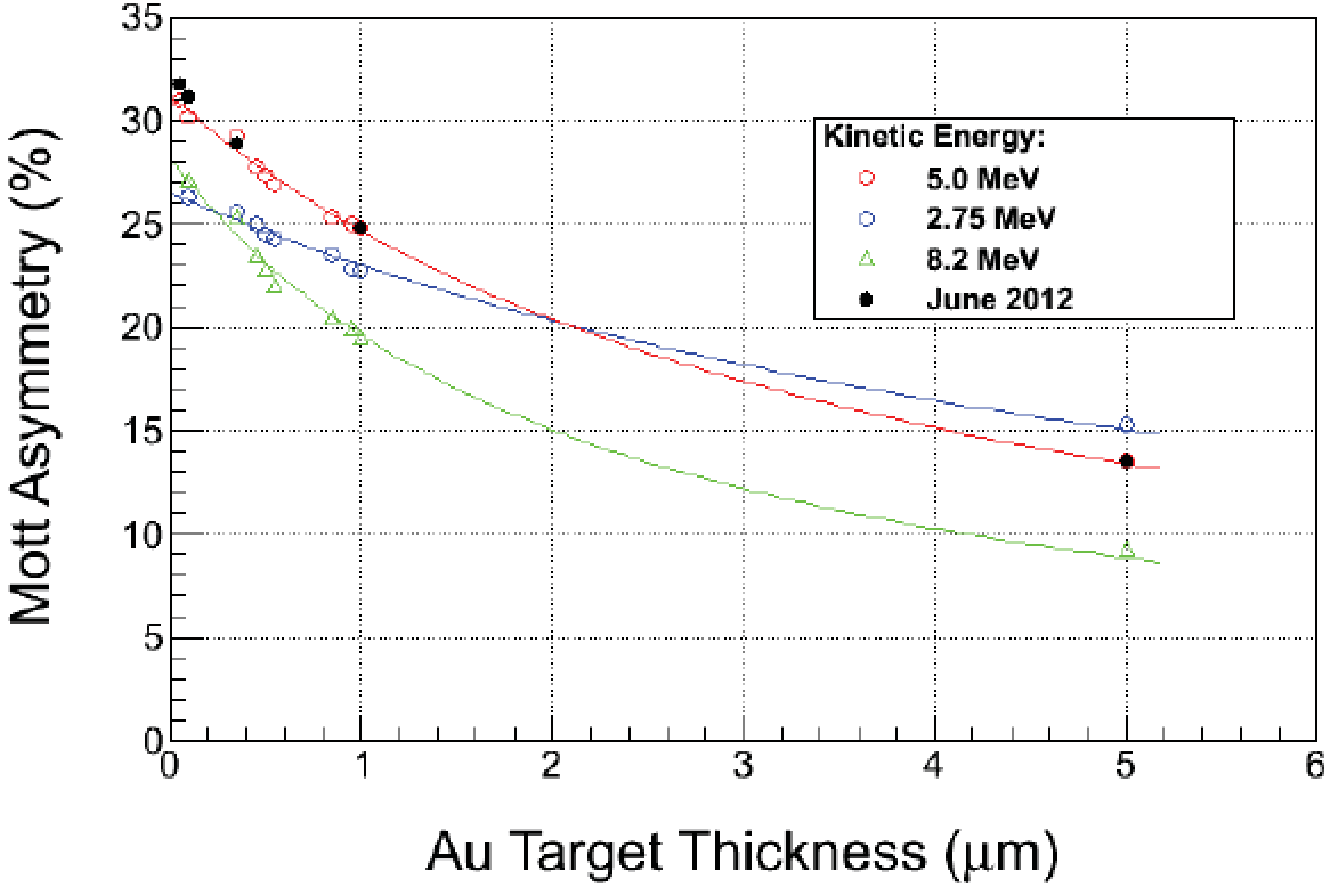
Experimental Problems With Mott Scattering

- Scattering is from multiple target atoms in only quasi-elastic scattering conditions
- Instrumental asymmetries
- Backgrounds
- Poor energy resolution (see above)
- Accuracy ultimately determined by that of theory

The Ascent to A_{TRUE}

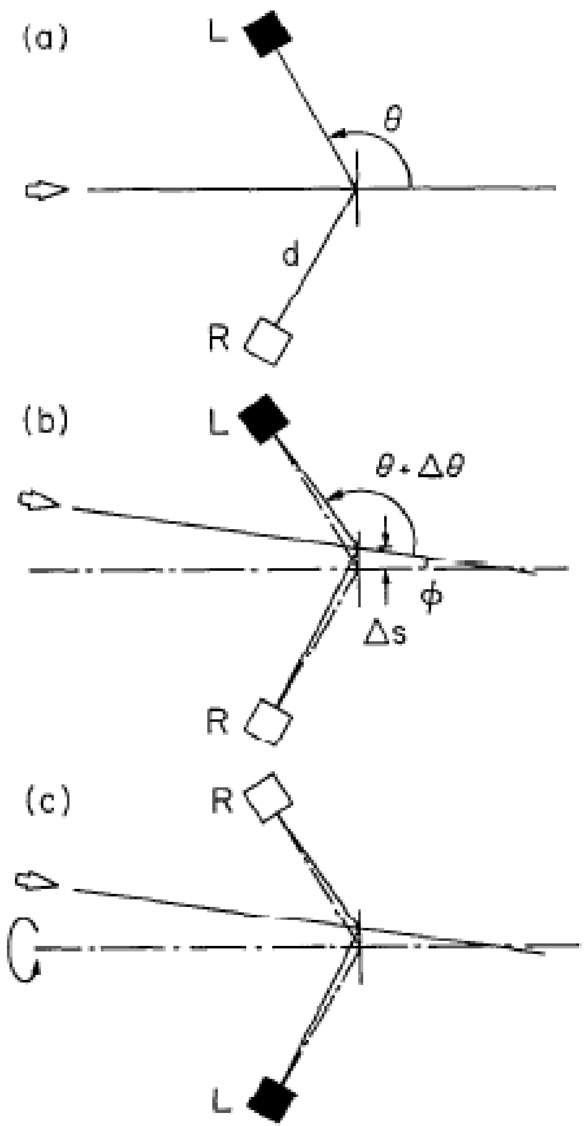


Extrapolation Procedures



$$A = a/(b + ct); \; A = ae^{-bt} + c; \; A = at^2 + bt + c\ldots$$

(Geometric) Instrumental Asymmetries

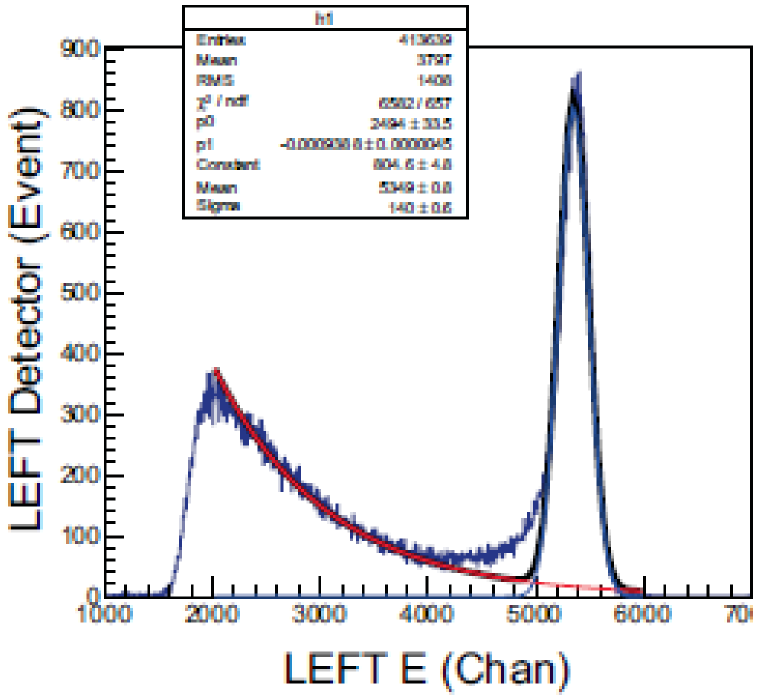


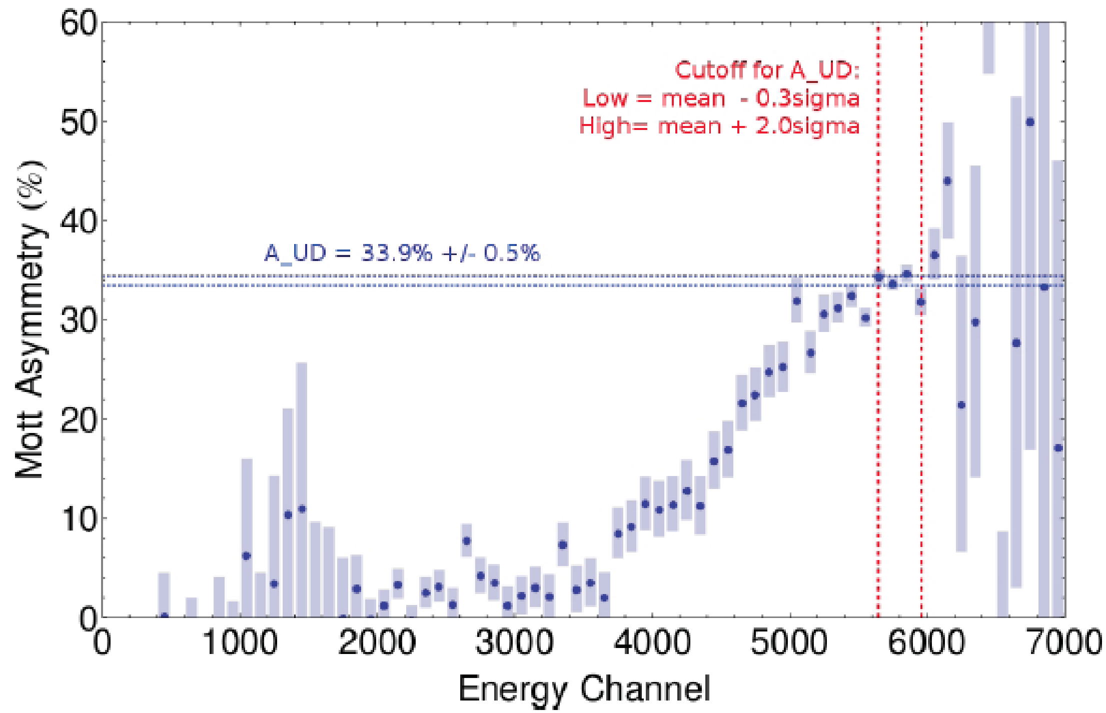
Optical Spin Reversal:

$$P_e S_{eff} = \frac{X-1}{X+1} \text{ where}$$

$$X \equiv (R_L R_R{}'/(R_R R_L{}')^{0.5}$$

Energy Resolution and Background Subtraction

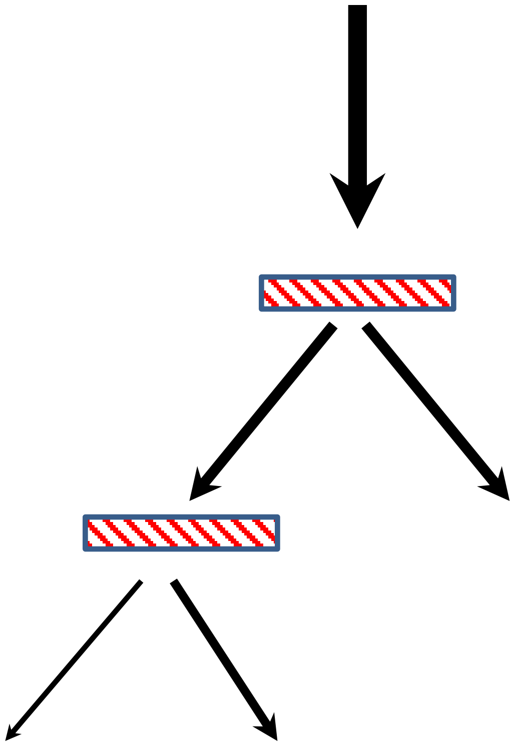




Photon vetoing, TOF discrimination, GEANT simulation, pulse height analysis, Be backstops….

Mott Scattering History

- Neville Mott, 1927; "Is spin a property of the free electron?"
- Proposes double scattering
- H. Bethe; beta rays
- Is the Dirac Equation right?
- First observation of free electron polarization by Schull, Chase, and Meyers (1943)

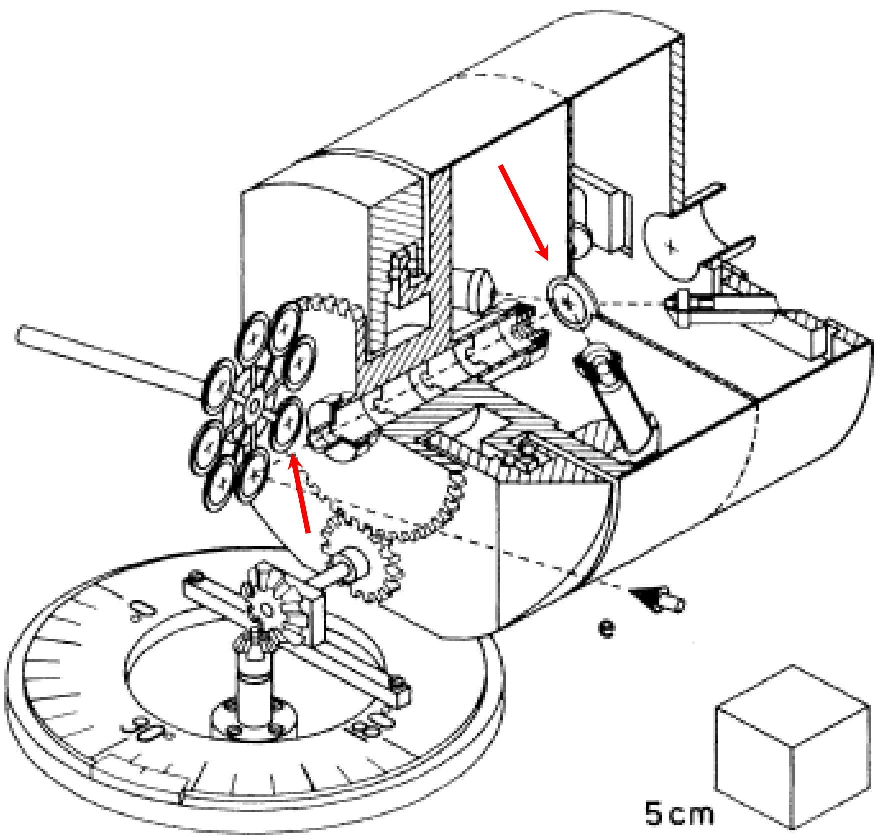


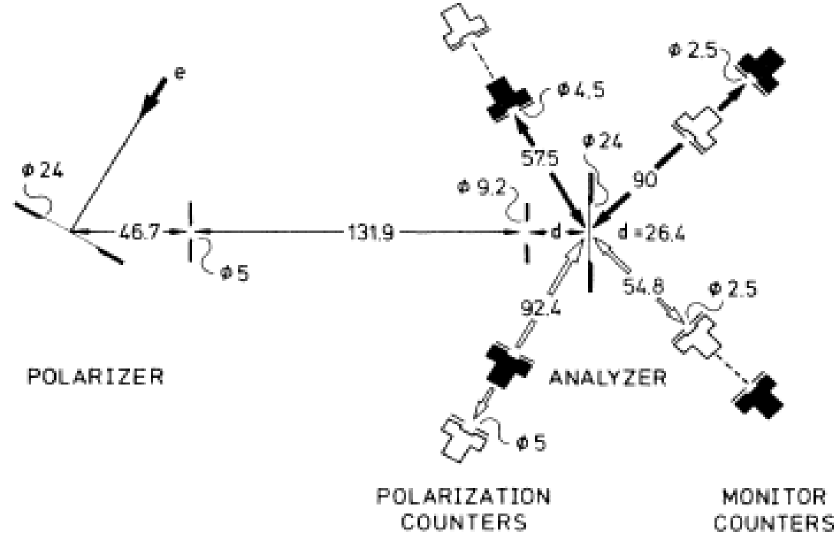
5 MeV State-of-the-Art Theory is carried out for the CEBAF Mott Polarimeter!

In 1956, with the goal of improving thermonuclear weaponry, Noah Sherman uses the UNIVAC, a high-speed electronic digital computer with tens of kilobytes of memory, to calculate the Mott scattering analyzing power. These calculations, which quote an accuracy of 1%, assume

- A point-like nucleus
- No K-shell (or any other) electrons in the target
- No QED effects, e.g., bremstrahlung
- Spherical extensions by Ugincius (1964), Motz (1970)

Double Scattering Calibrations (120 keV)





A. Gellrich u J.Keβler, Phys. Rev. A **43**, 204 (1991)

….somebody’s lying…….

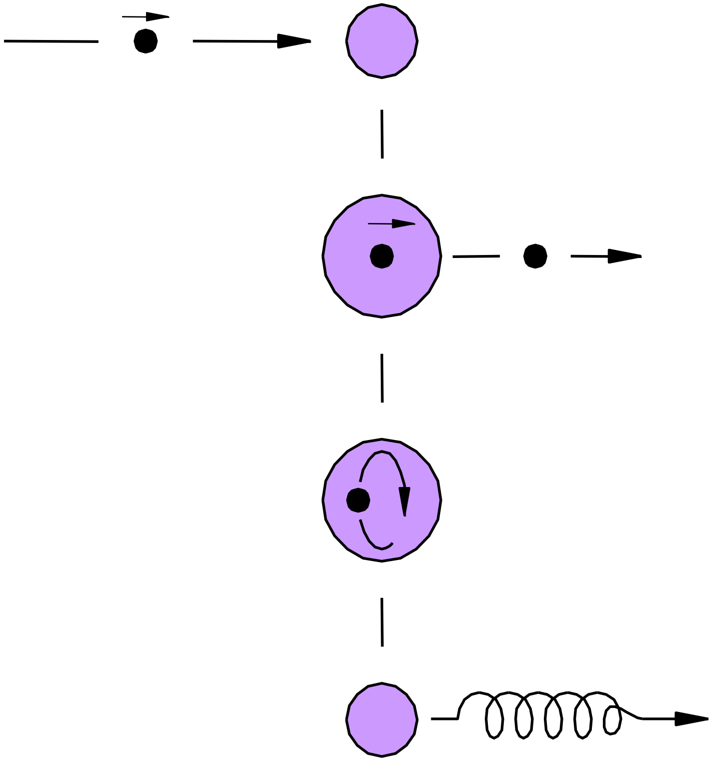
TABLE IV. $S(t=0, 120\ \text{keV})$. Results of a weighted linear least-squares fit of S_{eff}^{-1} vs t (including the error of the relative foil thicknesses and of S_{eff}) compared with different theoretical values. The fits and the accompanying reduced χ^2 values were calculated according to Ref. 25. At 120° the values of the 222-μg/cm^2 foil was not used in the extrapolation procedure because it clearly deviates from the straight line (cf. Fig. 14), on which our extrapolation is based.

θ	Extrapolation	χ^2_ν	Bühring[a]	Lin[b]	Holzwarth and Meister[c]	Ross and Fink[d]
120°	−0.4099(44)	1.63	−0.4068	−0.4072	−0.400	−0.404
125°	−0.4158(28)	0.47	−0.4108		−0.401	
130°	−0.4091(29)	0.59	−0.4074	−0.4067	−0.394	
	1991		1968	1964	1962	1991

NB - these calculations are all much more sophisticated than those of Sherman.

Theory accuracy for all results quoted is ~0.002

Exchange excitation of atomic fluorescence



Dayhoff (<1956)

First Proposal of Optical Electron Polarimetry

- Attributed to Dayhoff at a conference in 1956 by Keβler in RMP in 1968

First Real Proposal of Optical Electron Polarimetry*


J. PHYS. B (ATOM. MOLEC. PHYS.), 1969, SER. 2, VOL. 2. PRINTED IN GREAT BRITAIN

Optical detection of electron polarization

P. S. FARAGO and J. S. WYKES
Department of Natural Philosophy, University of Edinburgh
MS. received 8th April 1969

Abstract. A method is suggested for measuring the polarization of low-energy electron beams by observing the polarization of the light emitted by mercury atoms following their excitation by electron impact. It is shown that the asymmetry of the left and right circularly polarized components of the 2537 Å radiation of the even isotopes is approximately equal to the longitudinal polarization of the incident electron beam. The efficiency of such a detector is estimated for incident electron energies near the excitation threshold and its expected performance compares favourably with that of a typical Mott detector. Some distinctive advantages of the proposed scheme are pointed out.

1. Introduction

In recent years considerable progress has taken place in the production of polarized electron beams (Farago and Siegmann 1969, Raith 1968, Reichert 1969), but this has not been accompanied by any significant development in the methods of polarization detection. All the experiments known to the authors use Mott detectors, i.e. devices in which the transverse polarization of electrons causes an azimuthal asymmetry of the intensity of elastically scattered electrons. This method has features which often complicate the experimenters' task in an undesirable way. Except where Mott scattering is used for the production of polarized electrons, the beam emerges from the source in a state of longitudinal polarization. Thus, purely for detection purposes, a longitudinal-to-transverse polarization transformation is required. Again electrons produced at low energies (~ 100 ev) have generally to be accelerated to 50–150 kev because conventional Mott detectors (thin gold foils as scattering targets) work best in this energy range. If Mott scattering is performed at low energy (100–1000 ev) the measurement of the scattering asymmetry requires good angular and energy resolution to select electrons scattered elastically in a well-defined direction.

There have been a few experiments (Dehmelt 1958, Graff *et al.* 1968) involving polarized electrons in which the polarization has been monitored (but not measured quantitatively) by taking advantage of the spin dependence of the cross section for elastic or inelastic collisions between free electrons and atoms.

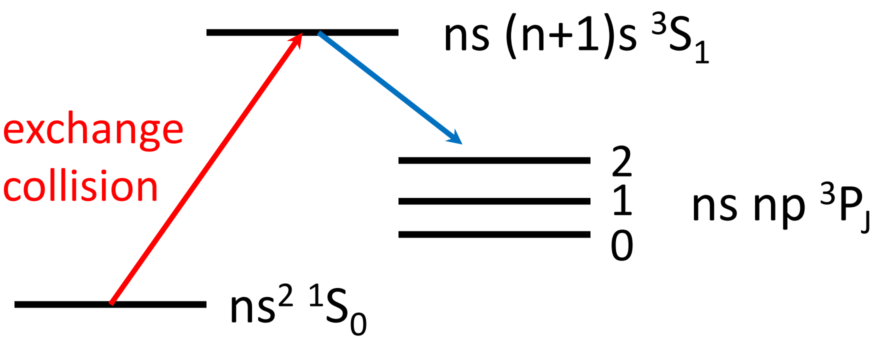
The purpose of this paper is to investigate the possibility of measuring quantitatively the polarization of low-energy electron beams through the polarization of the light emitted by atoms following excitation by the electrons concerned. After some qualitative considerations (§ 2) the collisional excitation of the ³P state of the even-A isotope of mercury is investigated in quantitative terms (§ 3) and a relation is established between the polarization of the incident electron beam and the polarization of the 2537 Å radiation excited by it (§ 4). The results are generalized for the odd-A isotopes and the natural mixture in § 5. In conclusion the feasibility of this optical method of measurement of electron polarization is considered (§ 6).

2. Polarization of mercury light excited by electron impact

Different aspects of the properties of atomic states excited by electron impact have been the subject of numerous theoretical and experimental investigations. The first to investigate the polarization of the mercury light excited by electron impact were Skinner and Appleyard (1927). They, like other authors later, studied the light emitted in a direction perpendicular to the incident electron beam and measured the intensity of the components polarized parallel to the electron beam ($I_\parallel$) and perpendicular to it ($I_\perp$). The

747

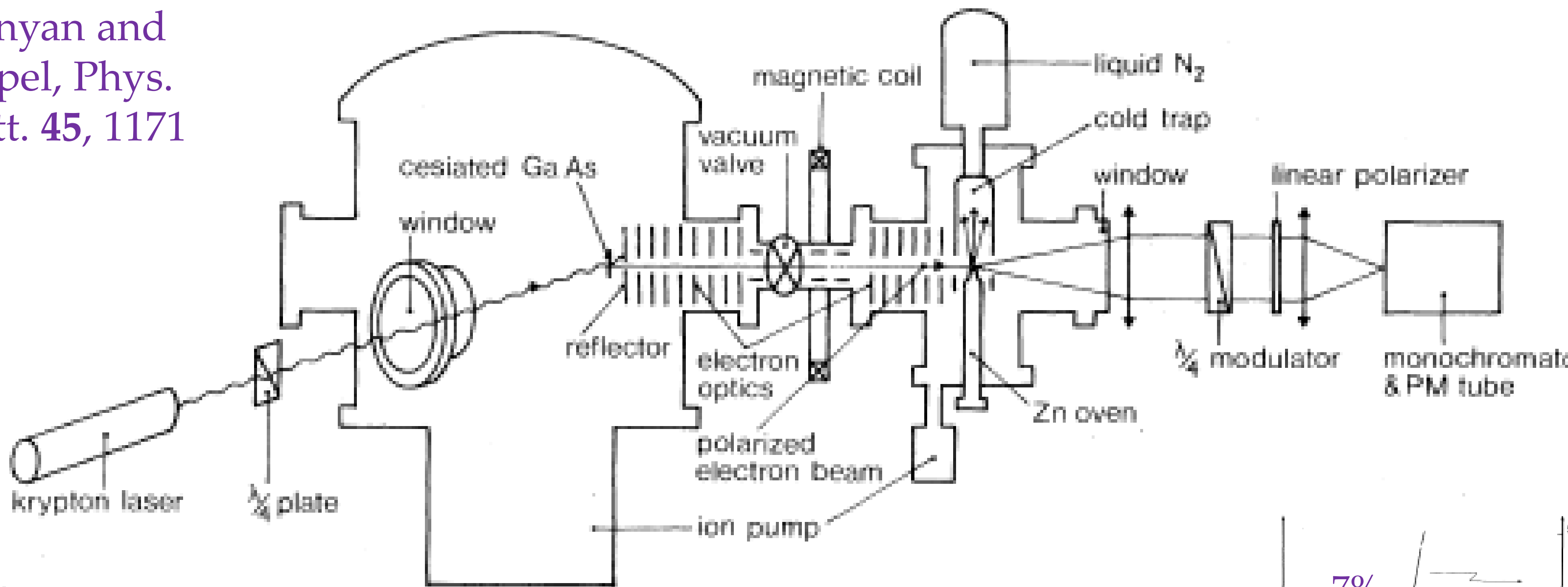
$$e^- + Hg(6s^2\ ^1S_0) \rightarrow Hg^*(6s6p\ ^3S_1)$$
$$\rightarrow Hg^*(6s5p\ ^3P_{0,1,2}) + \gamma(257nm)$$



*modified the next year to Zn or Cd

First Optical Observation of Free Electron Spin

M. Eminyan and G. Lampel, Phys. Rev. Lett. **45**, 1171 (1980)



Should use the heaviest possible atom (in order to resolve the fine structure) that still has LS-coupling → Zn.

- **J=1→ J=0; $P_3 = P_e$**
- **J=1→ J=1; $P_3 = (1/2)P_e$**
- **J=1→ J=2; $P_3 = -(1/2)P_e$**

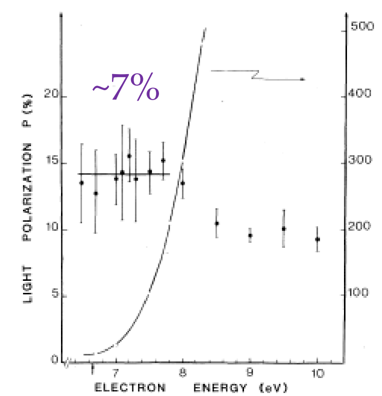
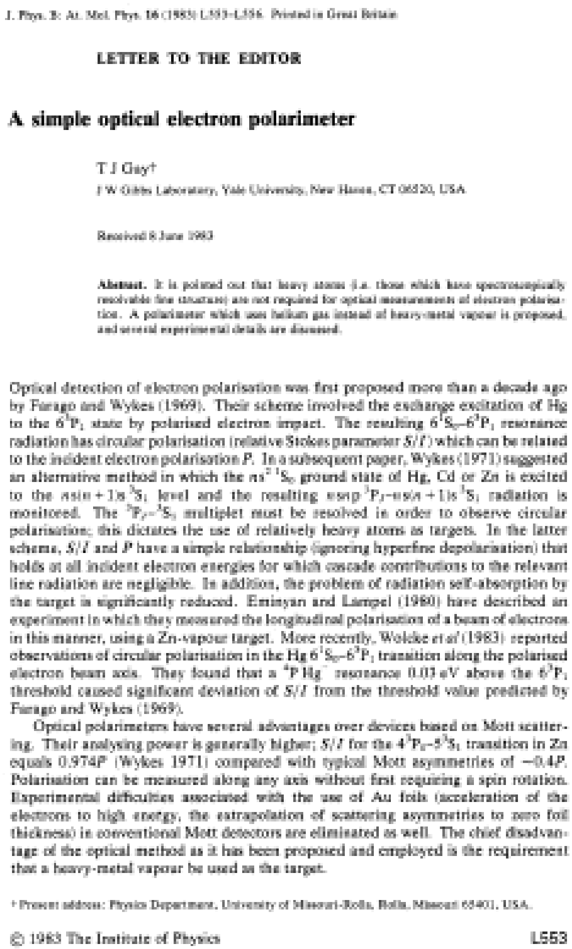


FIG. 3. Plots of the light intensity and the light polarization for the 5s $^3S_1$–4p $^3P_2$ transition, vs the electron energy. The arrow indicates the threshold and the horizontal line represents the mean value of the experimental points in the energy range of 0.92 eV above threshold. The error bars represent two standard deviations.

A new approach (1982)

$e^- + He(1s^2\ ^1S_0) \rightarrow He^*(1s3p\ ^3P) \rightarrow He^*(1s2s\ ^3S) +\ \gamma(389nm)$



J. Phys. B: At. Mol. Phys. 16 (1983) L553–L556. Printed in Great Britain

LETTER TO THE EDITOR

A simple optical electron polarimeter

T J Gay†
J W Gibbs Laboratory, Yale University, New Haven, CT 06520, USA

Received 8 June 1983

Abstract. It is pointed out that heavy atoms (i.e. those which have spectroscopically resolvable fine structure) are not required for optical measurements of electron polarisation. A polarimeter which uses helium gas instead of heavy-metal vapour is proposed, and several experimental details are discussed.

Optical detection of electron polarisation was first proposed more than a decade ago by Farago and Wykes (1969). Their scheme involved the exchange excitation of Hg to the 6^3P_1 state by polarised electron impact. The resulting 6^1S_0–6^3P_1 resonance radiation has circular polarisation (relative Stokes parameter S/I) which can be related to the incident electron polarisation P. In a subsequent paper, Wykes (1971) suggested an alternative method in which the $ns^2\ ^1S_0$ ground state of Hg, Cd or Zn is excited to the $ns(n+1)s\ ^3S_1$ level and the resulting $nsnp\ ^3P_J$–$ns(n+1)s\ ^3S_1$ radiation is monitored. The ^3P_J–$^3S_1$ multiplet must be resolved in order to observe circular polarisation; this dictates the use of relatively heavy atoms as targets. In the latter scheme, S/I and P have a simple relationship (ignoring hyperfine depolarisation) that holds at all incident electron energies for which cascade contributions to the relevant line radiation are negligible. In addition, the problem of radiation self-absorption by the target is significantly reduced. Eminyan and Lampel (1980) have described an experiment in which they measured the longitudinal polarisation of a beam of electrons in this manner, using a Zn-vapour target. More recently, Wolcke *et al* (1983) reported observations of circular polarisation in the Hg 6^1S_0–6^3P_1 transition along the polarised electron beam axis. They found that a $^4P\ Hg^-$ resonance 0.03 eV above the 6^3P_1 threshold caused significant deviation of S/I from the threshold value predicted by Farago and Wykes (1969).

Optical polarimeters have several advantages over devices based on Mott scattering. Their analysing power is generally higher; S/I for the 4^3P_2–5^3S_1 transition in Zn equals $0.974P$ (Wykes 1971) compared with typical Mott asymmetries of $-0.4P$. Polarisation can be measured along any axis without first requiring a spin rotation. Experimental difficulties associated with the use of Au foils (acceleration of the electrons to high energy, the extrapolation of scattering asymmetries to zero foil thickness) in conventional Mott detectors are eliminated as well. The chief disadvantage of the optical method as it has been proposed and employed is the requirement that a heavy-metal vapour be used as the target.

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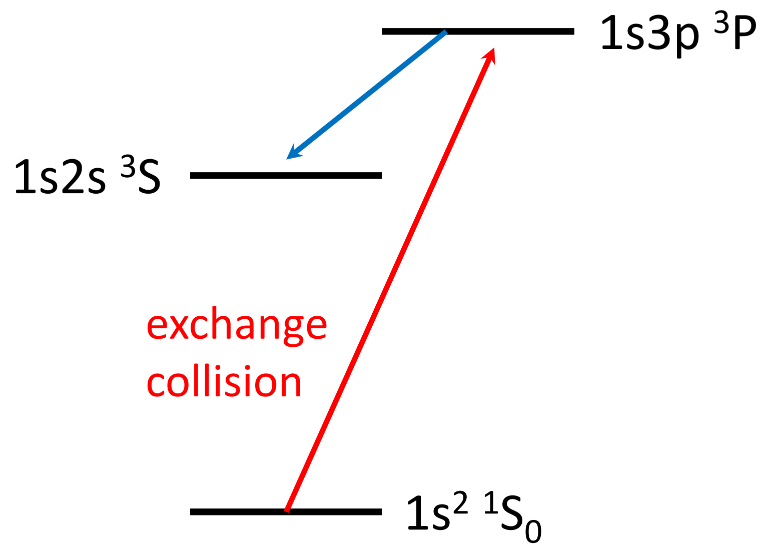

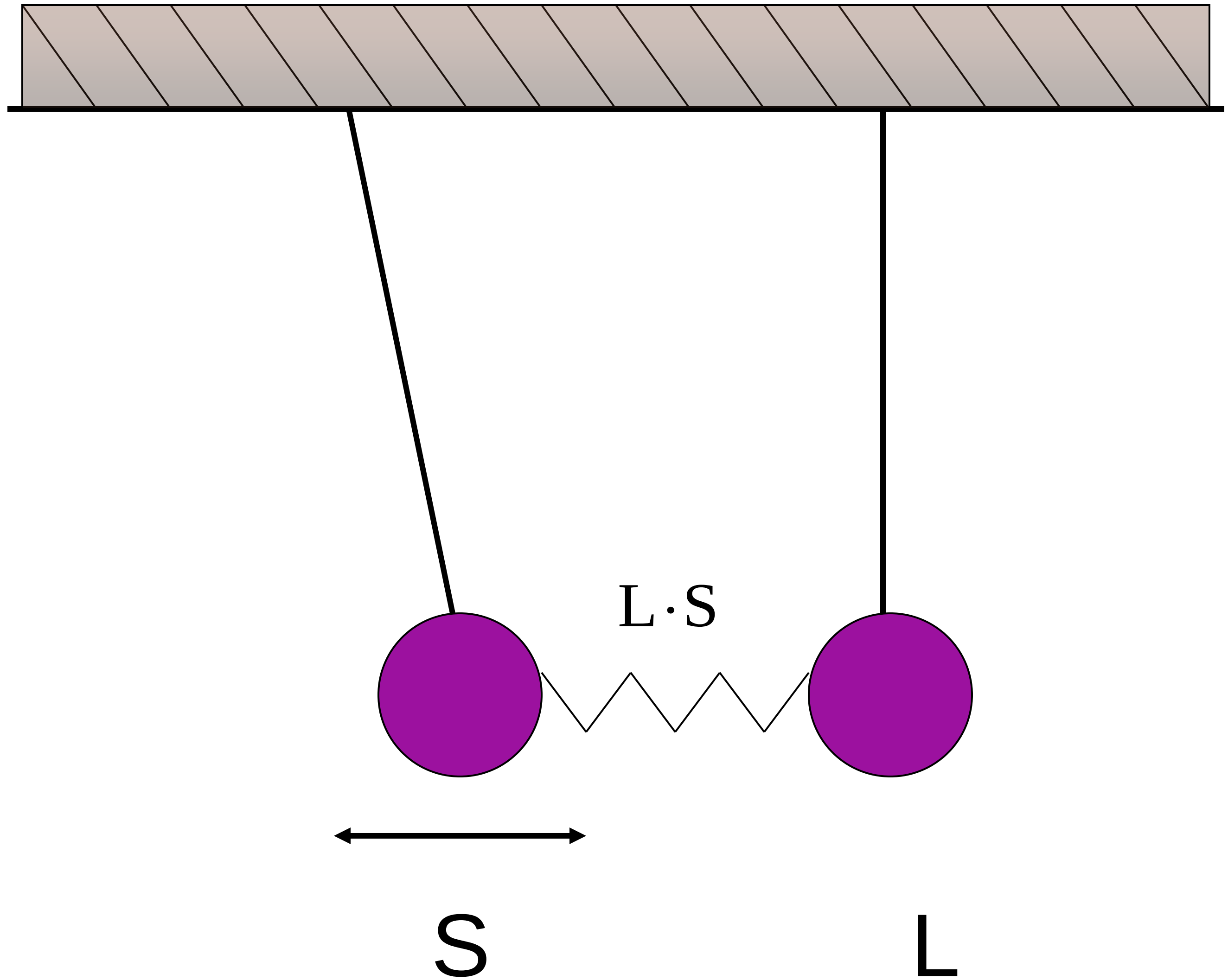
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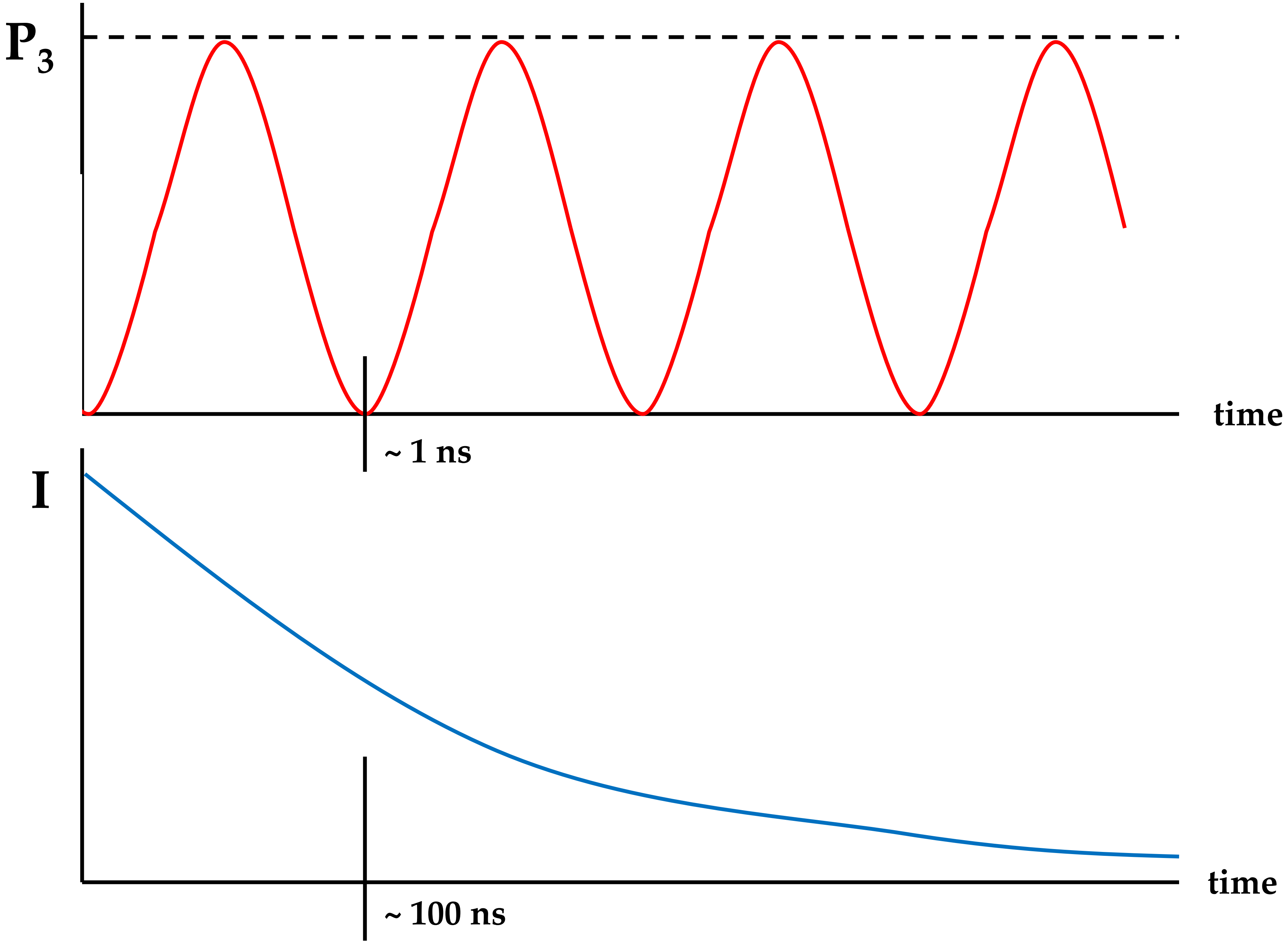
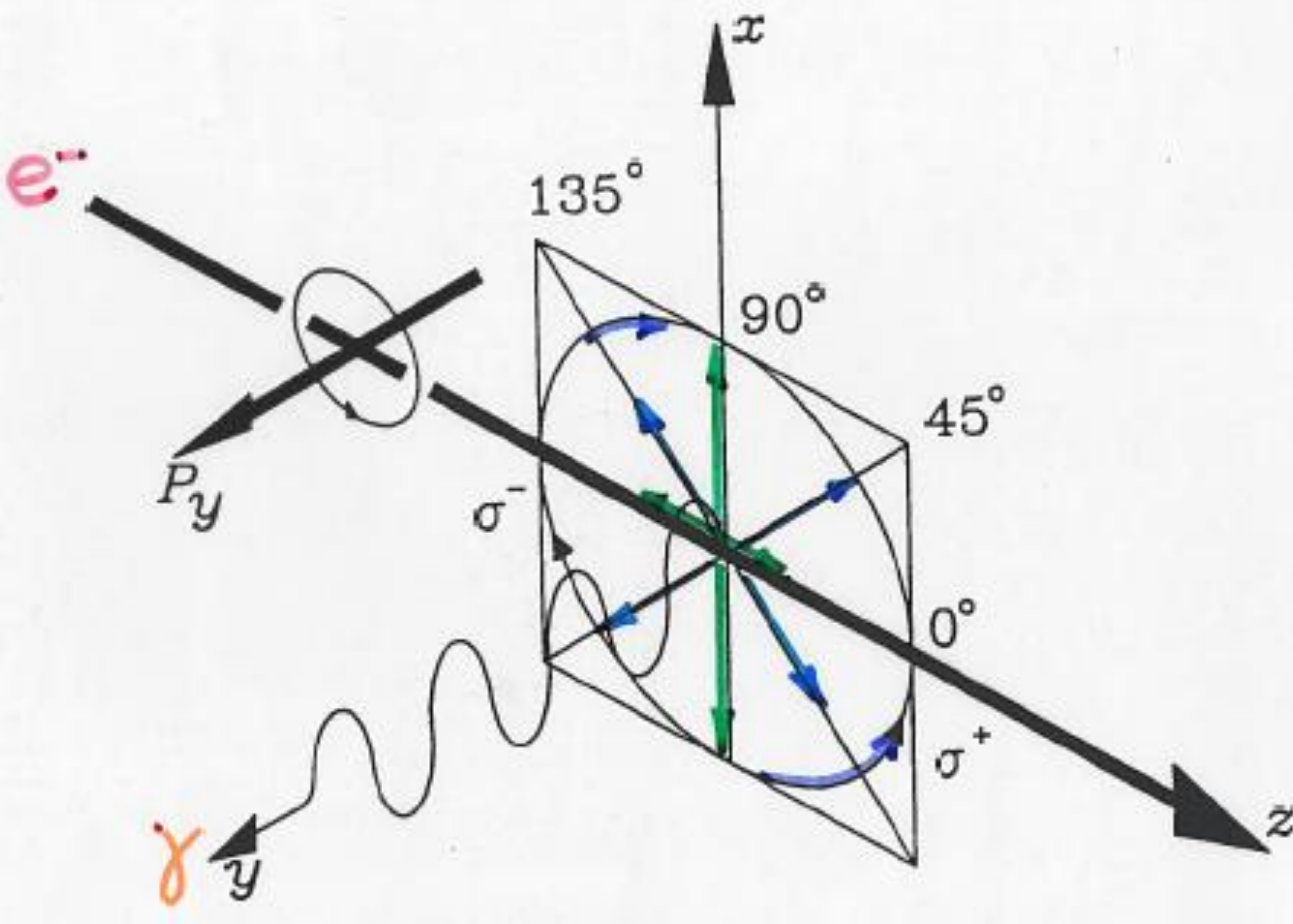


P_3
time
~ 1 ns
I
time
~ 100 ns

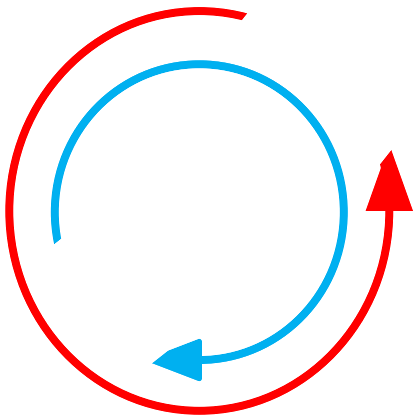


e⁻
x
135°
90°
45°
0°
σ⁻
σ⁺
P_y
γ
y
z

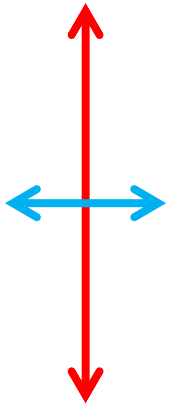
The general electron optical polarimeter equation

$$P_e = \frac{P_3}{[a + bP_1]}$$

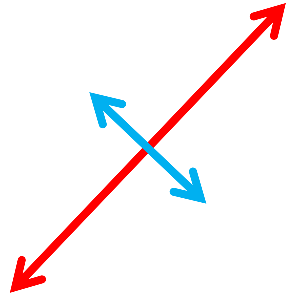
NB – a,b, exactly computable



$P_3 \rightarrow$ Electron polarization in the direction of the emission direction

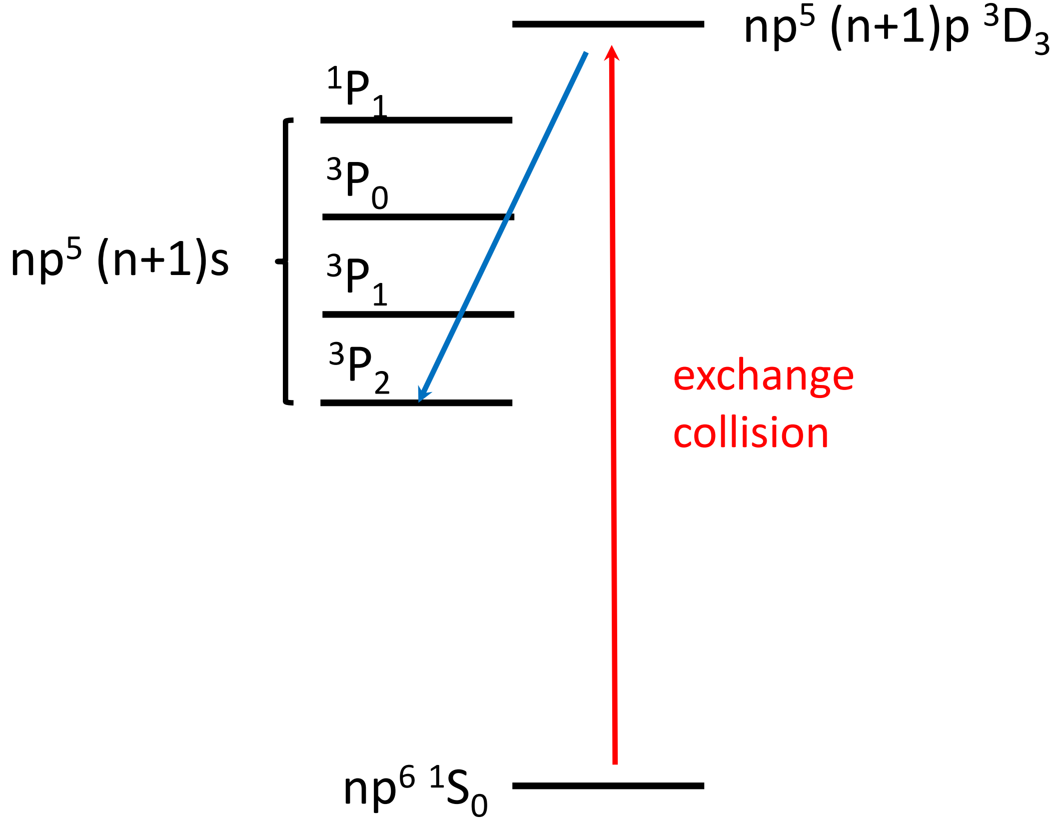


$P_1 \rightarrow$ Analyzing Power



$P_2 \rightarrow$ Validity of the kinematic assumptions

A More Recent Proposal; Heavy Noble Gases

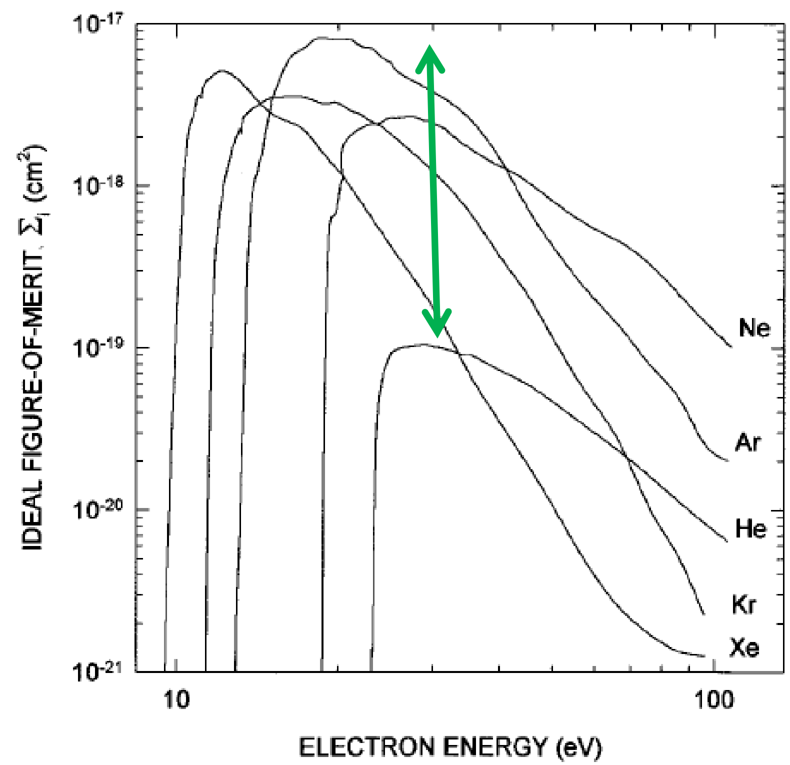


T.J.Gay *et alii*, Phys. Rev. A **53**, 1623 (1996)

TABLE I. Polarimetric transitions for the noble gases (see text). Values of γ, β, and A (threshold) are taken from Refs. [5] and [9].

Target	Transition	E_t (eV)	E_c (eV)	First cascading state	σ_{max} (10^{-19} cm^2)	γ	β	A (threshold)
He	$3\,^3P \rightarrow 2\,^3S$ (3889 Å)	23.00	23.59	$4\,^3S$[a]	7.0 (Ref. [13])	0.5000	−0.3333	0.4390
Ne	$3\,^3D_3 \rightarrow 2\,^3P_2$ (6402 Å)	18.55	19.66	$4\,^3P_2^o$	91 (Ref. [14])	0.6663	0.2230	0.7315
Ar	$4\,^3D_3 \rightarrow 3\,^3P_2$ (8115 Å)	13.07	13.90	$3d_3$	260 (Ref. [15])	0.6667	0.2222	0.7317
Kr	$5\,^3D_3 \rightarrow 4\,^3P_2$ (8112 Å)	11.44	12.11	$3d_3$	120[b] (Ref. [16])	0.6214	0.2768	0.6959
Xe	$6\,^3D_3 \rightarrow 5\,^3P_2$ (8819 Å)	9.72	9.94	$5\,^3F_4^o$	280[b] (Ref. [16])	0.6322	0.3098	0.7080

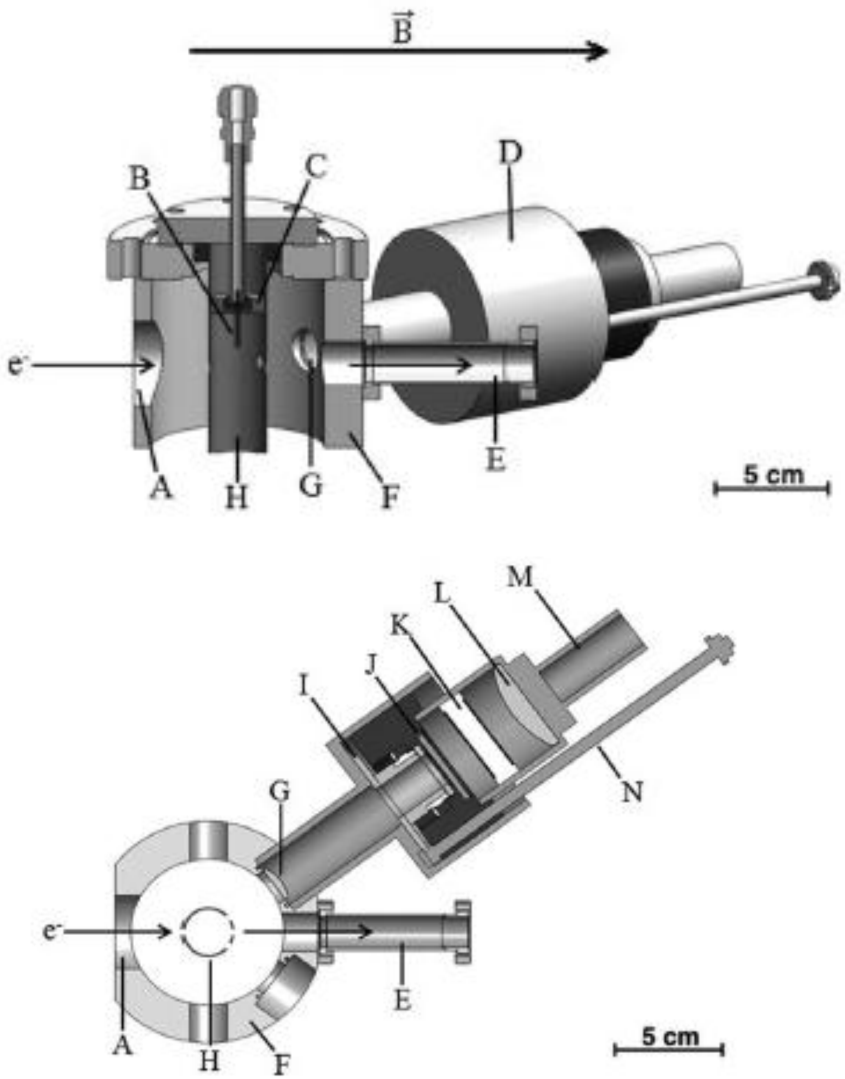
[a]The $3\,^3D$ state decays almost exclusively to the $2\,^3P$ state (see text).
[b]Extrapolated to zero target pressure.

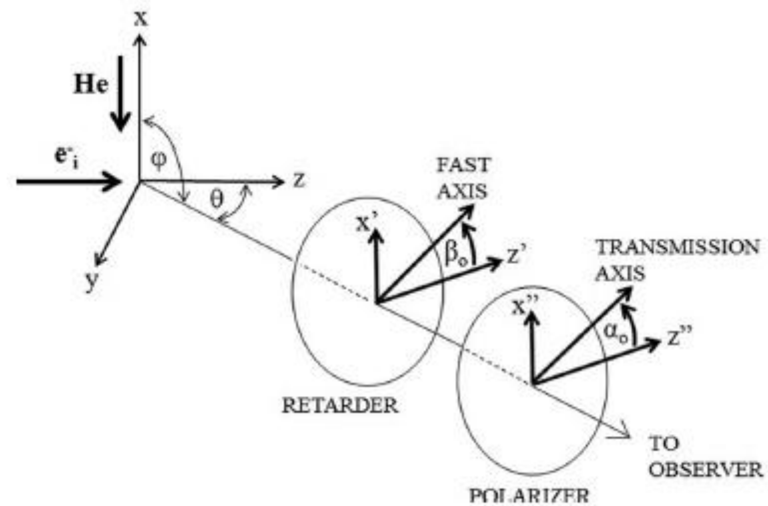


Advantages of the Optical Method

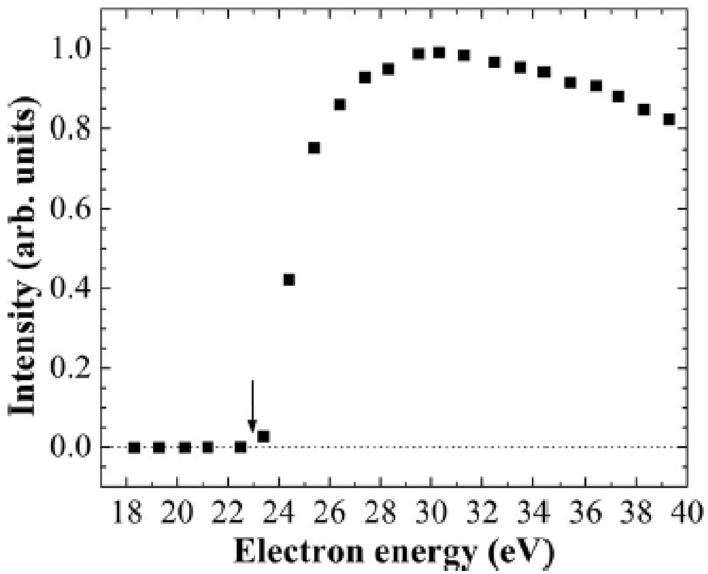
- Larger analyzing power (>2/3 for the neavy noble gases vs. 0.4-0.5 for Mott scattering)
- Omnidirectional
- Compact
- Absolute

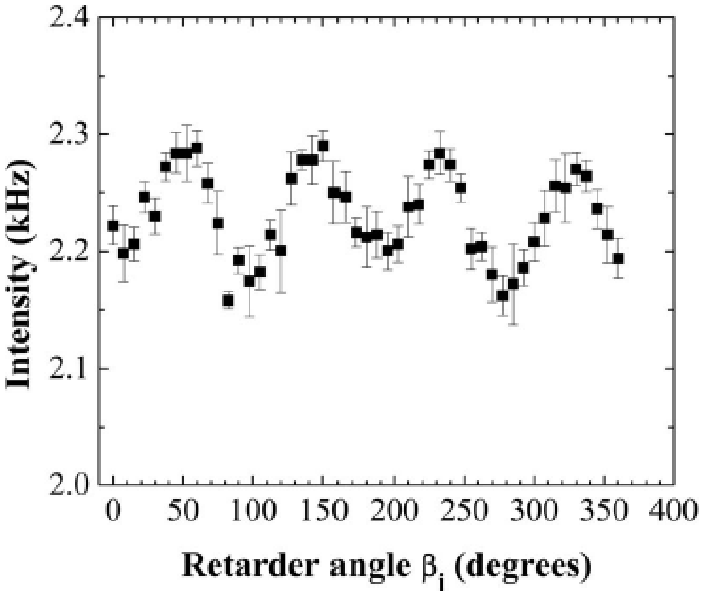
M. Pirbhai *et alii*, RSI **84**, 053113 (2013)

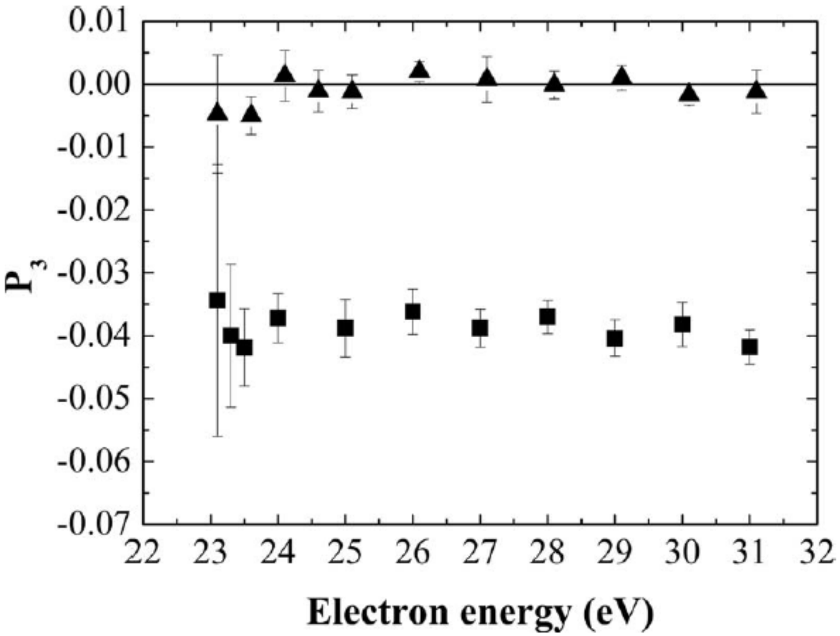




Data





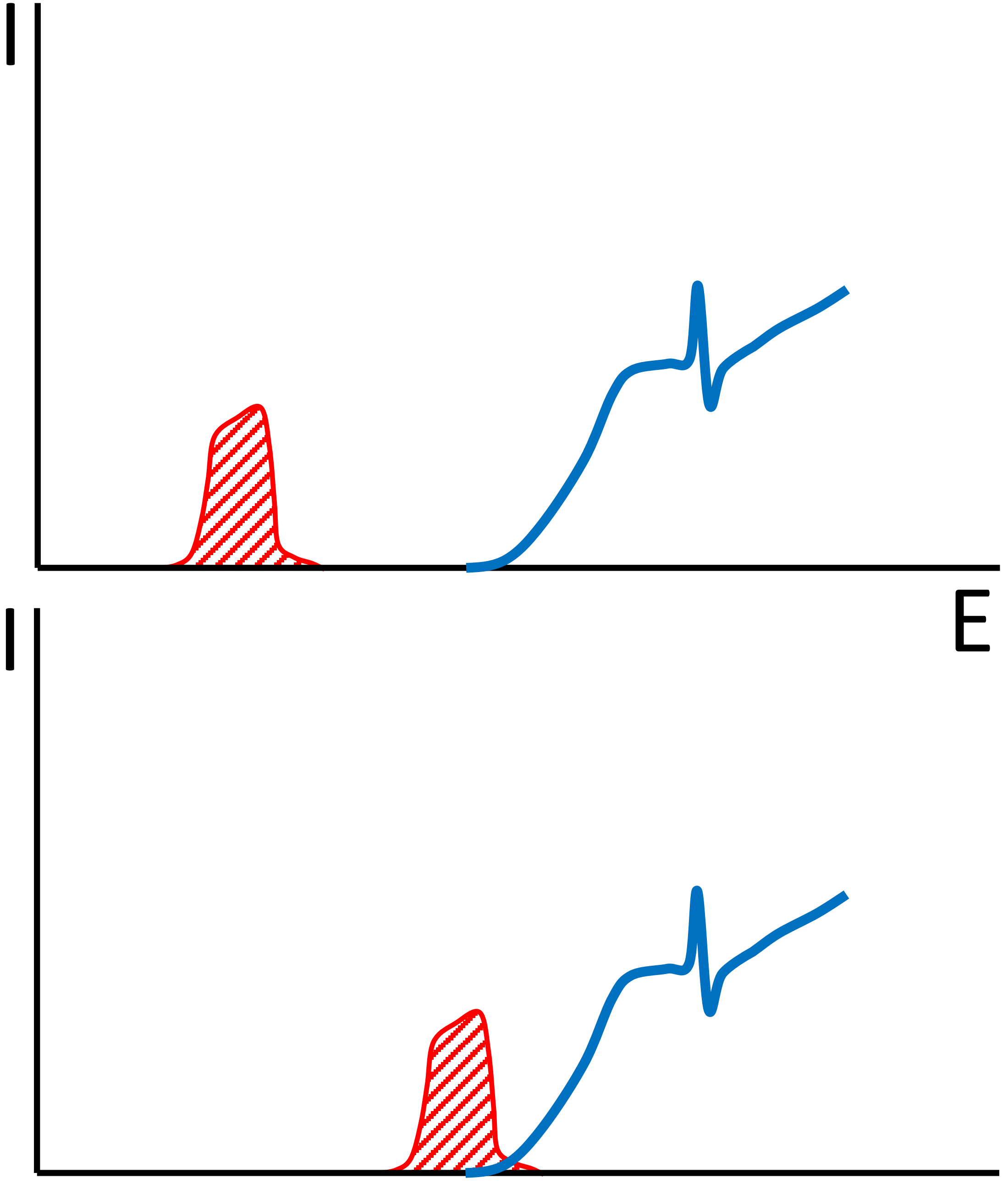


Argon Polarimetry

- Analyzing power = 0.73
- Efficiency = 500 Hz/nA
- Figure of merit = 270 Hz/nA
- 1 μA → Pe = 0.200(2) in 0.5 s

Skeletons

- Low efficiency compared with Mott scattering
- Rogue gas loads
- Cascades
- Energy dependence of efficiency $\oplus$ energy dependence of polarization within the beam width
- Hanle depolarization
- Pressure dependence of the Stokes parameters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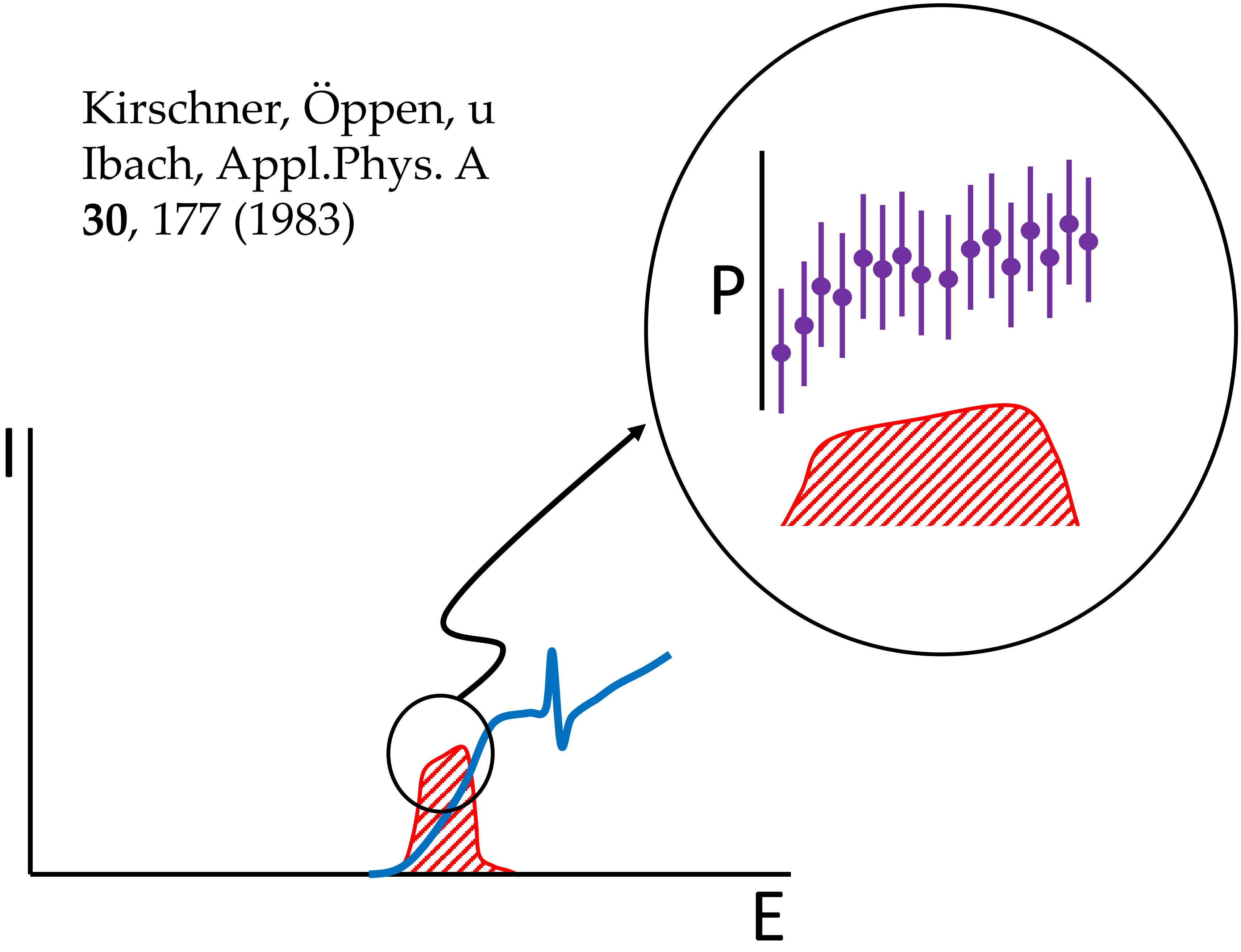
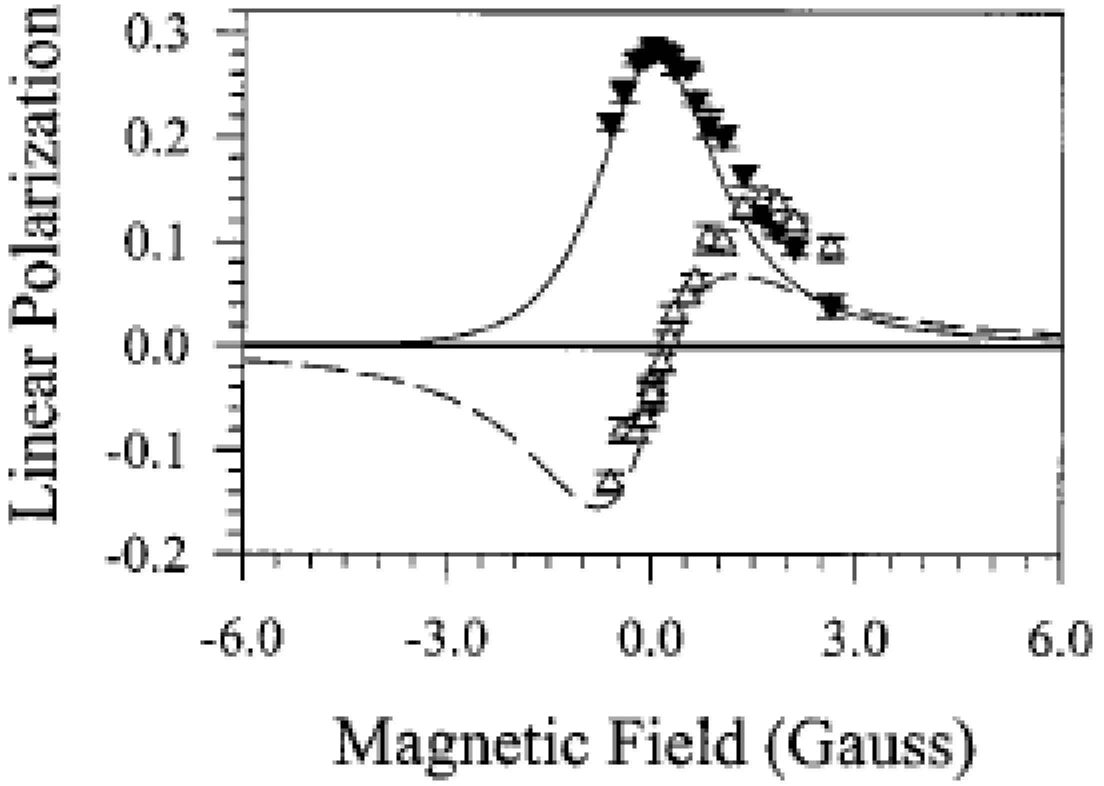
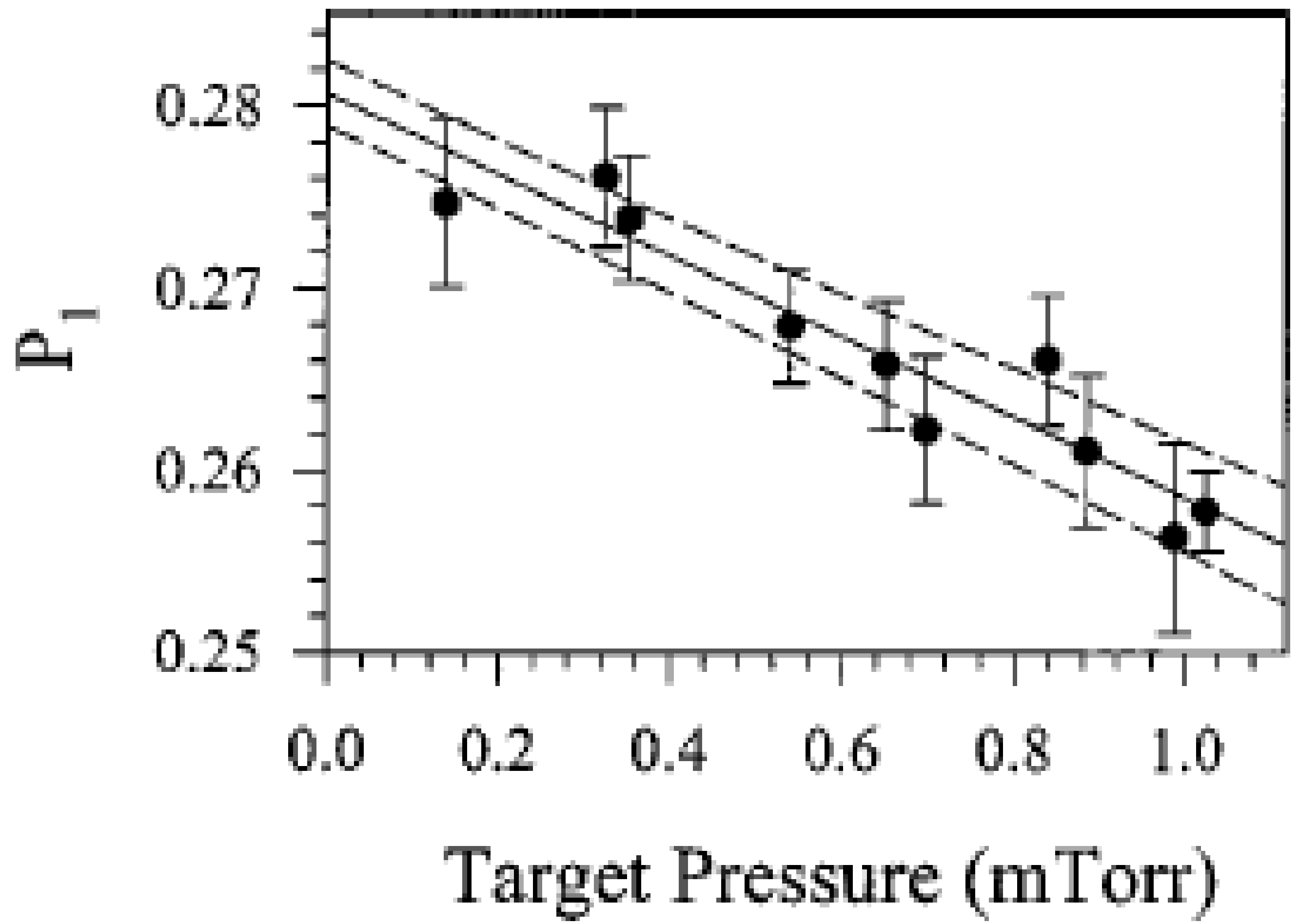
Kirschner, Öppen, u Ibach, Appl.Phys. A **30**, 177 (1983)



Hanle Depolarization

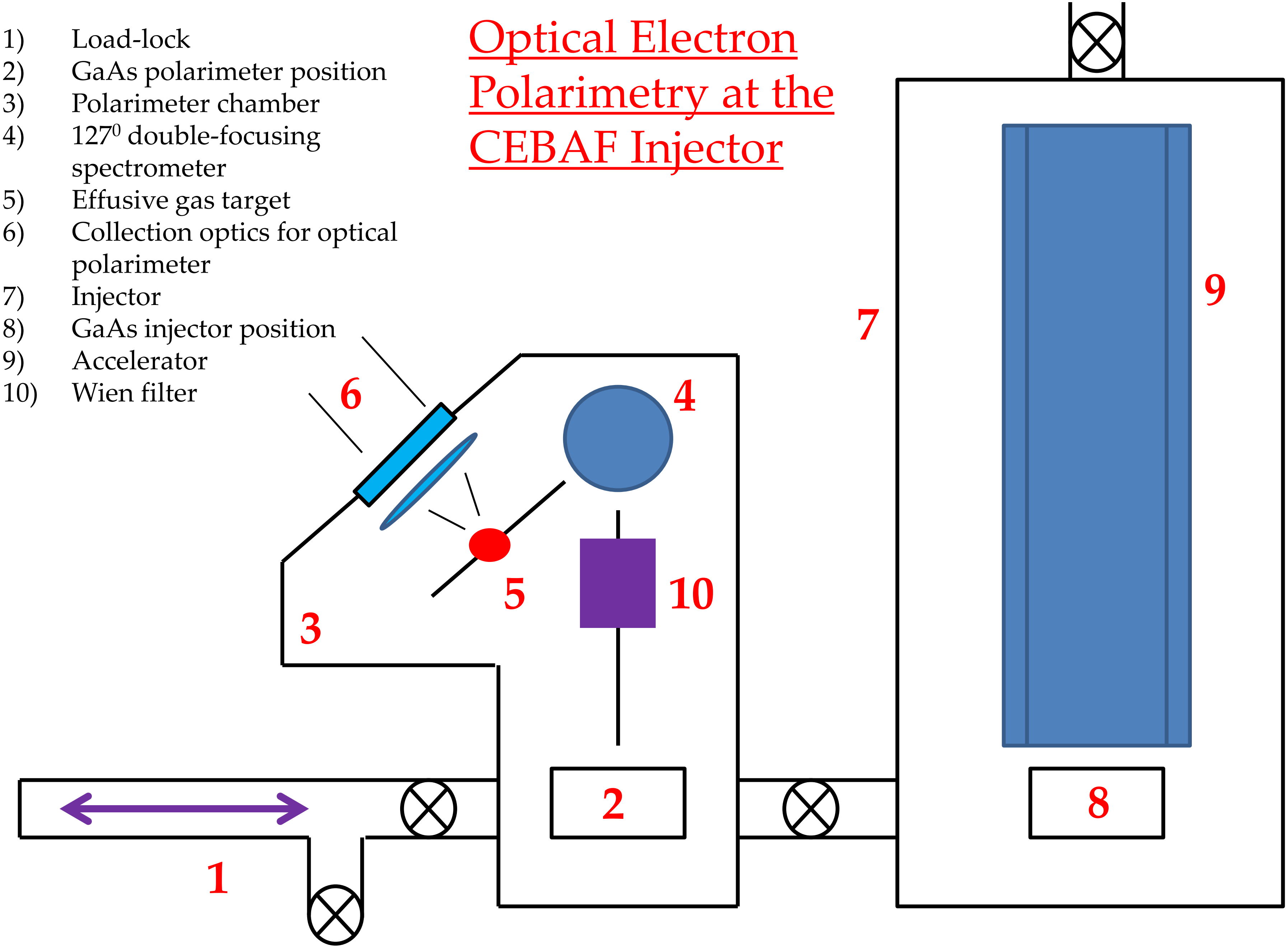


Cascading and Pressure-Dependent Effects



Optical Electron Polarimetry at the CEBAF Injector

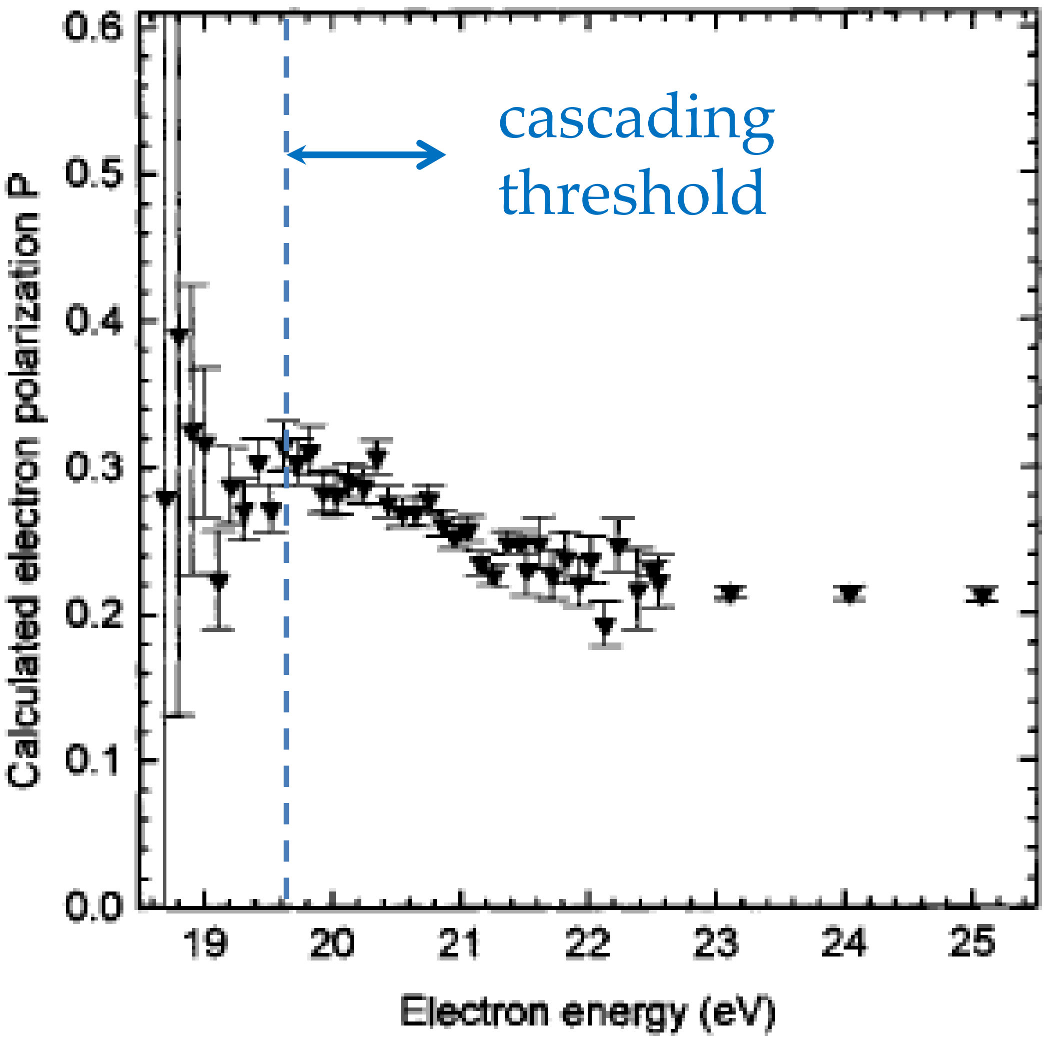
1) Load-lock
2) GaAs polarimeter position
3) Polarimeter chamber
4) 127^0 double-focusing spectrometer
5) Effusive gas target
6) Collection optics for optical polarimeter
7) Injector
8) GaAs injector position
9) Accelerator
10) Wien filter



POLO @ MAMI

- Used in 2004 with an effusive argon target and deceleration from 50 keV of the beam to be measured.
- Measured P_e with a precision of < 2%
- Very high backgrounds
- “Self calibration” not attempted
- B.Collin *et al.*, NIM A **534**, 361 (2004)

Accuracy (preliminary)



- P_e= 0.273(4)
- 1.5% absolute
- < 100 s acquisition time

Acknowledgements

- John Furst (Newcastle (Australia))
- Joe Grames (J-LAB)
- Dr. James McCarter (UVA, J-LAB)
- Marty McHugh (GWU)
- Dr. Munir Pirbhai (UNL)
- Matt Poelker (J-LAB)
- Charles Sinclair (TIAA-CREF)
- Riad Suleiman (J-LAB)
- KenTrantham (UNL)

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