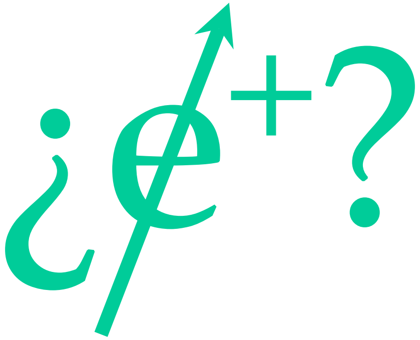
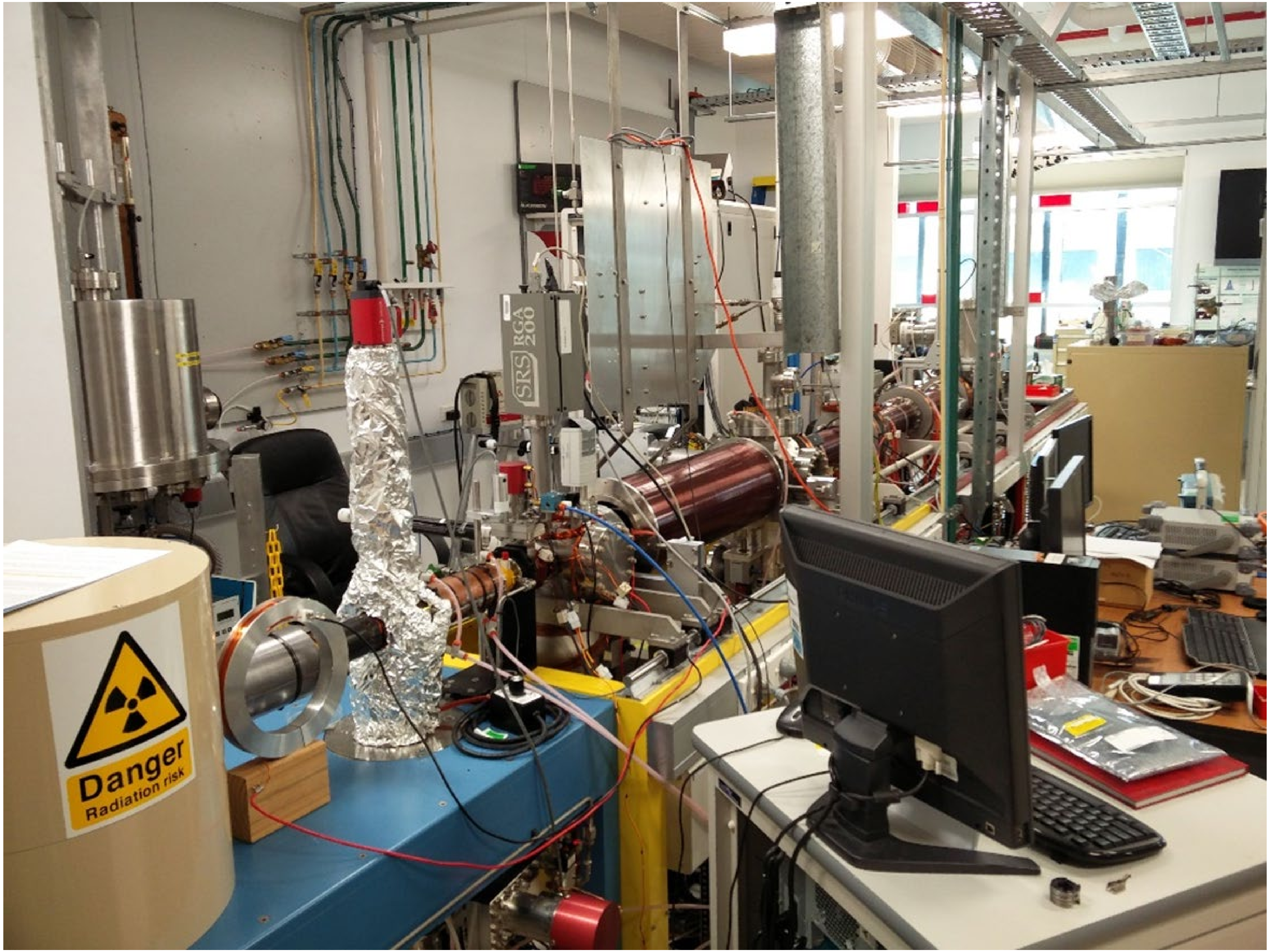

¿e+?

# Some New Ideas: Low-Energy Positron Physics at the ANU and a Proposal for a New Positron Polarimeter

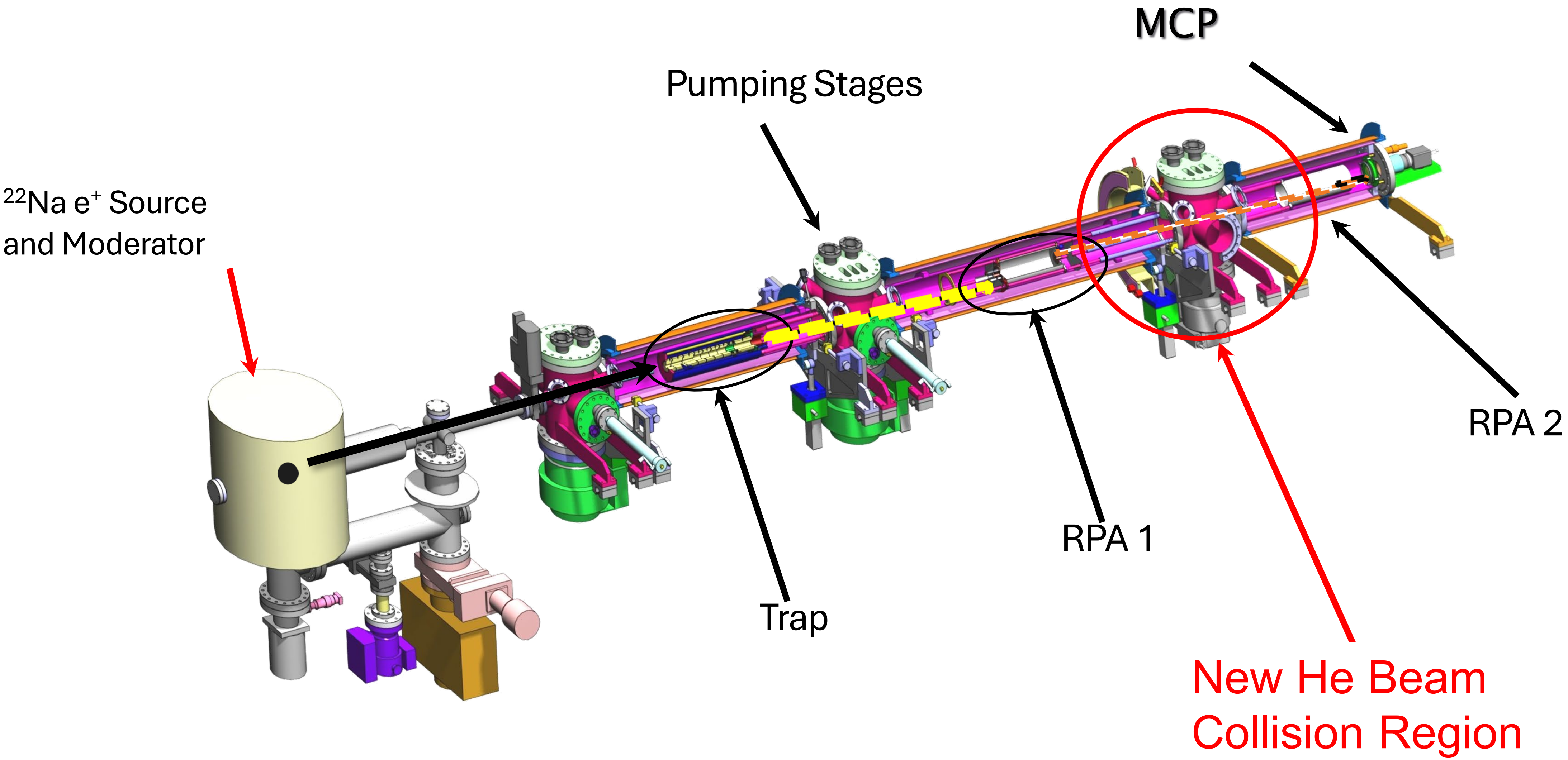
*T.J.Gay*
*University of Nebraska*

*J.R.Machacek, S.Hodgman, L.Wymer, S.Kumar*
*and S.J.Buckman*
*Australian National University*

# ANU Positron Beamline # 2



# ANU Positron Beamline



$^{22}$Na e$^+$ Source
and Moderator

Pumping Stages

MCP

Trap

RPA 1

RPA 2

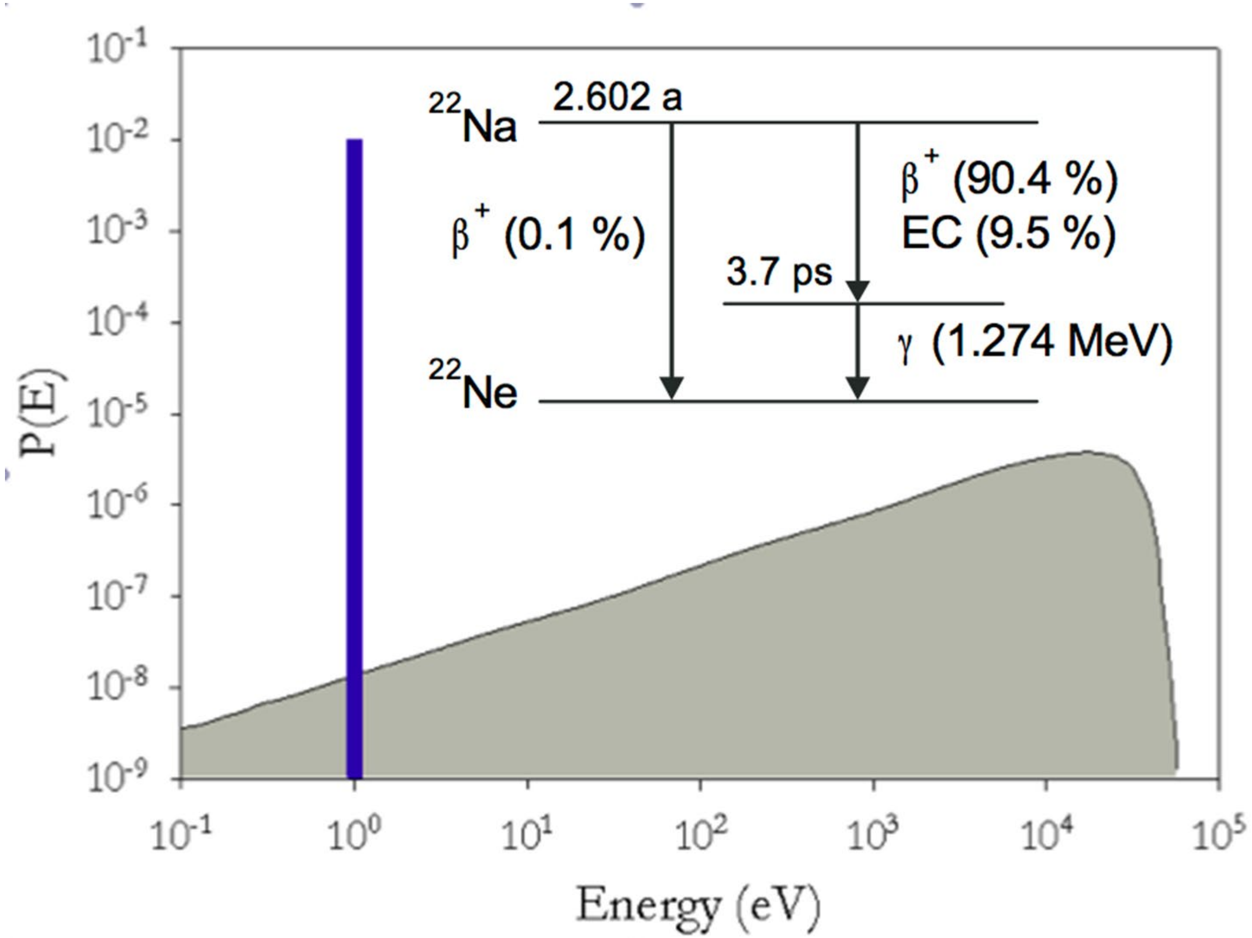
New He Beam
Collision Region

# Nuclear β Decay – Weak Interaction

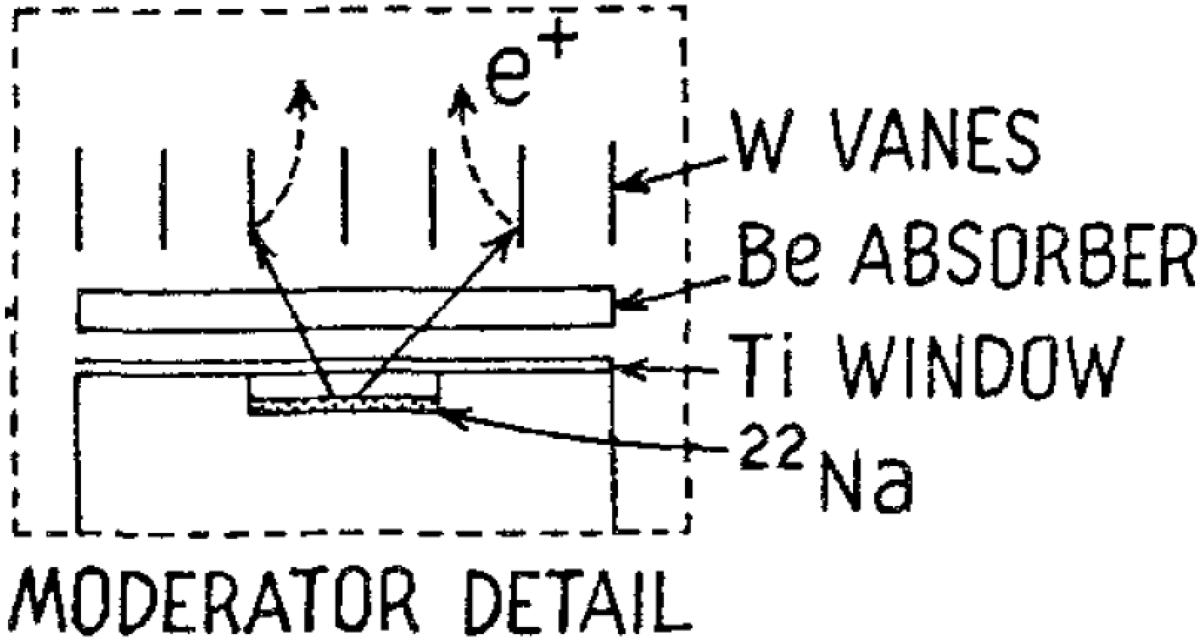
$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne}^{*} + e^{+} + \nu \rightarrow {}^{22}_{10}\mathrm{Ne} + \gamma(1.28\ \mathrm{MeV}) + e^{+} + \nu$$

Helicity: $H \approx \frac{v}{c} = 70\%$

for 200 keV



# Moderators



D.W.Gidley , A.Rich, J. Van House, and P.W. Zitzewitz, Nature **297**, 639 (1982)

¡ Need to know $P_{e^+} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$ !

# Possible Schemes for Low-Energy Positron Polarimetry

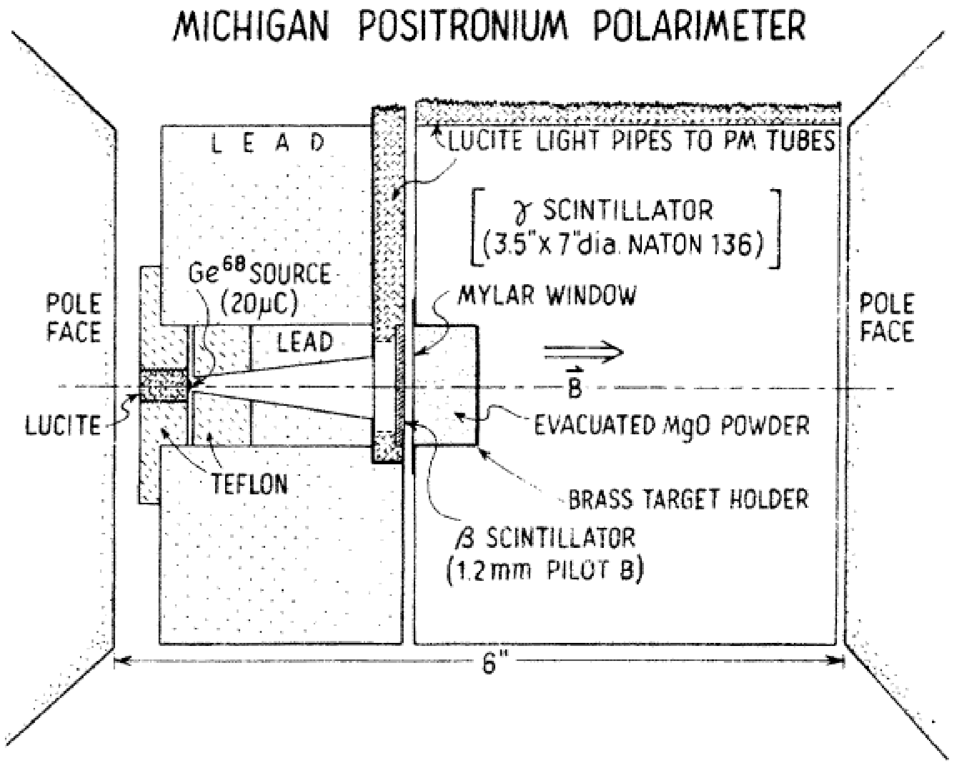
- ~~Mott Scattering~~ (wrong charge sign)

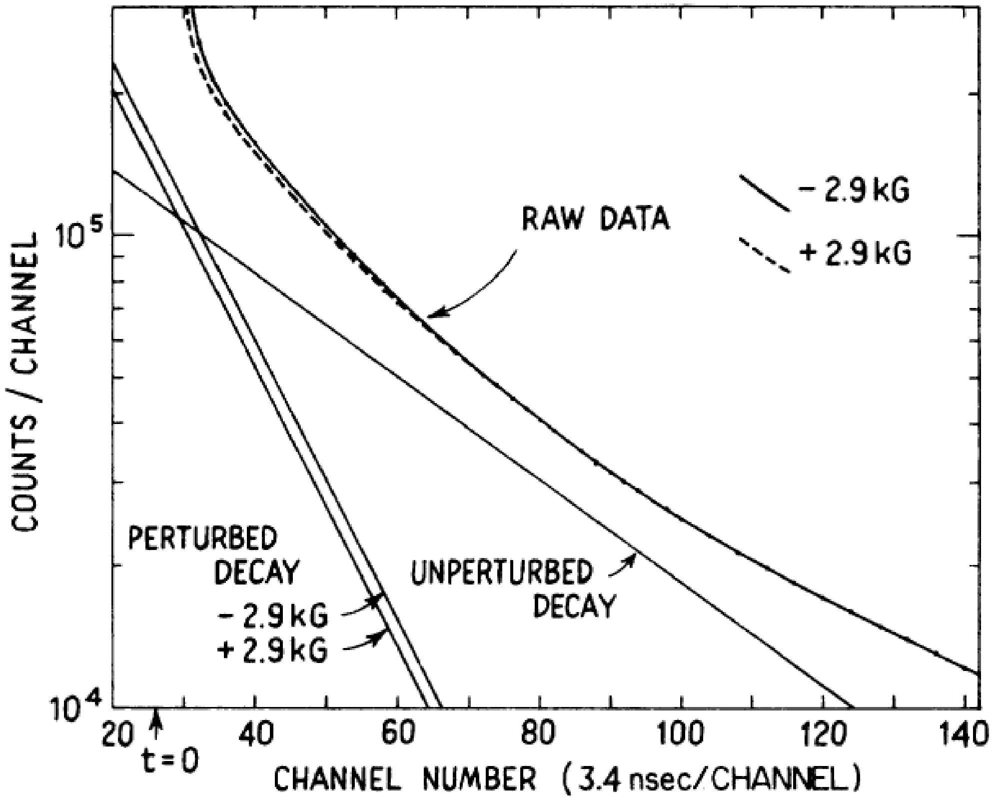
- ~~Bhabba scattering~~ (OK – above several MeV)

- The standard: methods involving high magnetic fields to quench positronium with subsequent decay gamma rays being detected with either time, energy, or angle cuts
    - non-fatal drawbacks: magnetic field flipping is not ideal
    - high magnetic field can pose spatial and stray field constraints

# Example:

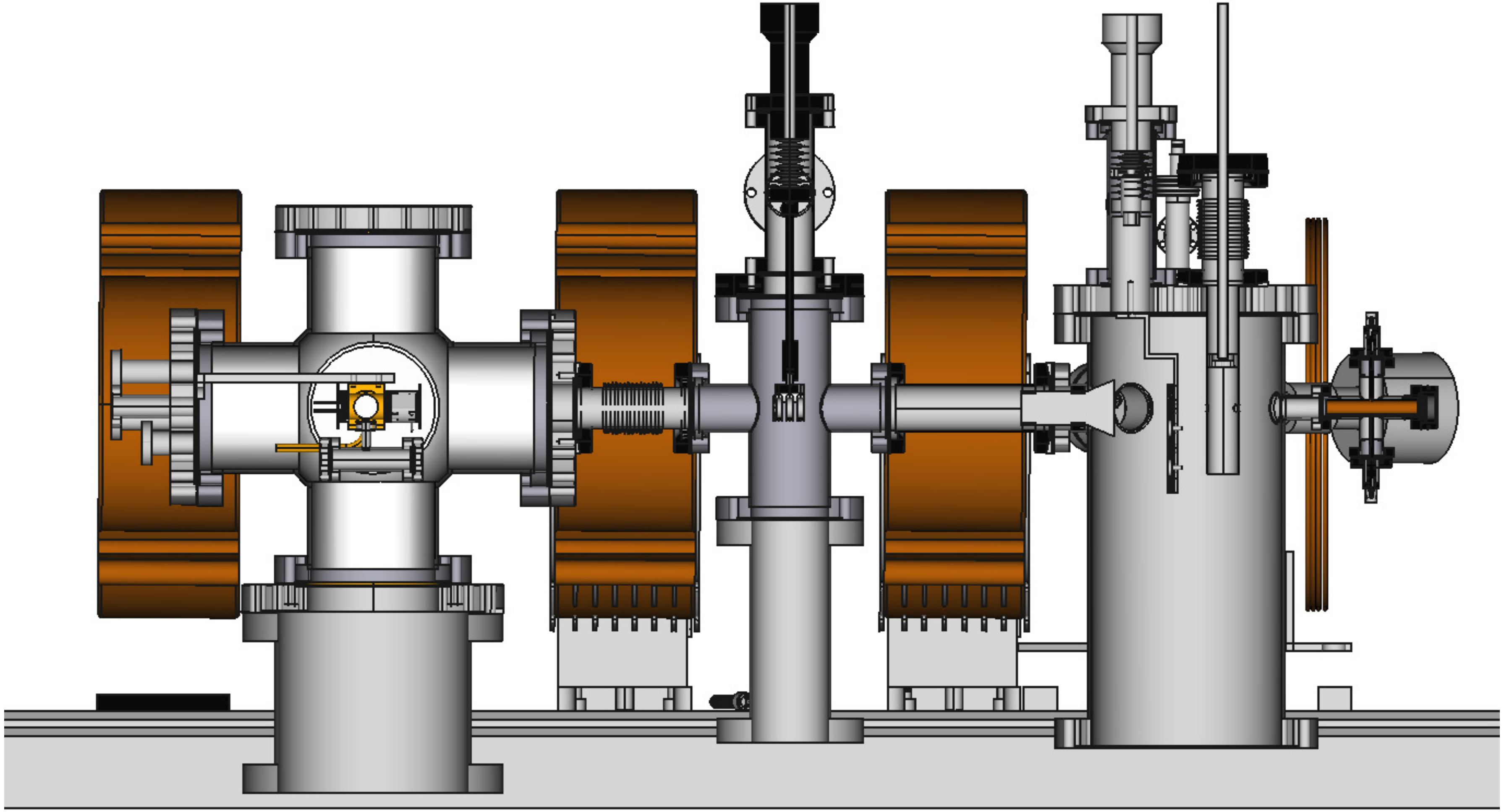
$$A = \frac{R^+ - R^-}{R^+ + R^-} \propto \vec{P} \cdot \vec{B}$$





G. Gerber *et al.*, Phys. Rev. D **15** 1189 (1977)

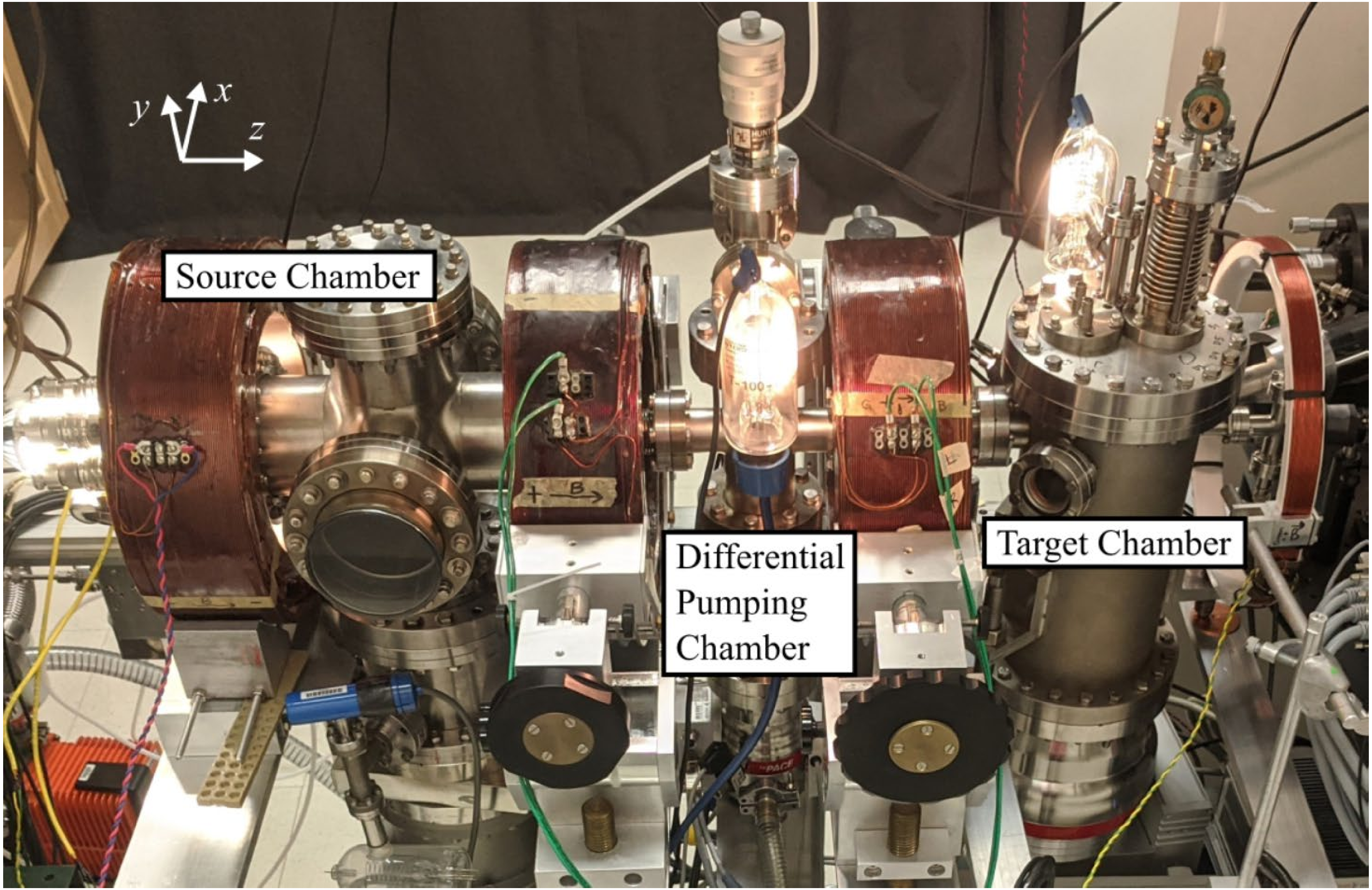
# A Relevant Technology – the Rb Spin Filter



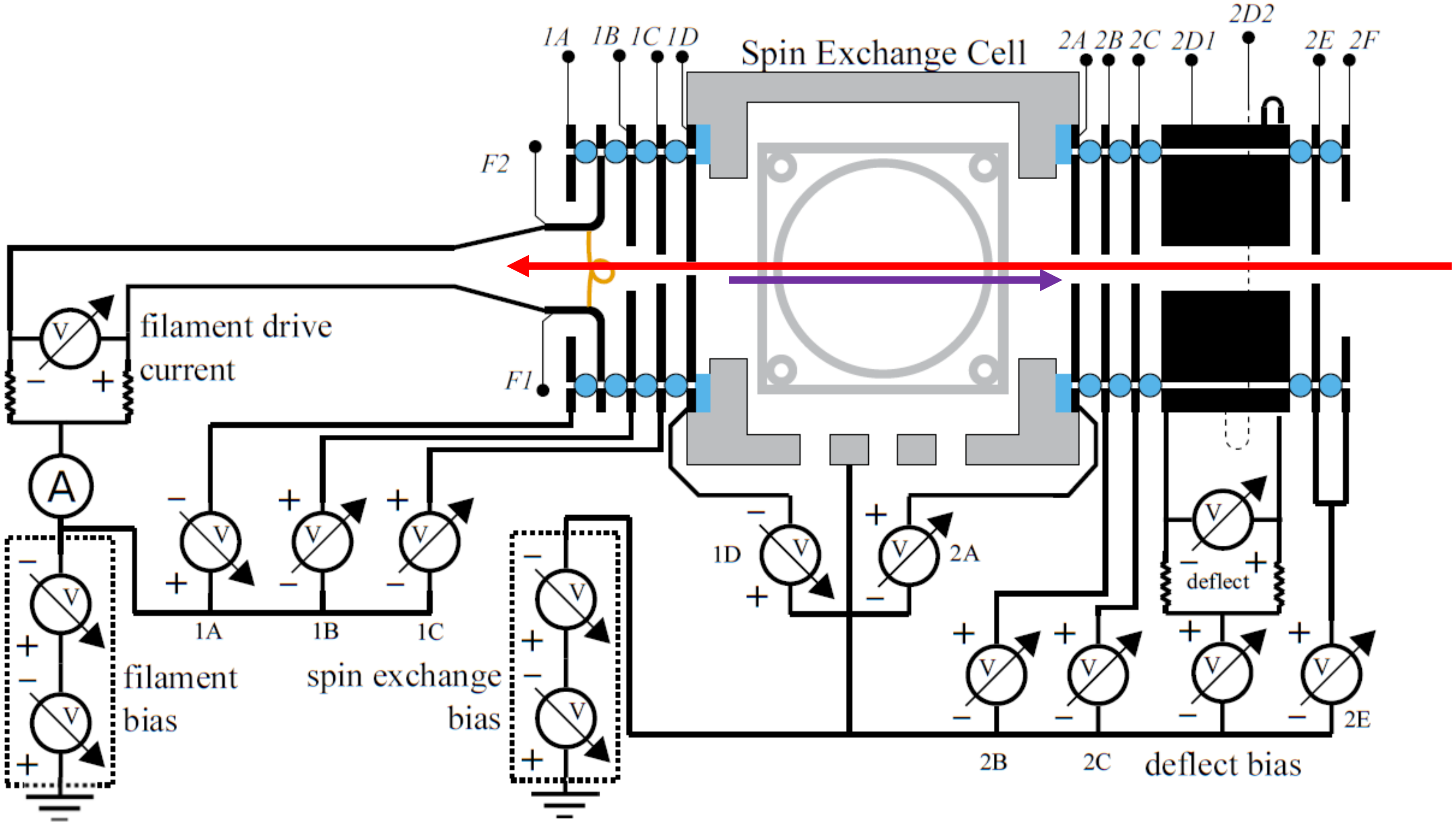
SOURCE

DIFFERENTIAL PUMPING &
TRANSPORT OPTICS

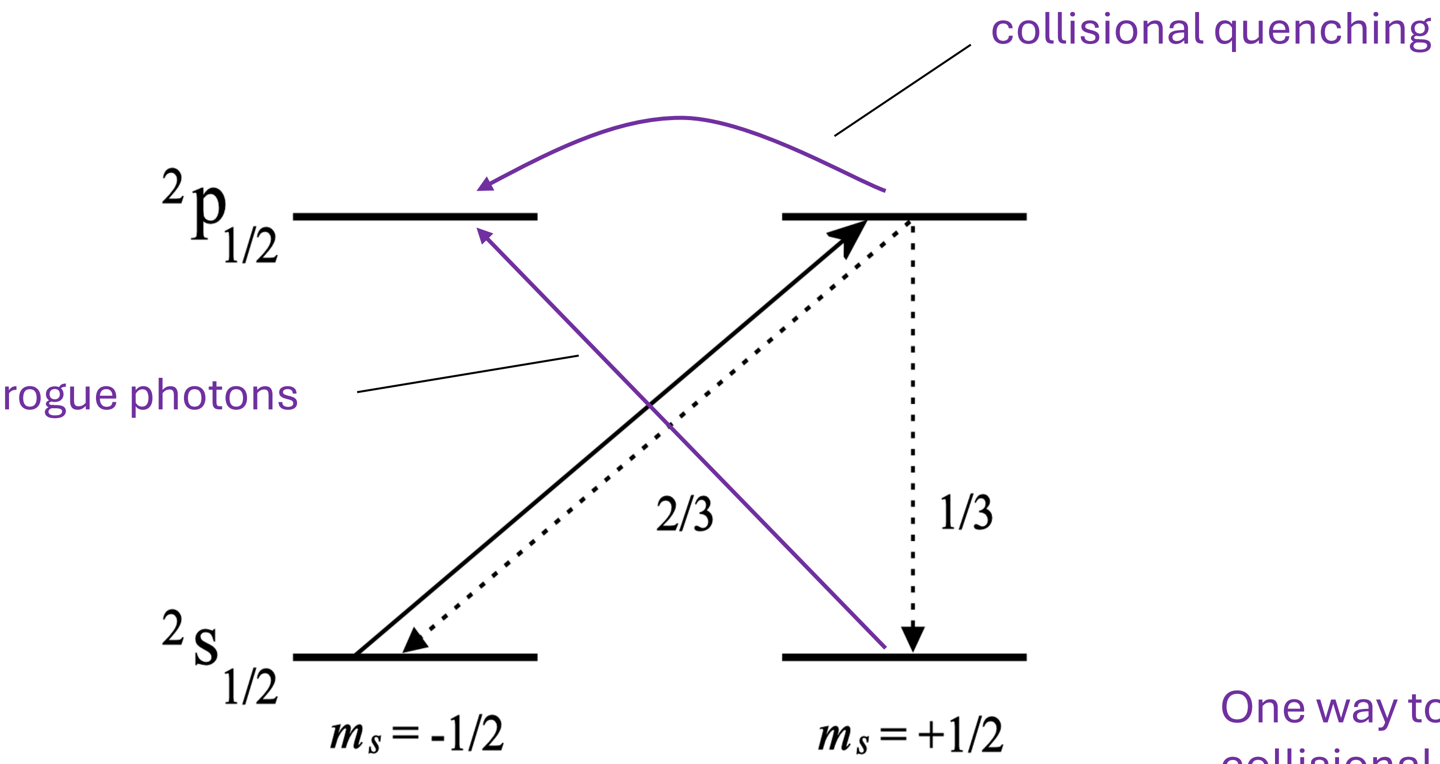
TARGET &
POLARIMETER


y
x
z
Source Chamber
Differential Pumping Chamber
Target Chamber

# Optically-Pumped Rb Spin-Transfer Cell

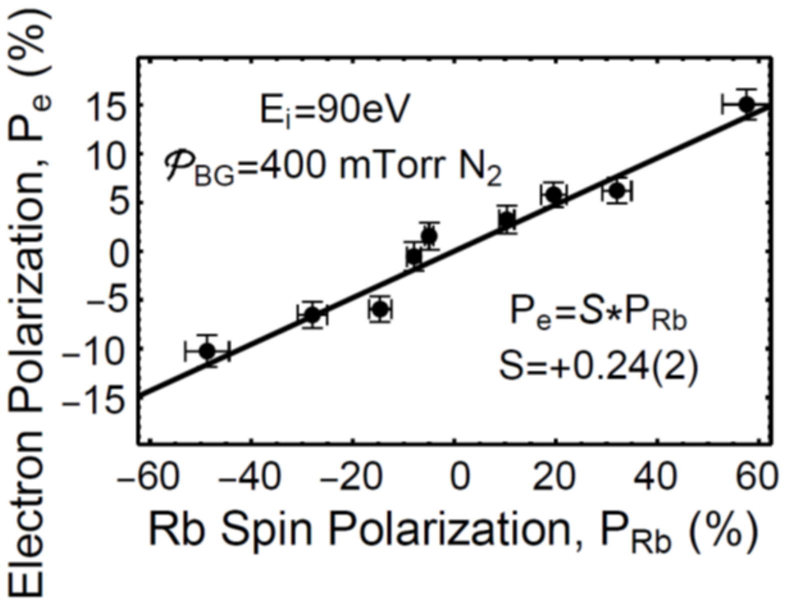


# Rb Optical Pumping and Radiation Trapping

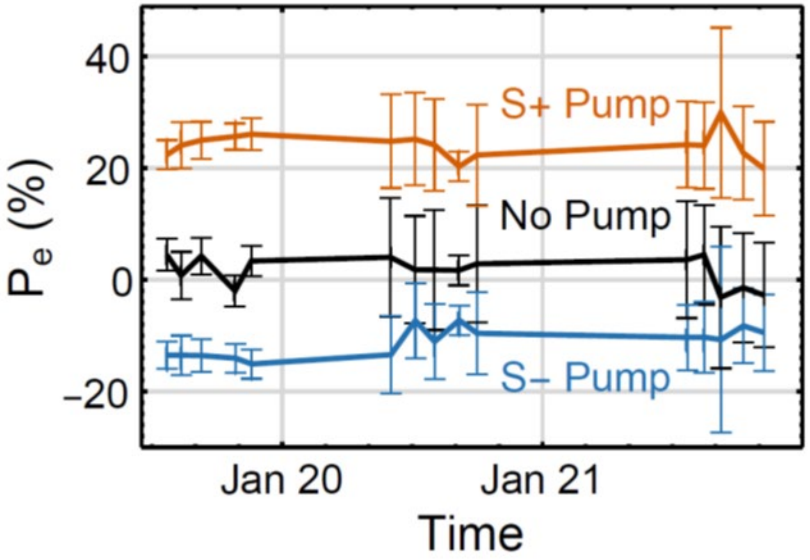


One way to solve both the collisional and radiation trapping problem is to use low densities of Rb vapor.

# Performance Parameters of the Rb Spin Filter



Spin transfer efficiency

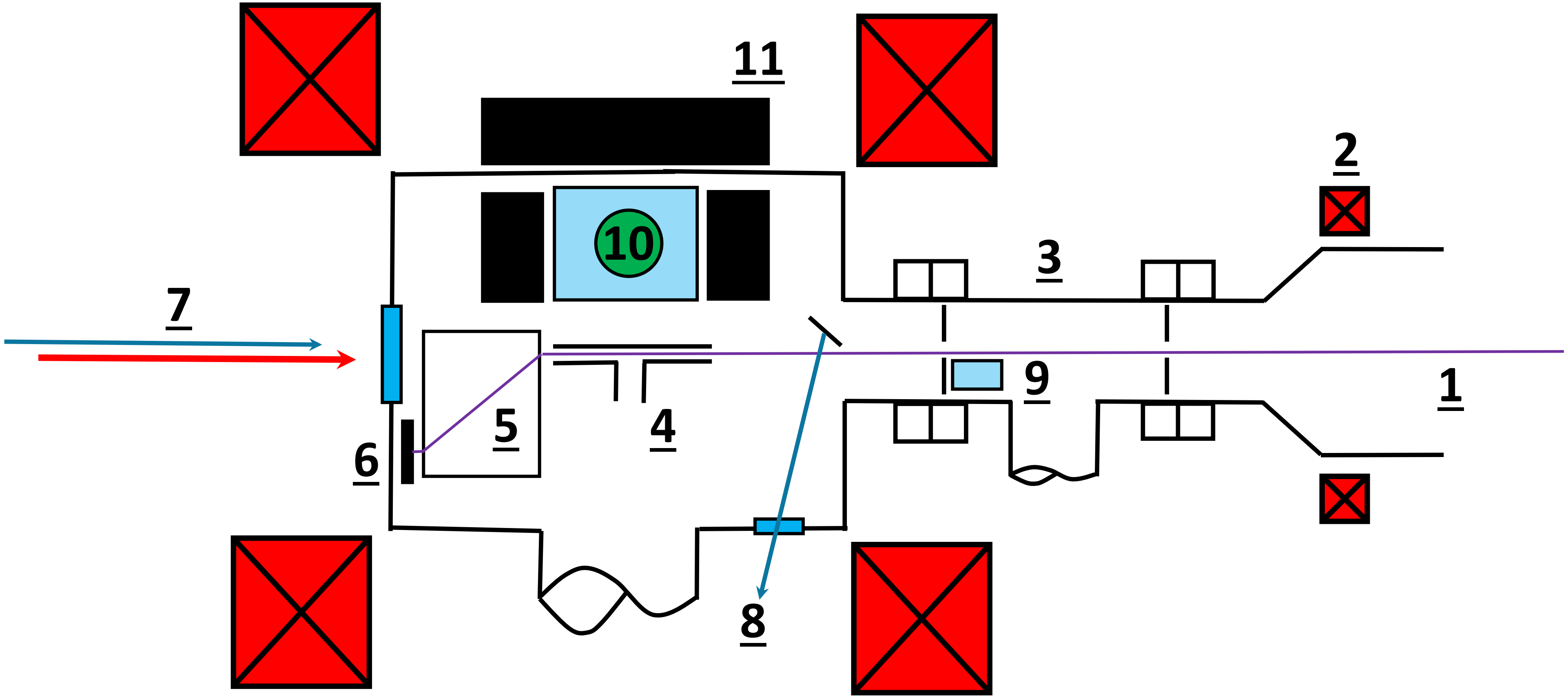


Spin stability over time

- $P_e$ = 23%
- $I_{out}$ > 4 μA
- Polarization Figure of Merit – 200 nA
- ΔE ≈ 1.5 eV
- Quasi-turn-key operation
- K.J.Ahrendsen, K.W.Trantham, D.Tupa, and T.J Gay, *Rev Sci Instrum* **94**, 083308 (2023)

# Optically-Pumped Rb Positron Polarimeter

1. Surko trap terminus and incident positron beam
2. Guiding solenoidal magnets
3. Differential pumping
4. Rb target
5. Trochoidal beam deflector
6. Beam dump
7. Optical pumping and probe lasers
8. Reflected probe beam to measure $P_{Rb}$
9. NaI scintillators (light blue)
10. Photomultiplier Tube
11. Pb blocks

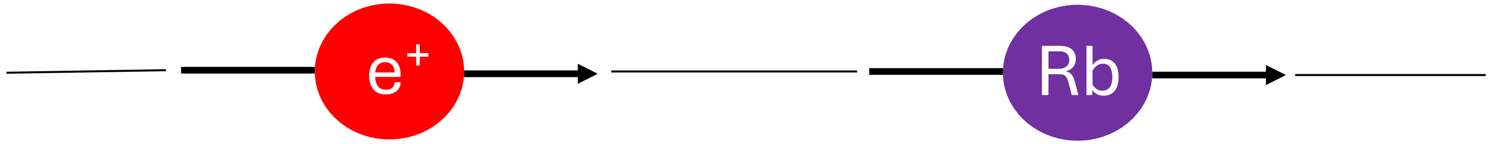


J.R.Machacek, S.Hodgman, S.J.Buckman, and T.J.Gay, Atoms **11**, 65 (2023)

# Polarimetry I

$$P_{e^+} = \frac{N^+ - N^-}{N^+ + N^-},$$

$$P_T = \frac{N_T^+ - N_T^-}{N_T^+ + N_T^-},$$



| **TARGET SPIN** | **BEAM SPIN** | **CONFIG. PROB.** | **REL. *o*-Ps PROD.** | **REL. *p*-Ps PROD.** |
|---|---|---|---|---|
| **+** | **+** | ¼(1 + $P_{e^+}$ + $P_T$ + $P_{e^+}P_T$) | **1** | **0** |
| **+** | **-** | ¼(1 - $P_{e^+}$ + $P_T$ - $P_{e^+}P_T$) | **½** | **½** |
| **-** | **+** | ¼(1 + $P_{e^+}$ - $P_T$ - $P_{e^+}P_T$) | **½** | **½** |
| **-** | **-** | ¼(1 - $P_{e^+}$ - $P_T$ + $P_{e^+}P_T$) | **1** | **0** |

# Polarimetry II

$$N_{para} = \frac{1}{4}N\sigma nl\left[3 - P_{e^+}P_T\right]$$

wait 100ns $\longrightarrow$

$$N_{ortho} = \frac{1}{4}N\sigma nl\left[3 + P_{e^+}P_T\right]$$

$$A_{flip} = \frac{R^+ - R^-}{R^+ + R^-} = \frac{1}{3}P_{e^+}P_T$$

- N = number of incident positrons
- σ = Ps formation cross section
- n = target density
- l = target length

# Optically-Pumped Rb Positron Polarimeter - Details

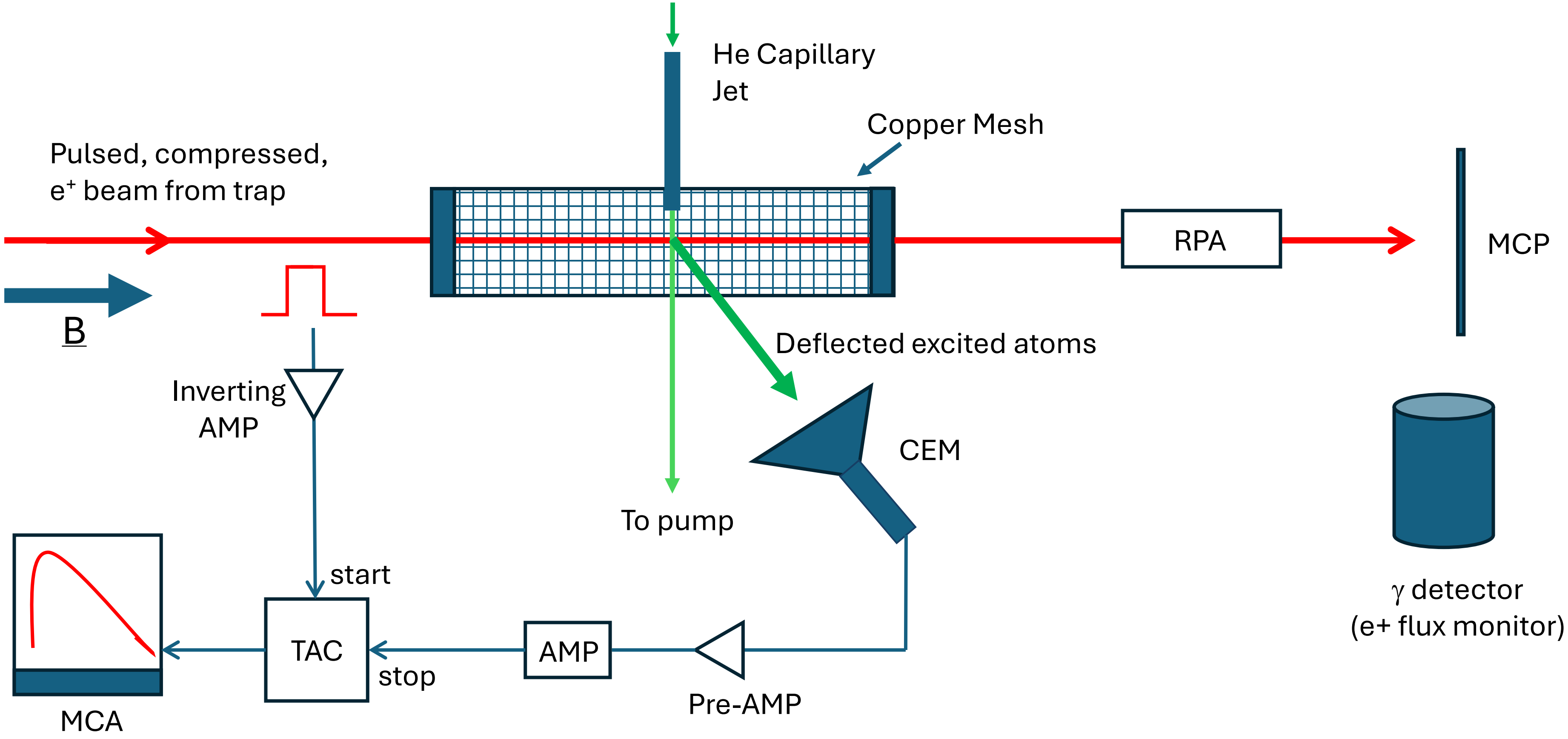
- Narrow heat pipe target to suppress optical trapping of depolarization
- <1W circularly-polarized pump laser at the Rb D1 line (795 nm)
- μW probe laser at Rb D2 line (780 nm) to measure $P_{Rb}$ using optical rotation
- Target spin is flipped not by the weak ($10^{-2}$ T) constant magnetic field but by the pump laser helicity
- $P_{Rb} \approx 100\%$
- $n_{Rb} \sim 10^{11}$ cm$^{-3}$
- $l = 3$cm
- Positron energy = 2.4 eV; precludes capture to excited states of Ps
- σ(positronium formation) = 25 x $10^{-16}$ cm$^2$;
- σ(Rb 5s – 5p excitation) = 20 x $10^{-16}$ cm$^2$;
- Σ(quasi-elastic scattering) = 100 x $10^{-16}$ cm$^2$
- Scattered $e^+$ won't annihilate at target walls because of their cyclotron motion in the magnetic field

# Polarimetric Efficiency

- $e^+$ pulses from our Surko trap: 2 x $10^6$ positrons at 1 Hz
- o-Ps production rates of 1.1 x $10^3$ per second (¡need more flux!)
- After a delay of 100 ns, half of these are gone; the rest are counted as signal
- Solid angle: 10% of gammas will hit the scintillators
- ~100% detection rate (NaI - 38 visible photons/keV and a 10% PMT quantum efficiency)
- → 55 Hz useable count rate

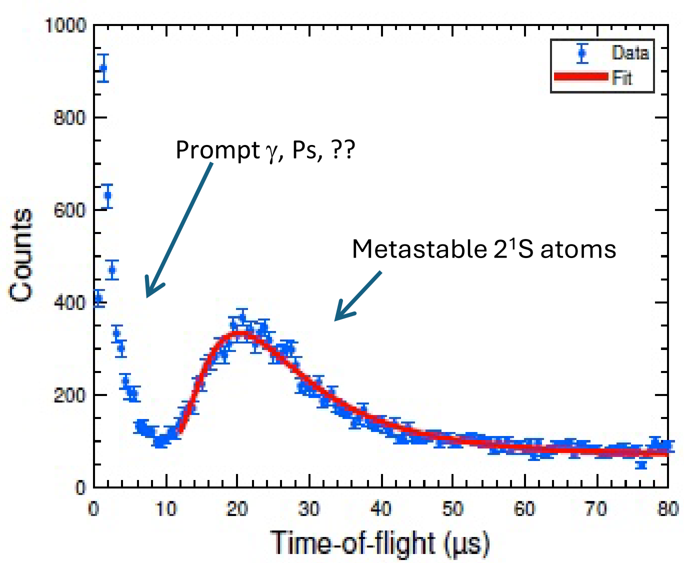
For a $P(e+)$ = 22%, a measurement precision of 2% can be achieved in < 6 minutes

# Science with Positrons (both polarized and unpolarized)



# Positron Excitation of Metastable Helium

$$e^+ + \mathrm{He}(1s^2) \rightarrow e^+ + \mathrm{He}^*(1s2s2^1\mathrm{S})$$



Positron ToF Spectrum

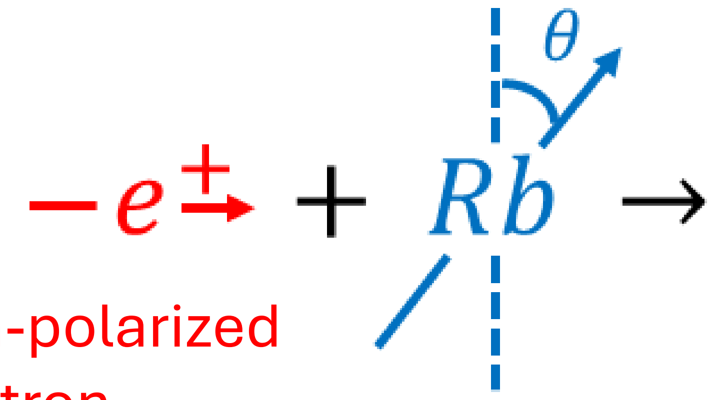
- Time between beam pulse and CEM detection is recorded
- Fast particles are separated from slow particles
- Gas beam is at room temperature and thus has a Maxwellian distribution

- Comparison to previous ANU measurement with a gas-cell and a CCC calculation by Utamuratov *et al*.
- L.Wymer, S.Kumar, T.J.Gay, S.S.Hodgman, S.J.Buckman, and J.R.Machacek, Eur. Phys. J. D **80**;12 (2026)

# Open Questions

- Can Positrons Excite He $2^3S$ states ?
  - Only possible via Spin-Orbit interaction which is weak/negligible for positrons
  - $2^3S$ state has a threshold of 19.82 eV; the $2^1S$ threshold is 20.62 eV
  - Our positron beam has an energy width < 50 eV
  - Can we put an upper limit on it ?
- Extend to heavier rare gase triplet states where there is little or no work on positron excitation measurements.
  - The S-O interaction also scales as $Z^2$
  - A test for theory for larger atomic systems

# Spin-Dependent Positronium Production with Rb



Spin-polarized
rubidium atom

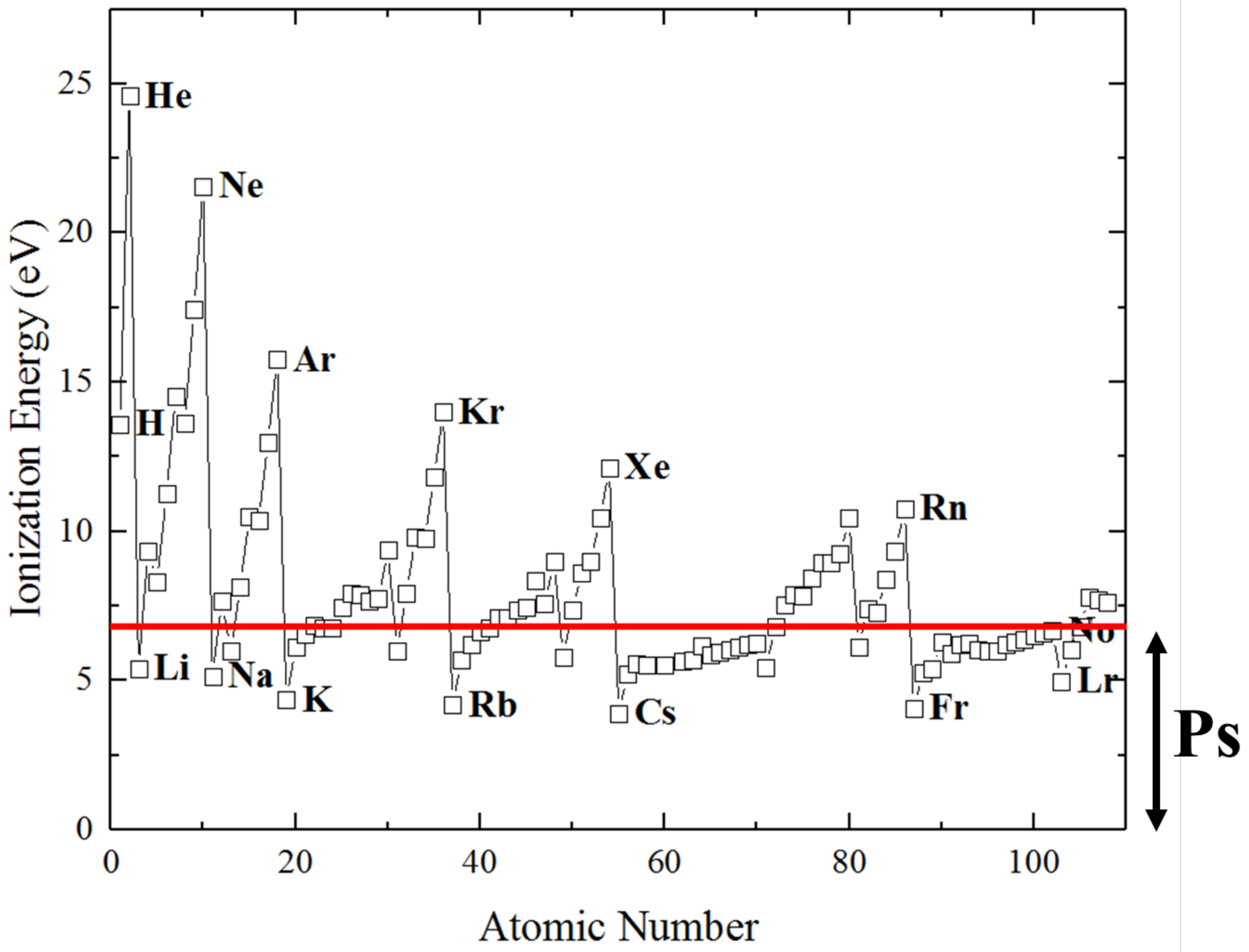
Rubidium ion

$$-e^{\pm}\!\!\rightarrow + Rb \rightarrow Ps(e^{+}, e^{-}) + Rb^{+}$$

Spin-polarized
positron

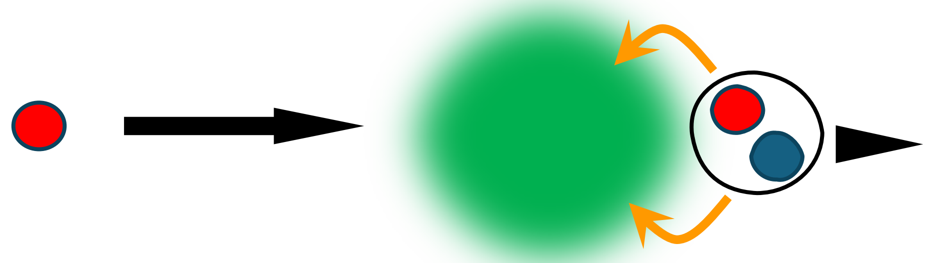
Ortho-positronium or
Para-positronium

# Atomic Targets



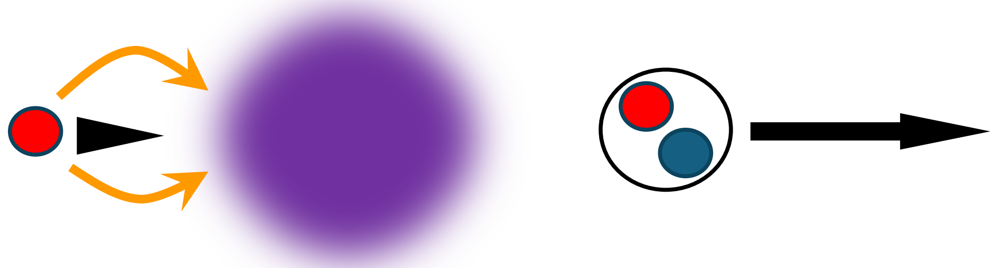
# The Dynamics of Positronium Formation

## Endothermic (Xe)



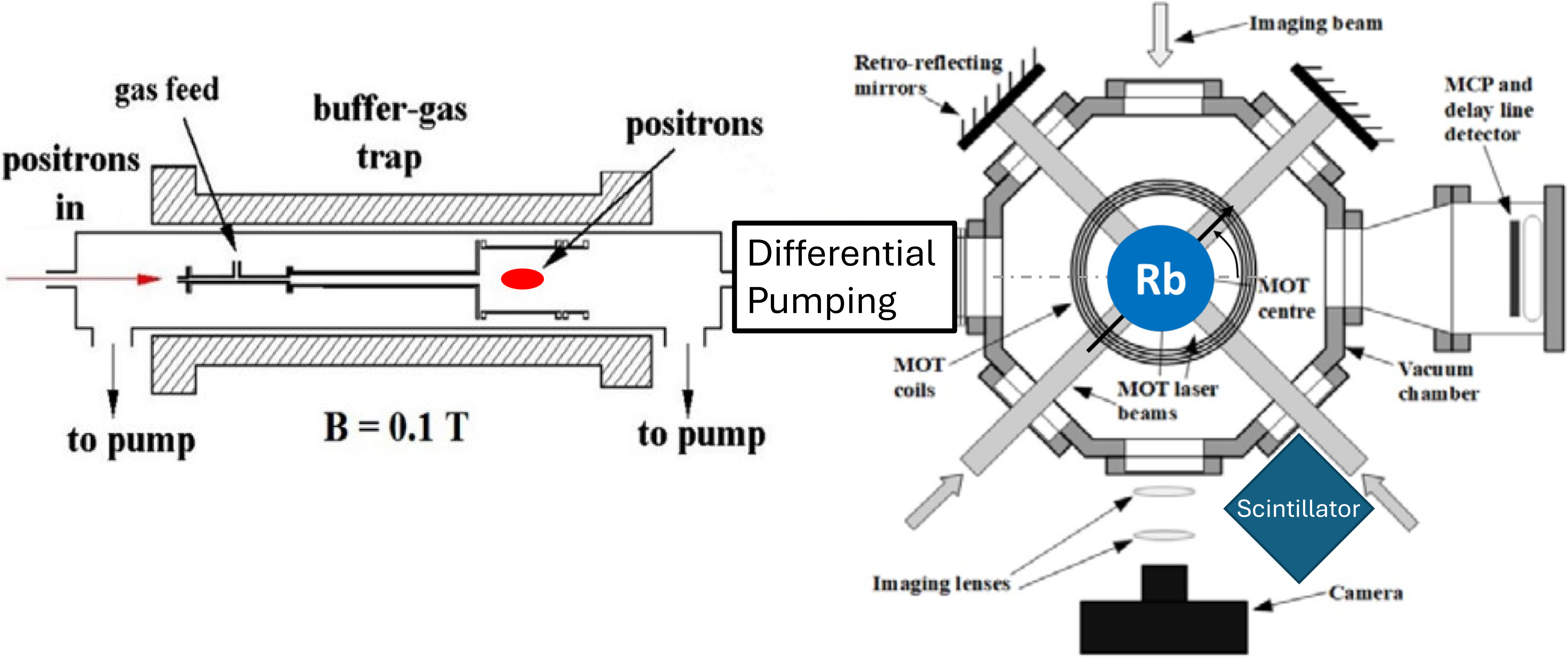
strongest interaction at threshold is between the Ps and the residual target

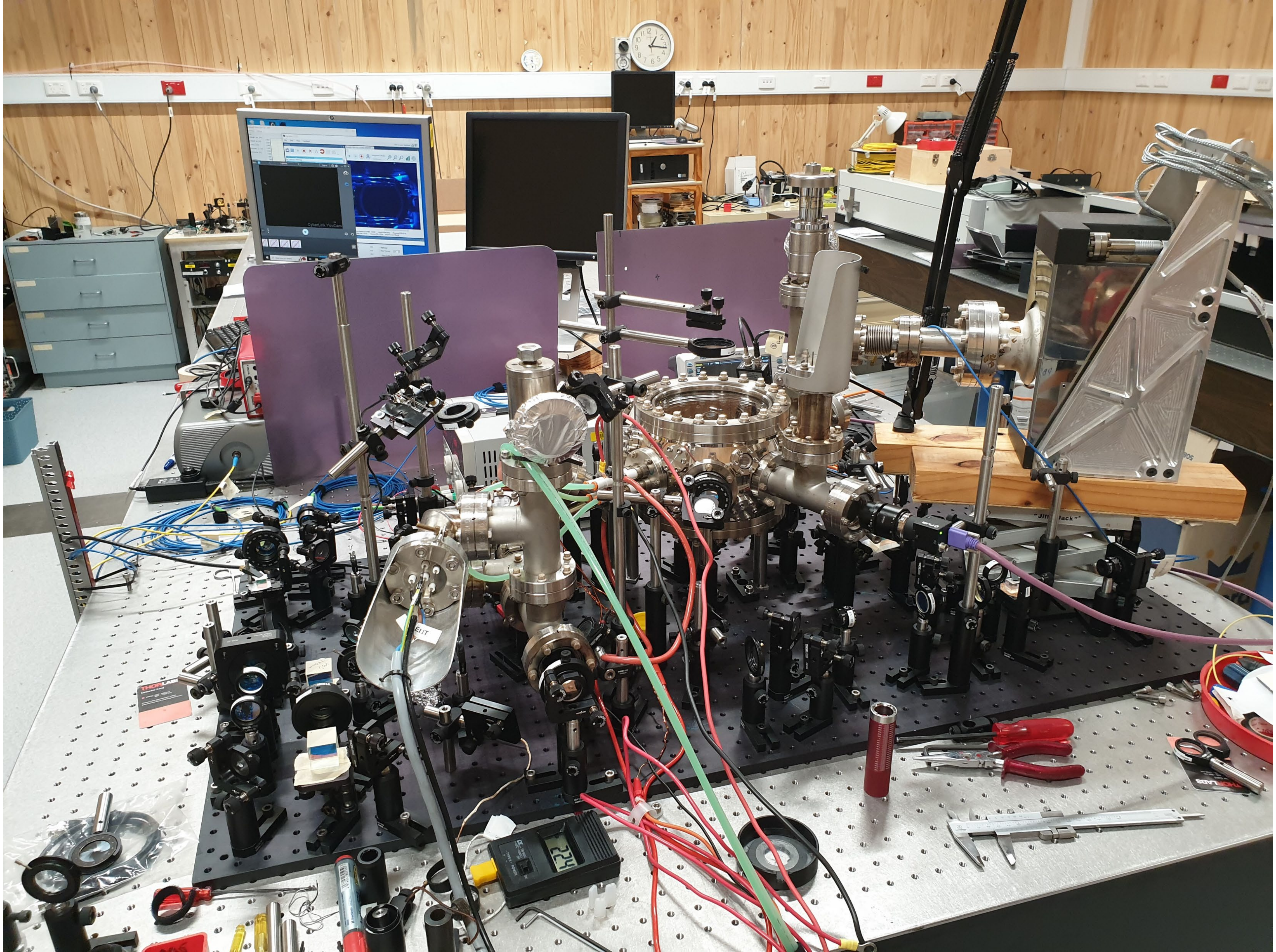
## Exothermic (Rb)



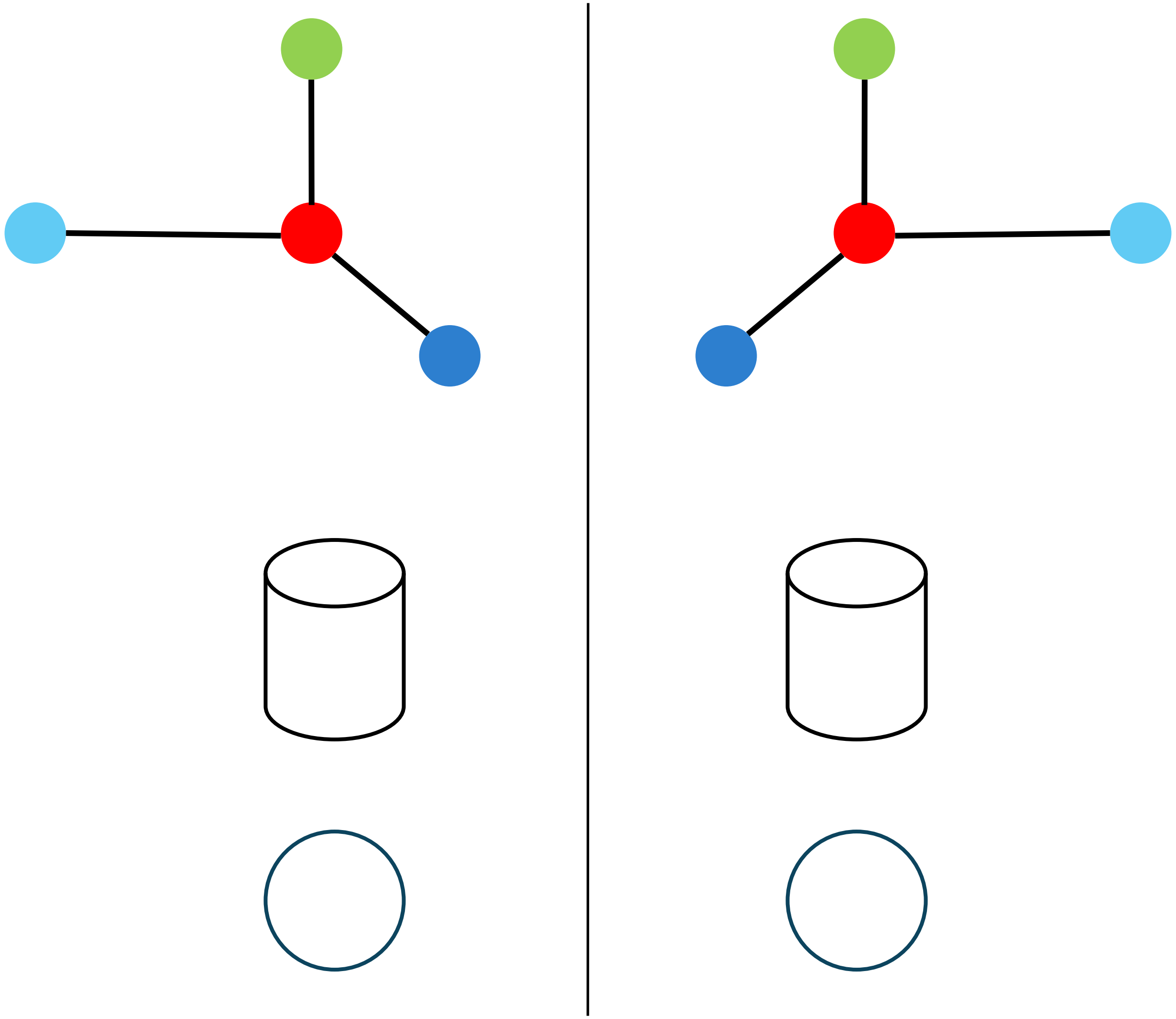
strongest interaction at low energy is between the $e^+$ and the target (there is no threshold)

# Experimental Apparatus

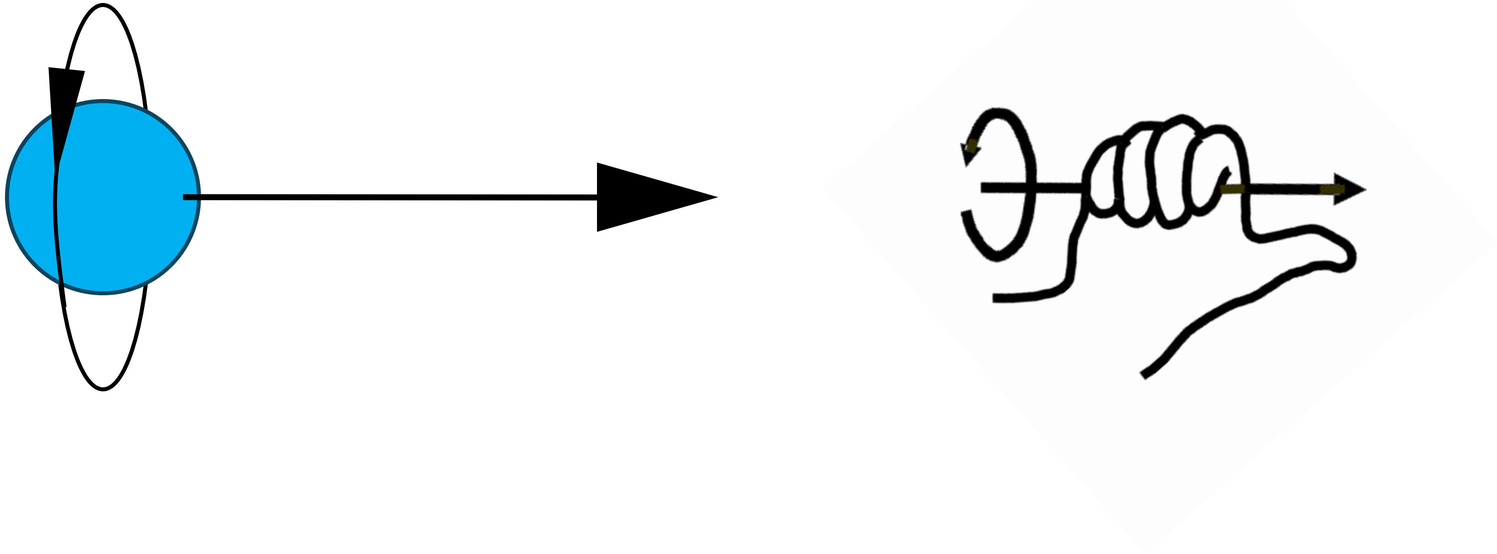



EIT
THORLABS

# Chiral Collision Dynamics – and we're not talking vector boson here…



Plane of Mirror Symmetry



¡ positrons are chiral!

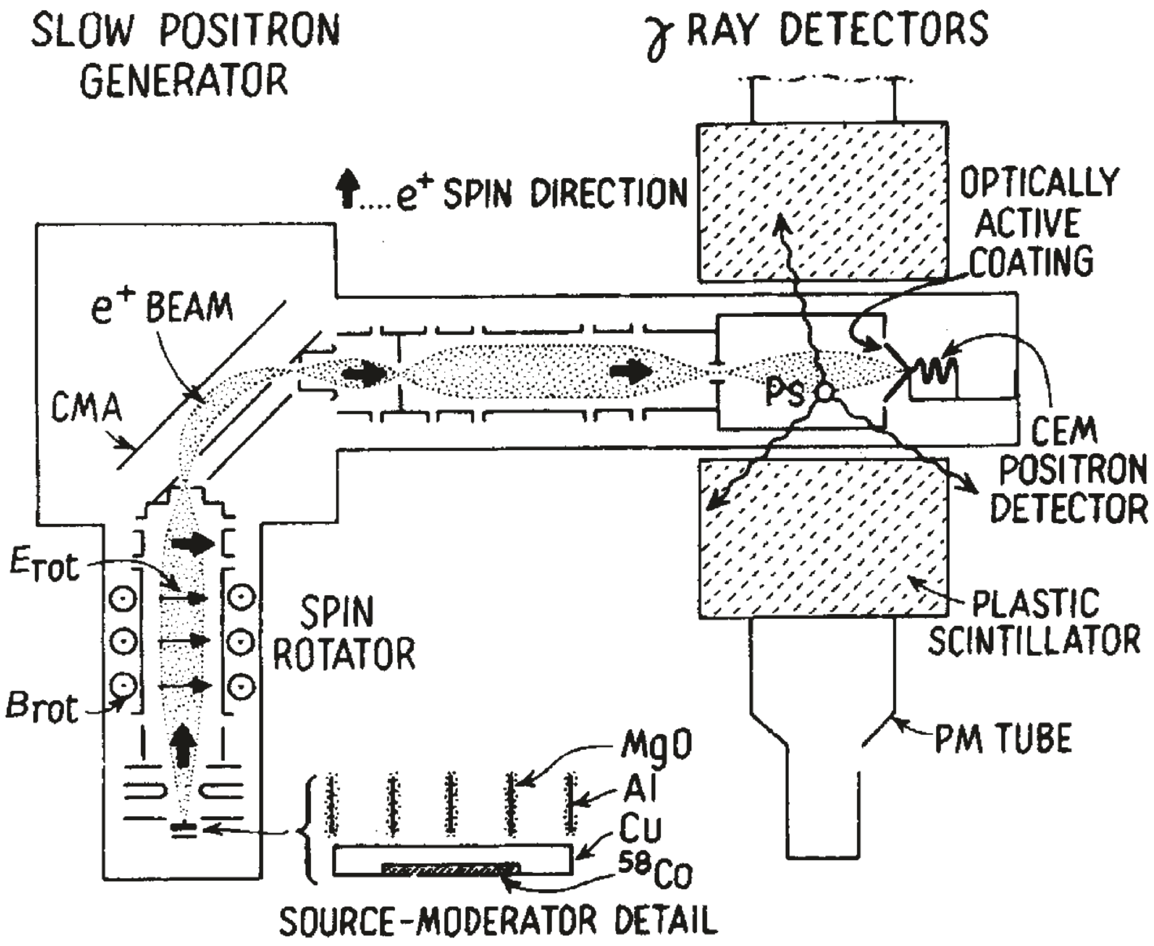
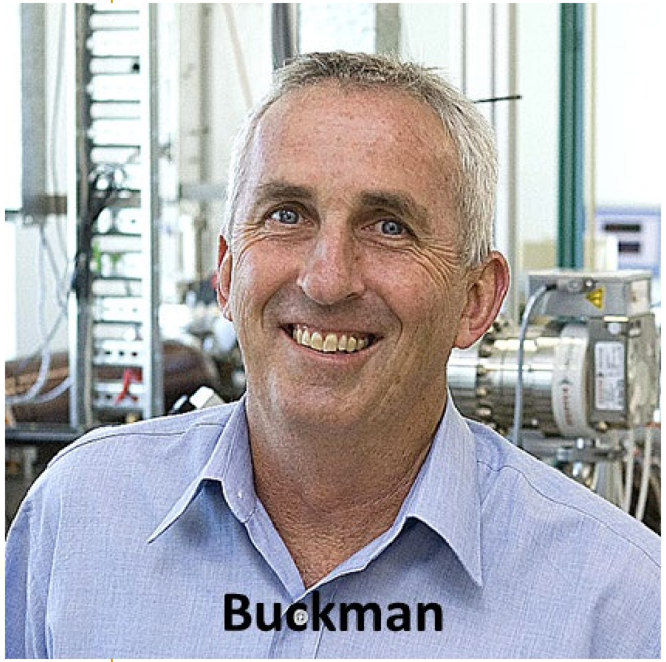


**Fig. 1** The experimental apparatus used to measure asymmetries in triplet positronium formation. The beam consists of $3 \times 10^3$ positrons $s^{-1}$ and initial helicity $h_0(e^+) = 0.21 \pm 0.02$ (ref. 13). The Wien filter spin rotator (crossed electric and magnetic fields) allows rotation of the average spin direction ($\langle \hat{\mathbf{s}}_i \rangle$) of the beam with minimal effect on the average direction of the beam's momentum ($\langle \hat{\mathbf{p}}_i \rangle$). Thus $h_0(e^+)$ may be continuously varied from +0.21 to −0.21.

| Molecule | Annihilation Asymmetry (pp 10,000) |
|---|---|
| **Cysteine** | <7 |
| **Tryptophan** | <7 |
| **Leucine** | 31(7) |

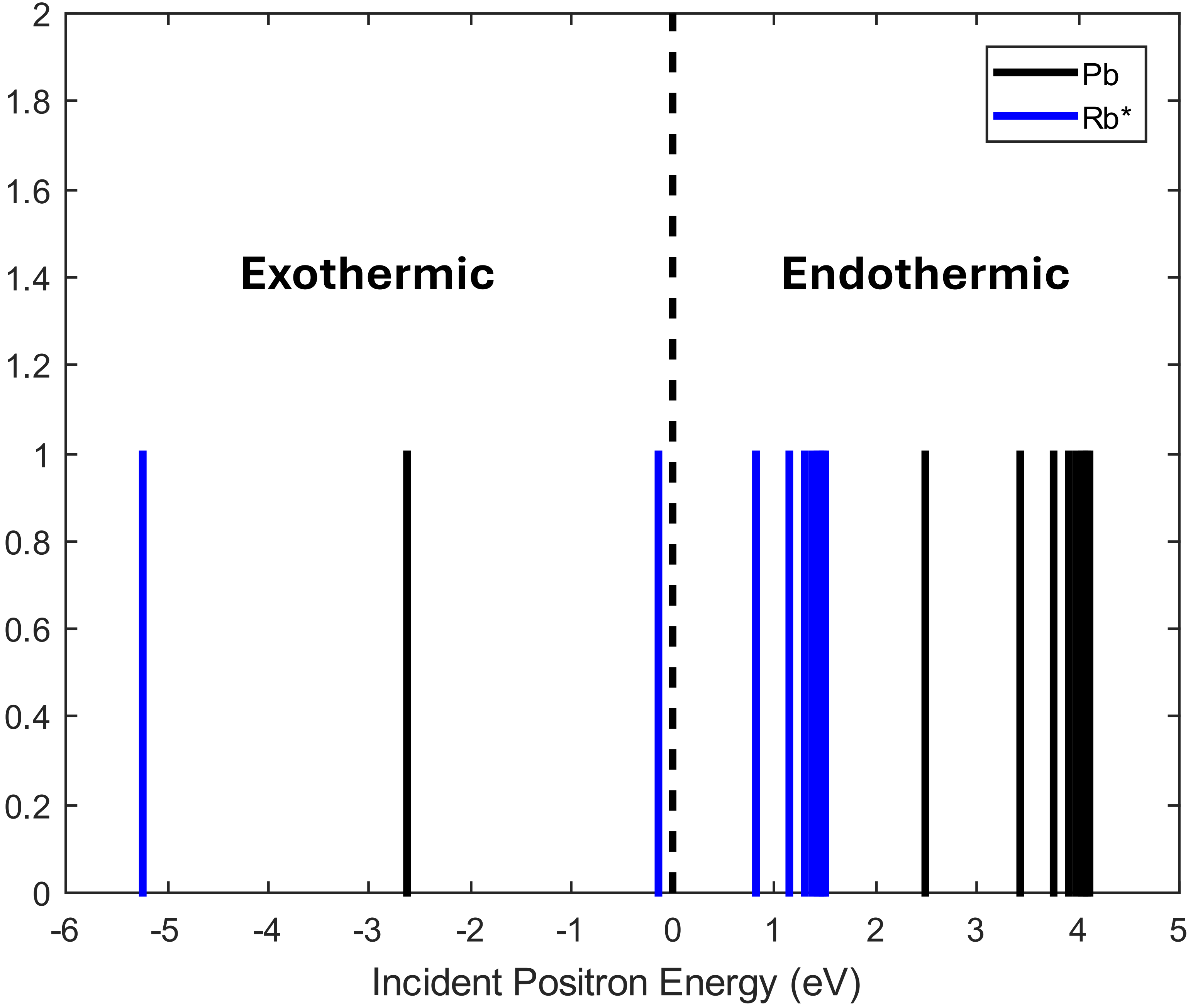
D.W.Gidley , A.Rich, J. Van House, and P.W. Zitzewitz, Nature **297**, 639 (1982)

# Co-Perpetrators



Australian
National
University

(no photos available for Liam Wymer, Sharan Kumar)


Exothermic
Endothermic
Pb
Rb*
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Incident Positron Energy (eV)