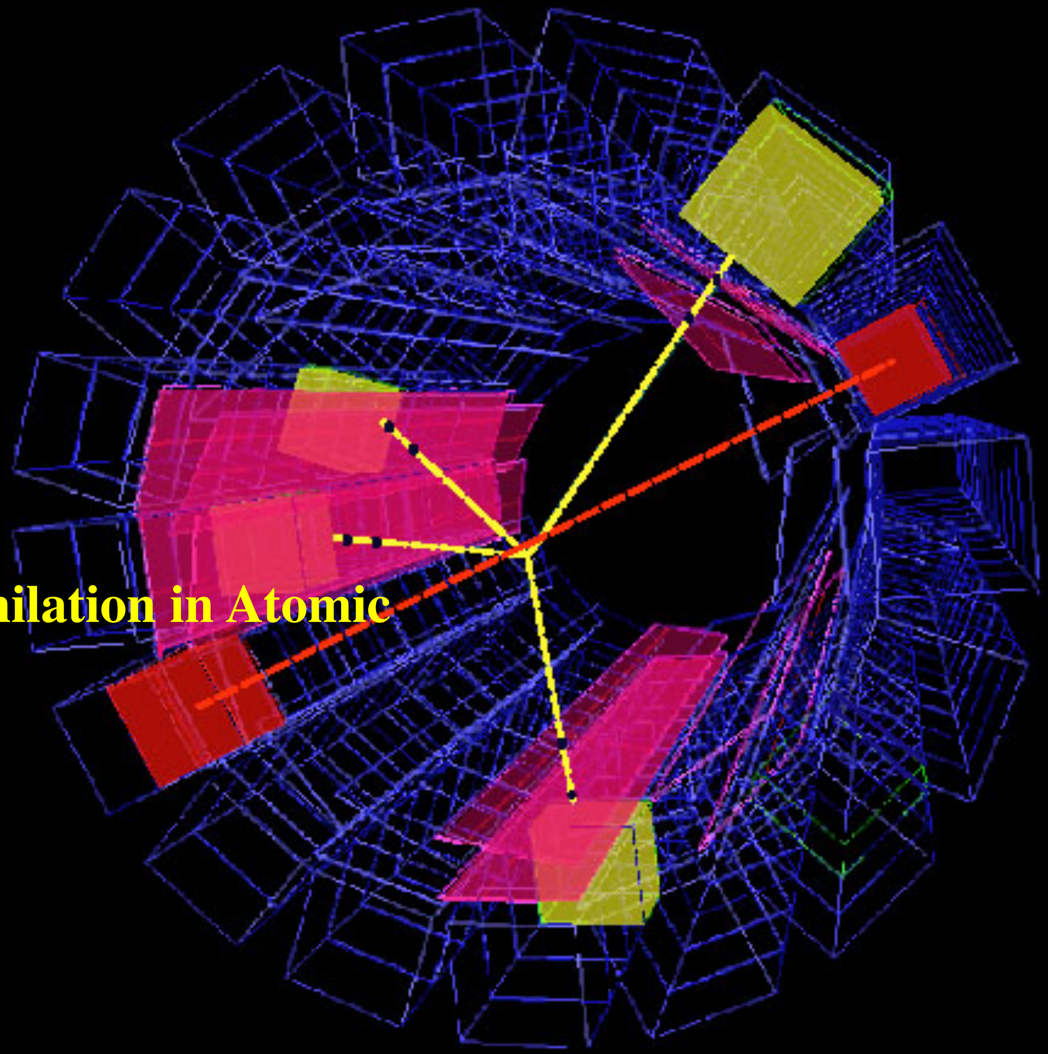

nihilation in Atomic

Mike Charlton, Physics,
Swansea University
UK

Positrons in Astrophysics – March 2012

Summary of Talk

Basic processes of positron and positronium physics

Measurements, results and insights; from the bulk to beams and traps

91% H (or H_2); 9% He: 0.1% "metals"

Partial Chronology - Experiment

Swansea University
Prifysgol Abertawe

1949:- Discovery of Ps
1949-50:- Discovery of “ACAR”
1955:- Discovery of antiproton
1950’s:- First attempts to make positron beams
1963:- Anomalous annihilation rates on some molecules
1968:- Ps formation in powders
1971-2:- First lab-based beam
1978-88:- Understanding of beam production
1981:- Discovery of Ps^-
1986:- Solid neon moderator
1988:- First positron plasma in lab. (accumulation device)
1995-6:- Discovery of antihydrogen (relativistic)
2000’s:- Development of robust plasma manipulation techniques for positrons
2002:- First cold antihydrogen
2007:- Discovery of Ps_2
2010:- Trapped antihydrogen
2011-12: First measurement of antihydrogen transition

Basic Processes - Positrons

Direct Annihilation:

$e^+ + A \longrightarrow 2\gamma + A^+$

Cross section at low energies = $\pi r_0^2 c Z_{eff}/v$

$Z_{eff} \approx 9$ for H and 4 for He. Can be considerably larger for other species (e.g. classes of organic molecules)

Positronium Formation:

$e^+ + A \longrightarrow Ps + A^+$

Threshold at positron kinetic energy $E_{ps} = (E_i - 6.8/n^2)$ eV for formation into a Ps state with principal quantum number, n

Cross section typically rises rapidly from threshold, peaks within around 10-15 eV and falls off at higher energies. It is a small fraction of the total inelastic scattering cross section above 100 eV.

Basic Processes - Positrons

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Positronium Formation:

$e^+ + A \longrightarrow Ps + A^+$

Some examples of E_{ps}

H (~ 6.8 eV); H_2 (~8.6 eV); He (17.8 eV)

However, there are many species for which $E_{ps} < 0$
(Li, Na, K, Rb, Cs, Ca, Sc, Ti, V, Cr, Ga, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Hf, Fr, Ra, Ac …
… and several more where E_{ps} is within 0.5 eV of zero
(Mn, Mo, Tc, Ru, Rh, Ag, Sn, Pb, Bi)

Basic Processes - Positrons

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Positronium Formation:

$e^+ + A \longrightarrow Ps + A^+$

For those many species for which $E_{ps} \approx 0$, little is known about the size of the cross section, except that it will be very large and diverge as E tends to 0.

Excited states of Ps may also be preferred in these cases.

Basic Processes - Positrons

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Excitation:

$$e^{+}(E) + A \longrightarrow e^{+}(E - E_{ex}) + A^{*}$$

For a threshold at E_{ex}

Cross section typically rises smoothly from threshold; usually only a few excited states make important contributions to the overall inelastic scattering cross section.

Ionization:

$e^+(E) + A \longrightarrow e^+(E - \Delta E) + A^+$

Threshold at E_i

Cross section, $\sigma_i(E)$, typically rises smoothly from threshold to become the dominant process when Ps formation ceases to occur.

ΔE around 20-40 eV. Need to know single differential cross section, $d\sigma_i(E)/d(E - \Delta E)$ to model energy loss due to this process.

Higher order ionization process (for atoms other than H) can be ignored.

Basic Processes - Positronium

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Annihilation:

$Ps(1^3S) \longrightarrow 3\gamma$: Vacuum lifetime around 142 ns

$Ps\ (1^1S) \longrightarrow 2\gamma$: Vacuum lifetime about 125 ps

Excited S states have lifetimes longer by a factor of n^3.
Higher angular momentum states are essentially stable against annihilation, but radiatively decay with lifetimes expected to be around twice those of corresponding state in H.

Basic Processes - Positronium

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Scattering:

$$
\mathrm{Ps} + \mathrm{A} \longrightarrow
\begin{cases}
\mathrm{Ps} + \mathrm{A} \\
2\gamma + e^- + \mathrm{A}^+ \\
\mathrm{Ps}^* + \mathrm{A} \\
\mathrm{Ps} + \mathrm{A}^* \\
e^+ + e^- + \mathrm{A} \\
\mathrm{Ps} + e^- + \mathrm{A}^+
\end{cases}
$$

The cross sections for some of these processes are known for a few targets (typically the noble gases). However, with typical collision frequencies in astrophysical environments much lower than the inverse lifetime, these processes don’t seem to important.

Measurements and Results - Bulk

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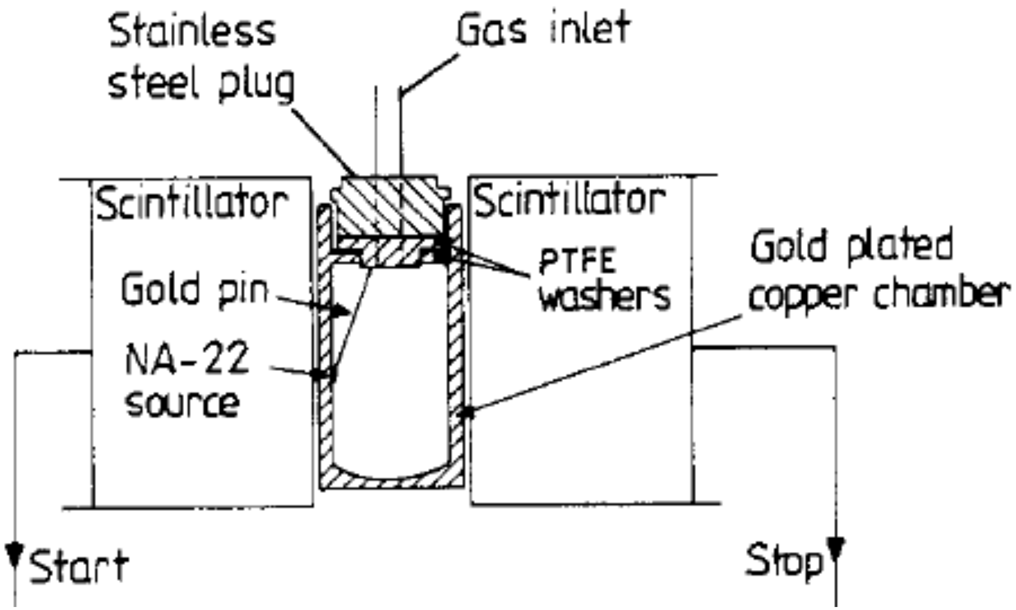


Time-honoured traditional positron lifetime method.

Measured parameters are Z_{eff}, ${}_1Z_{eff}$ (pick-off parameter for Ps) and the positronium fraction, F.

Noble gases and a variety of small molecules

Endeavour 20, 1961

Positronium

F. F. HEYMANN

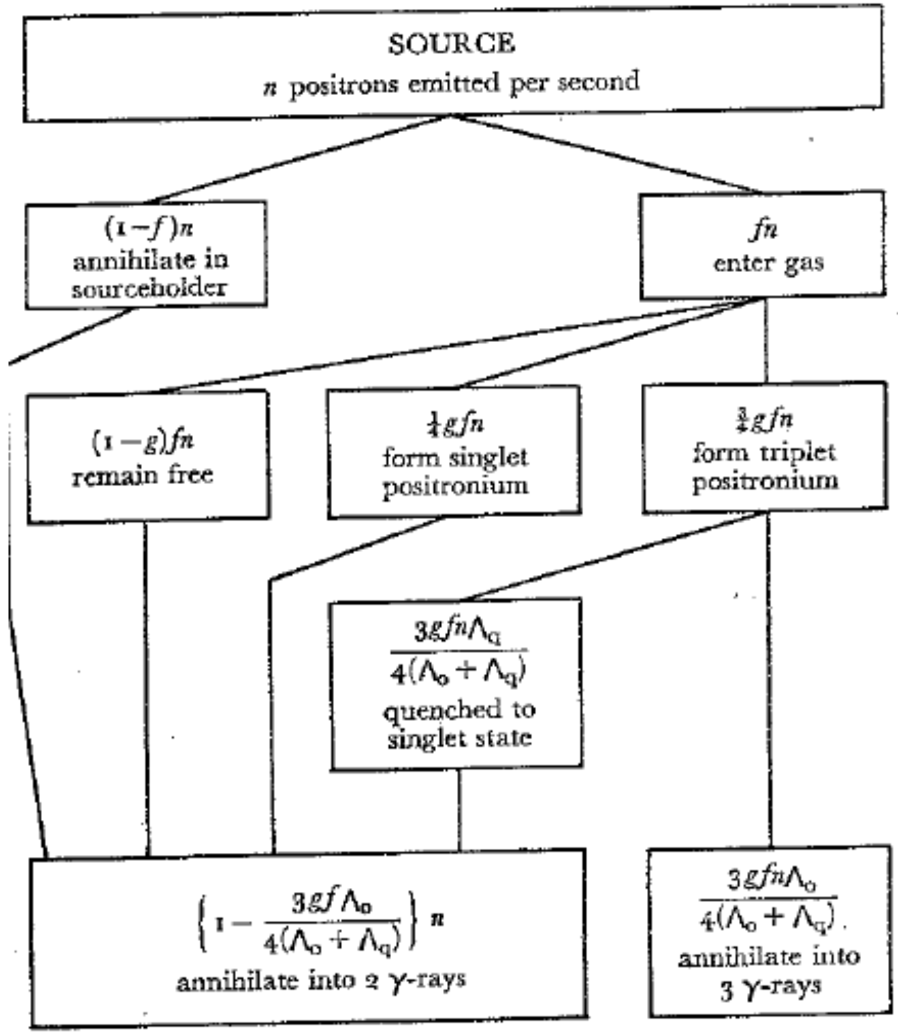
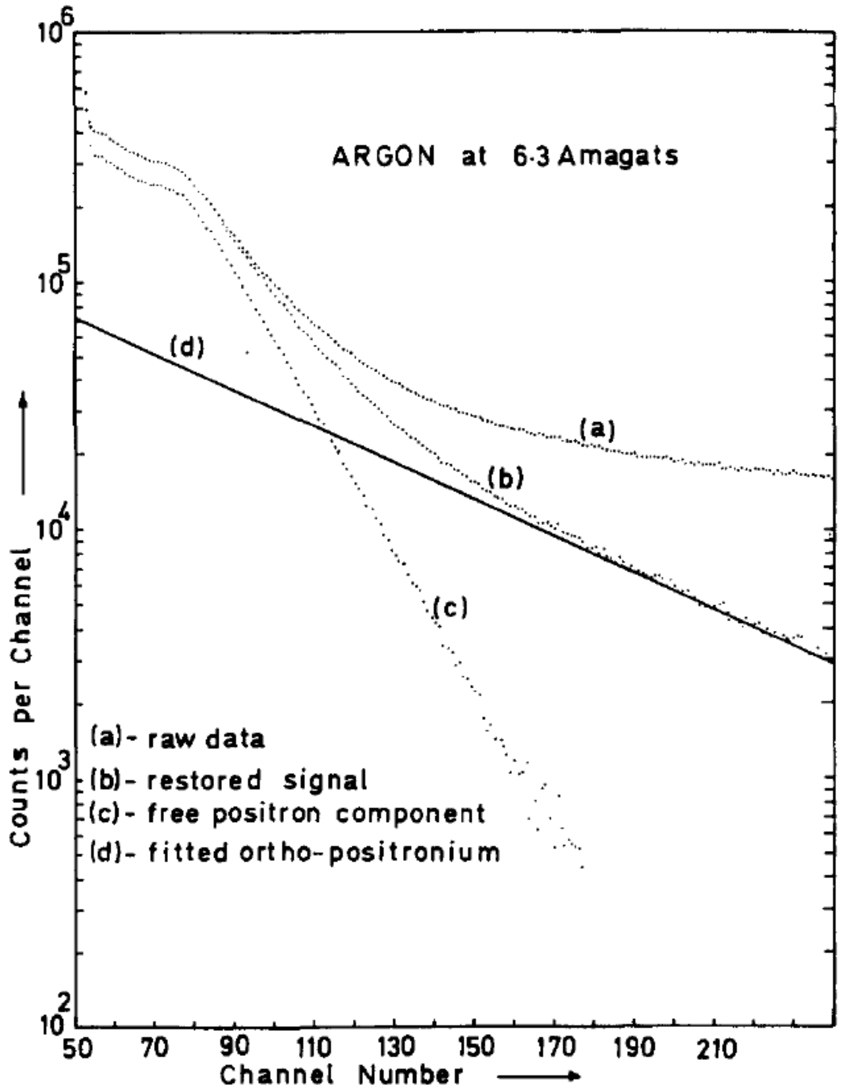


FIGURE 2 – *Possible fates of positrons in a gas* [6].

Measurements and Results - Bulk



1 amagat = 2.69×10^{25} m^{-3}

"Shoulder" at short times due to annihilation before thermalization. Effect mostly below about a couple of eV.

Thermalization time about 350 ns-amagat; approx. 1.3 x 10^{16} sm^{-3}

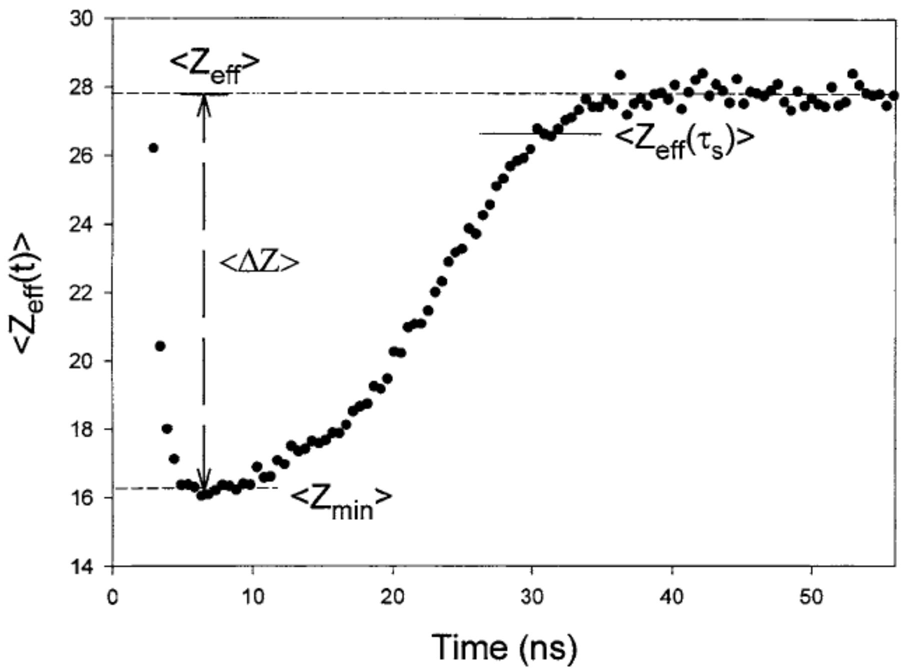
All gas atoms with an appreciable E_{ps} will have similar thermalization times.

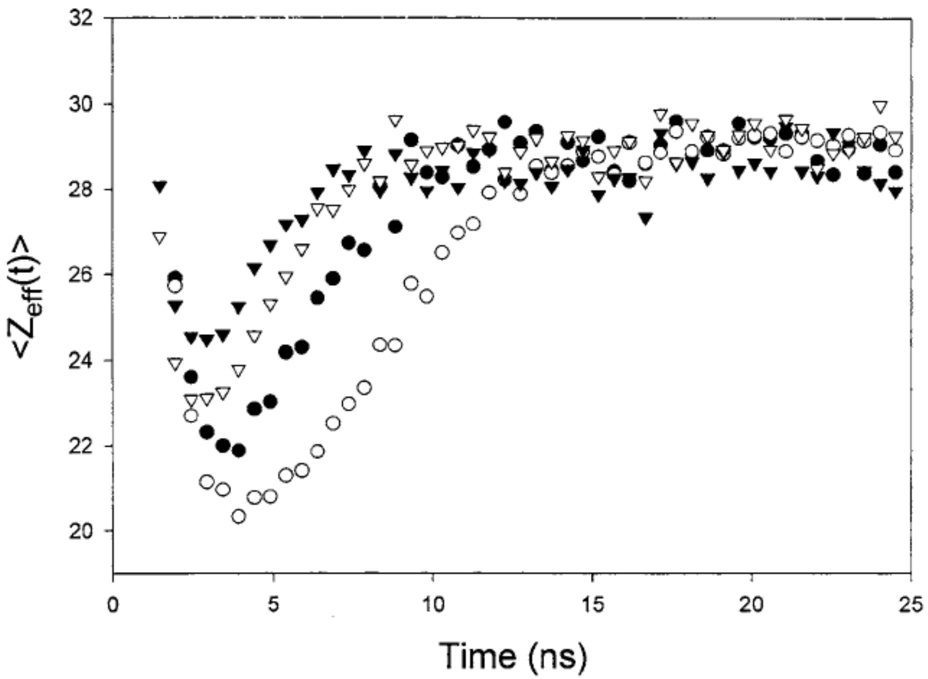
Thermalization times of positrons in molecular gases

Ilham Al-Qaradawi†, Michael Charlton‡, Ivan Borozan and Ralph Whitehead§

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

Various amounts of N_2O added to Ar. Max. amount about 1%.





J. Phys. B: At. Mol. Opt. Phys. 33 (2000) 2725–2732. Printed in the UK PII: S0953-4075(00)50404-0

Thermalization times of positrons in molecular gases

Ilham Al-Qaradawi†, Michael Charlton‡, Ivan Borozan and Ralph Whitehead§
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

Received 27 March 2000, in final form 31 May 2000

1ns-amagat ≈ 2.7 x 10^{10} scm^{-3}
… or about 800 y at 1 cm^{-3}

Some examples: (in ns-amagat)

H_2	2.4
N_2	14
CO	1.1
CO_2	0.1
SF_6	0.04
He	1700
Ar	360

However – not strictly applicable to astrophysical context …

Measurements and Results - Bulk

Swansea University Prifysgol Abertawe

Positronium Fraction, F

Global parameter – fraction of positrons forming Ps after slowing down in the gas.

Not equivalent to astrophysical measurements as Ps collisions lead to break-up when Ps kinetic energy exceeds 6.8 eV. Apply so-called Ore model (uniform E).

$F_{min} = (E_{ex} - E_{ps})/E_i$ $\qquad$ $F_{max} = 6.8/E_i$

Measurements and Results - Bulk

Swansea University Prifysgol Abertawe

Positronium Fraction, F

Some examples

Species	F_{min}	F_{max}	F
H	0.25	0.50	?
He	0.14	0.28	0.23
Ne	0.09	0.32	0.26
Ar	0.17	0.43	0.33
Kr	0.20	0.49	0.11
Xe	0.26	0.56	0.03
H_2	0.18	0.44	0.32
N_2	0	0.44	0.19
CH_4	0.18	0.52	0.40

Positronium Fraction, F

How about gas mixtures?

Imagine adding another atomic species with a very low E_{Ps} to a H sample …

The H Ore gas is from 6.8-10.2 eV. Any positron which falls to a very low energy will have a good chance of forming Ps with the added gas, as the only competition is energy loss via momentum transfer in e^+-H collisions.

Such a method was used to deduce Ps formation cross sections (with lots of assumptions) before beam measurements became available.

Measurements and Results - Beam and Trap

Swansea University Prifysgol Abertawe

Reasonably mono-energetic beams of positrons available since ~ 1970. ($\delta E \sim 1$ eV) Cross sections for a number of processes and targets exist.

What can trap-based devices deliver?

Trapped clouds and plasmas for experimentation
(annihilation, antihydrogen)

Ability to manipulate in position and time to produce controlled plasmas and/or large instantaneous fluxes of positrons (and hence positronium) – on target, or as a target
(molecular Ps, Ps spectroscopy, positron lifetimes in solids)

Slow-release narrow energy-width beams for scattering and annihilation studies with unprecedented energy resolution

H and He are best known from theory. H more-or-less exact at all important energies for the major processes.

σ_T :: total scattering cross section σ_{Ps} :: Ps formation

σ_{ex} :: excitation σ_i :: ionization

Also "total ionization" :: $(\sigma_{Ps} + \sigma_i)$

Measurements and Results - Beam and Trap

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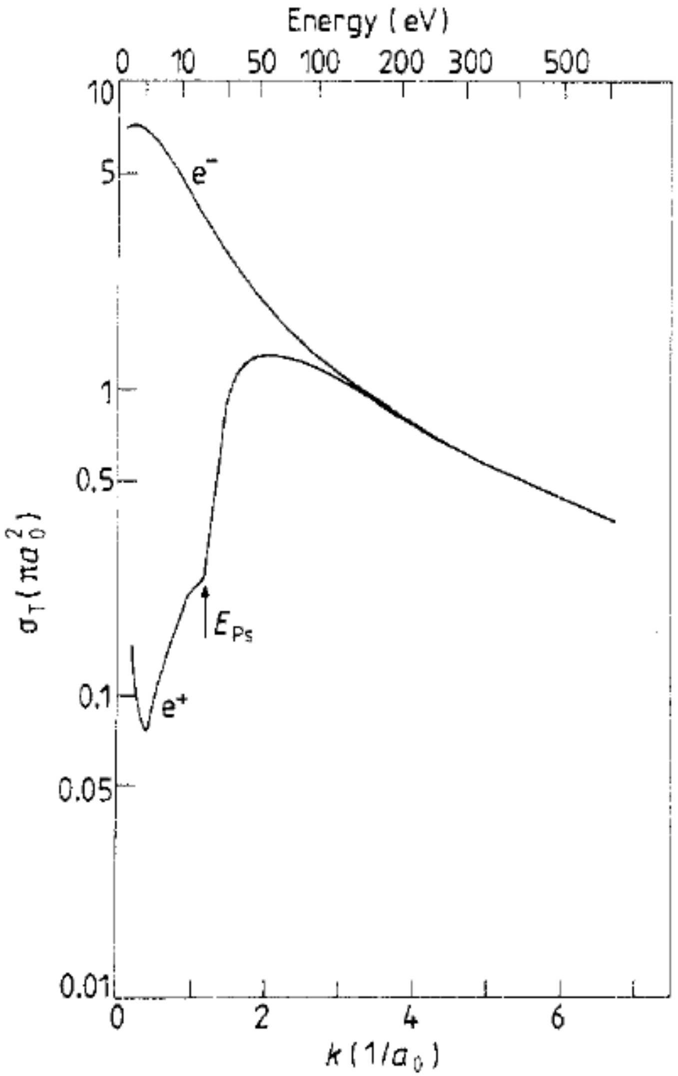
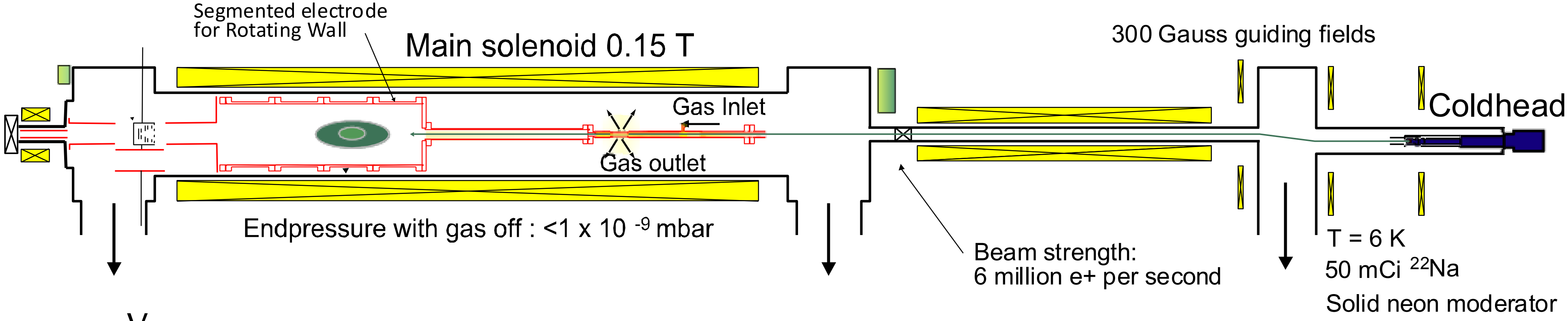


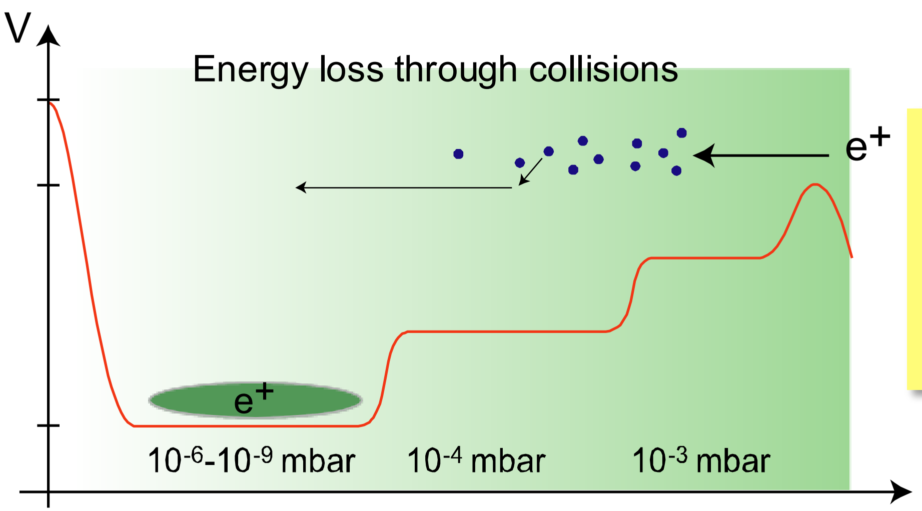
Comparing electron and positron total scattering cross sections for He

The underlying interactions:

	Positron	Electron
Static	Repulsive	Attractive
Polarization	Attractive	Attractive
Exchange	No	Yes

Measurements and Results - Beam and Trap





Based upon the industry standard …

{Solid-Ne moderator -plus - UCSD Penning Malmberg buffer gas trap: Surko and co-workers}

$$e^{+}(E_i) + N_2 \rightarrow e^{+}(E_f) + N_2^{*}$$

Measurements and Results - Beam and Trap

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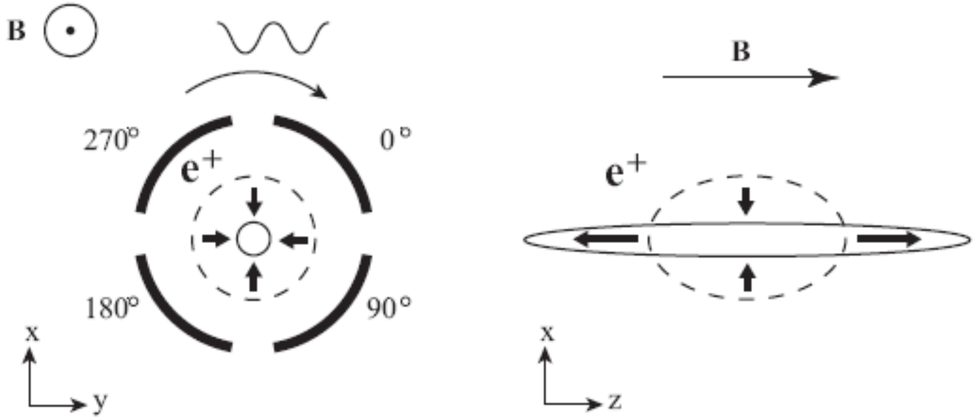
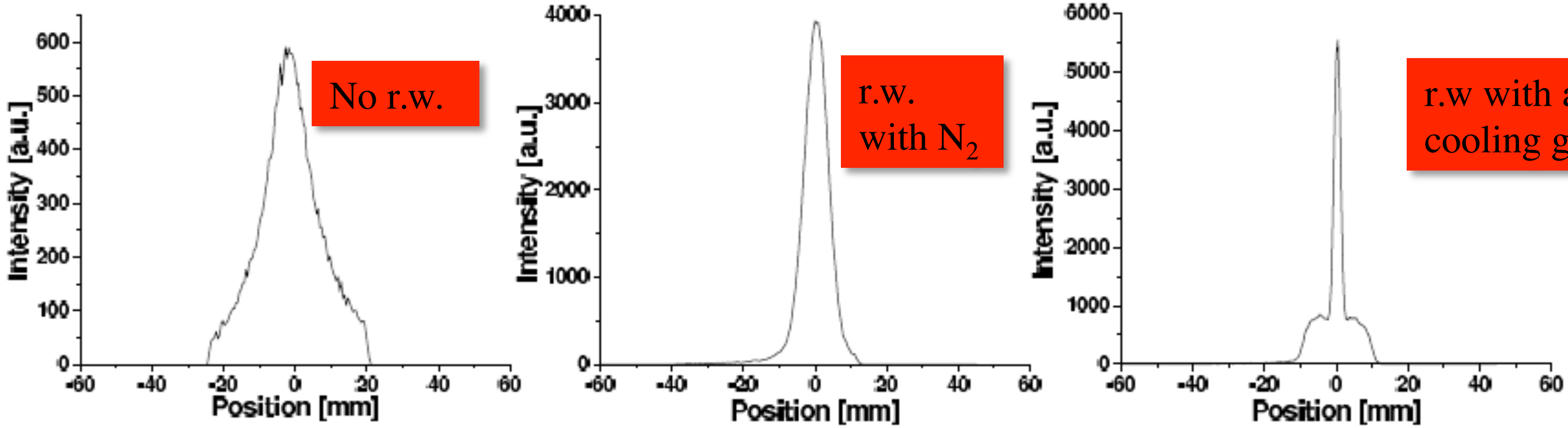
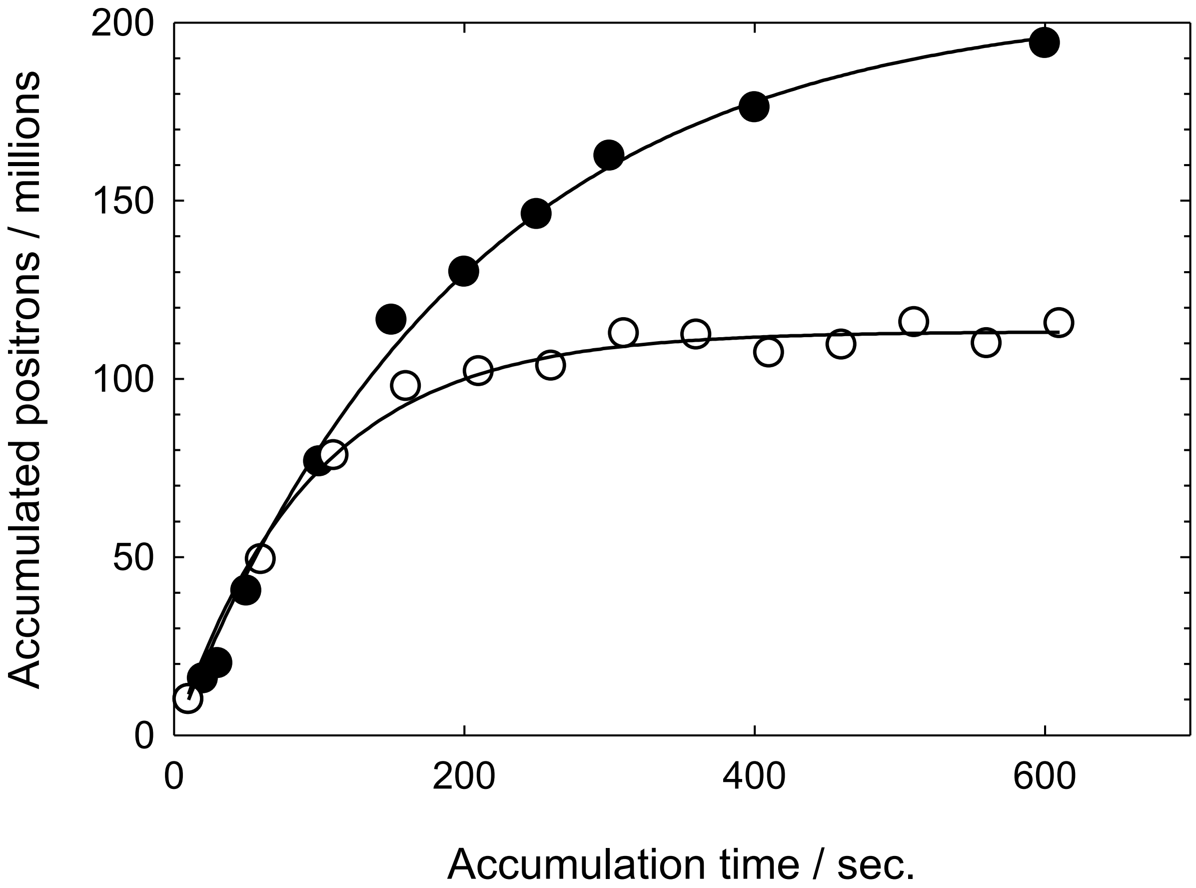


Rotating electric field in same sense as **ExB** drift

Positron plasma radial distributions



Measurements and Results - Beam and Trap



Open circles:
no rotating electric field

Closed circles:
rotating field applied

Plasma formed after about 10-15 s

Measurements and Results - Beam and Trap

Swansea University
Prifysgol Abertawe

PHYSICAL REVIEW A **80**, 032710 (2009)

High-resolution positron scattering from helium: Grand total and positronium-formation cross sections

P. Caradonna, A. Jones, C. Makochekanwa, D. S. Slaughter, J. P. Sullivan, and S. J. Buckman*
ARC Centre for Antimatter-Matter Studies, Research School of Physics and Engineering, Australian National University, Canberra, Australian Capital Territory 0200, Australia

I. Bray and D. V. Fursa
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(Received 26 June 2009; published 22 September 2009)

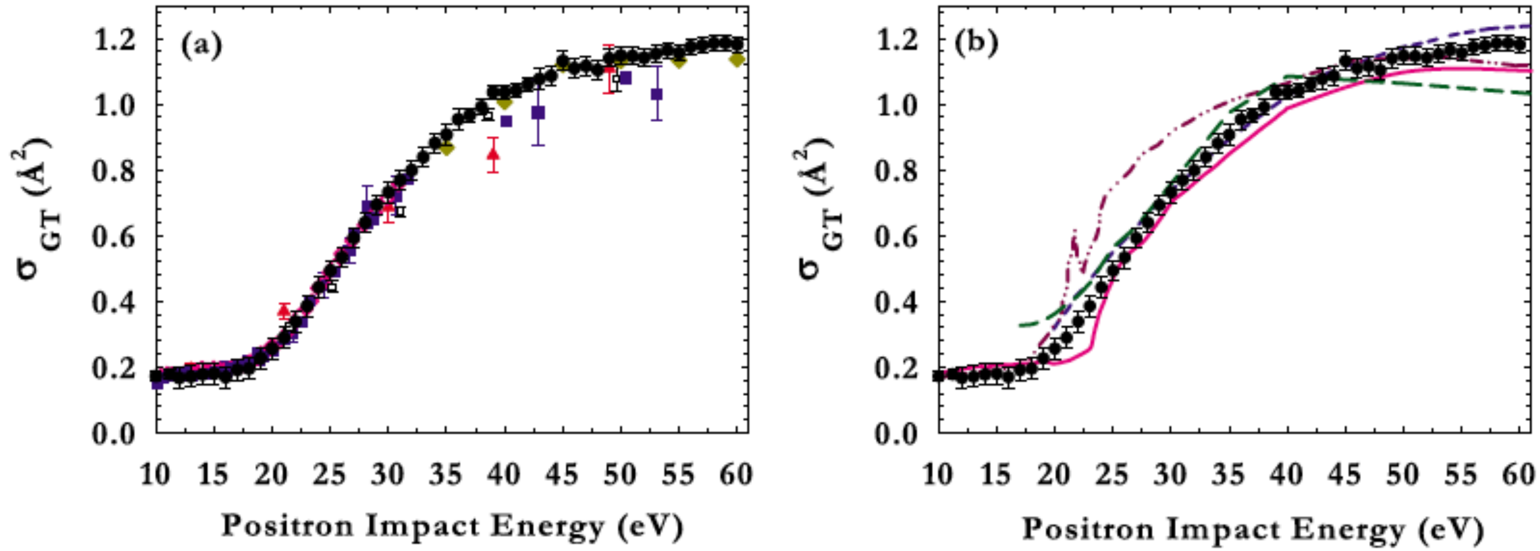

FIG. 3. (Color online) (a): Present grand total cross section (●) and the experimental results of Brenton *et al.* [6] (▲), Kauppila *et al.* [9] (♦), Canter *et al.* [7] (■), Stein *et al.* [10] (◇), and Coleman *et al.* [8] (□). (b): Present grand total cross section (●) compared with theoretical calculations of Baluja *et al.* [18] (– – –), Cheng *et al.* [19](—— —) Campbell *et al.* [20] (-·-·-·) and present CCC from l_{max}=8 calculation (–) (see text).

Measurements and Results - Beam and Trap

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CARADONNA *et al.* PHYSICAL REVIEW A 80, 032710 (2009)

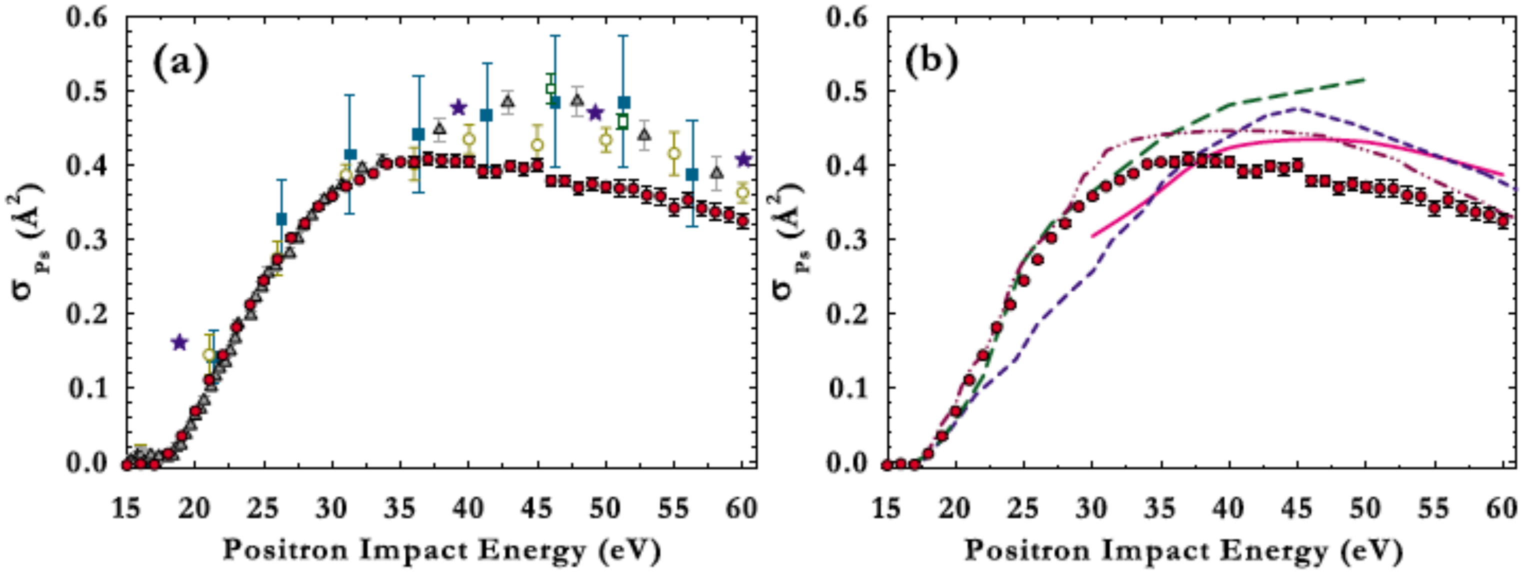

FIG. 4. (Color online) (a): Comparison between present positronium-formation cross section results (●), and those of Murtagh *et al.* [23] (▲), Overton *et al.* [21] (★), Fromme *et al.* [24] (○), Diana *et al.* [25] (□), and Fornari *et al.* [22] (■). (b): Present positronium-formation cross section results (●) compared with theoretical calculations of Cheng *et al.* [19](— —), Campbell *et al.* [20] (-·-··), McAlinden *et al.* [27] (– – –), and present CCC theory (–).

Measurements and Results - Beam and Trap

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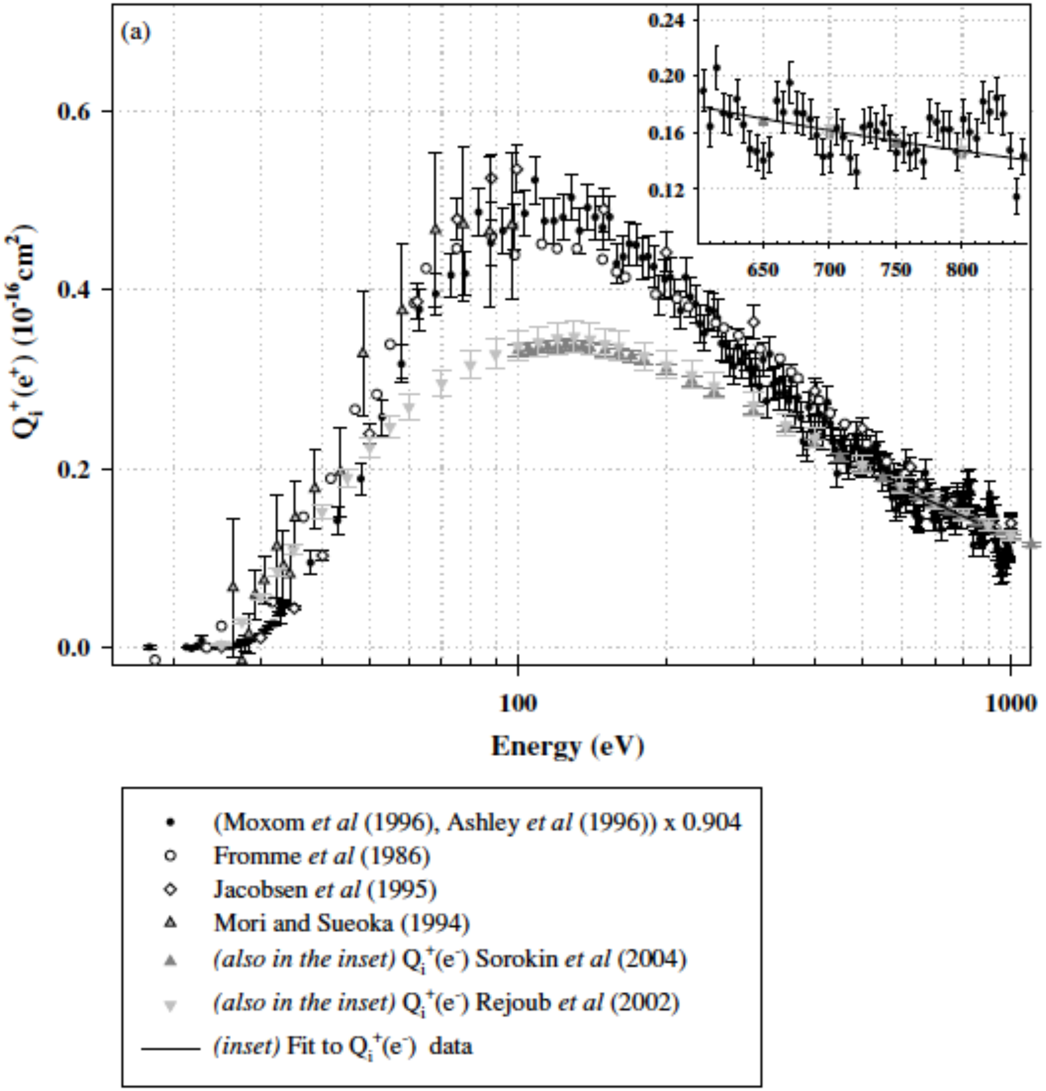
INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS
J. Phys. B: At. Mol. Opt. Phys. **38** (2005) 3857–3866 doi:10.1088/0953-4075/38/21/008

Positron-impact ionization and positronium formation from helium

D J Murtagh, M Szłuińska, J Moxom[1], P Van Reeth and G Laricchia

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK



Measurements and Results - Beam and Trap

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS B: ATOMIC, MOLECULAR AND OPTICAL PHYSICS

J. Phys. B: At. Mol. Opt. Phys. **35** (2002) 2525–2540 PII: S0953-4075(02)32270-3

Total positron-impact ionization and positronium formation from the noble gases

G Laricchia, P Van Reeth, M Szłuińska and J Moxom[1]

Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

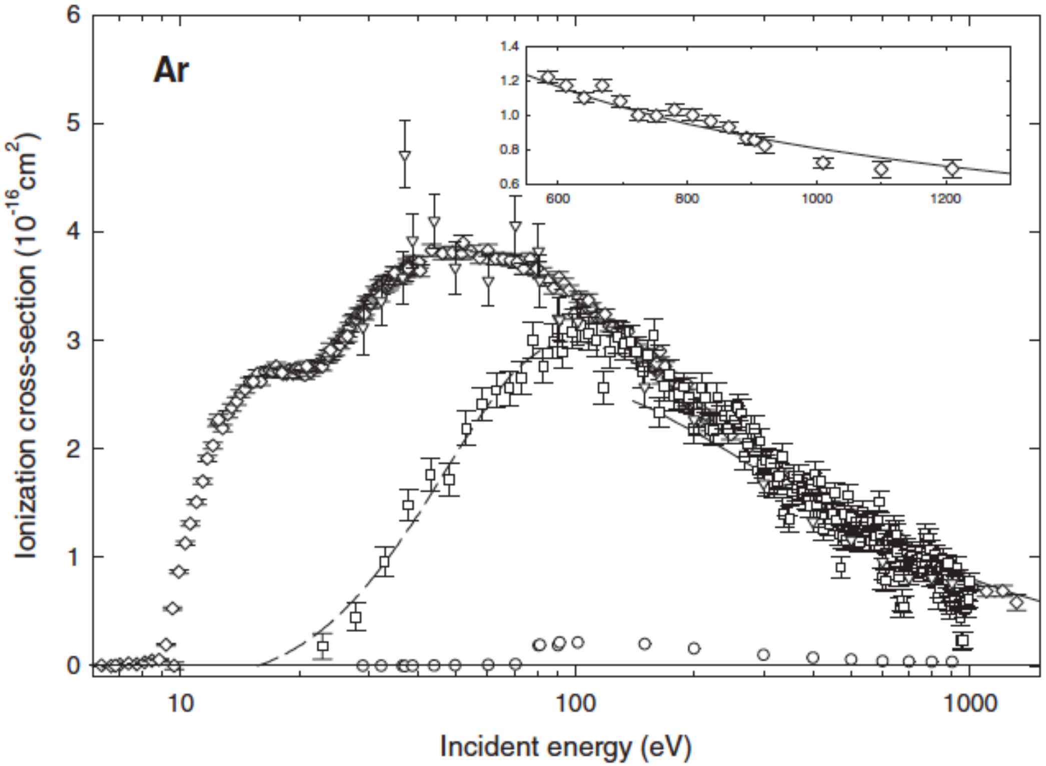


Figure 2. Total and direct ionization cross-sections for positron impact on Ar: ◇—present total ionization cross-section; □—direct ionization cross-section of Moxom *et al* (1996); ▽—total single-ionization cross-section of Bluhme *et al* (1999b); ○—double-ionization cross-section of Bluhme *et al* (1999b); dashed curve—polynomial fit to direct ionization cross-section. The ionization cross-section for electron impact (Sorokin *et al* (2000); solid curve) used for normalization purposes is also shown.

Ps formation in e⁺-H collisions

190 *4 Positronium formation*

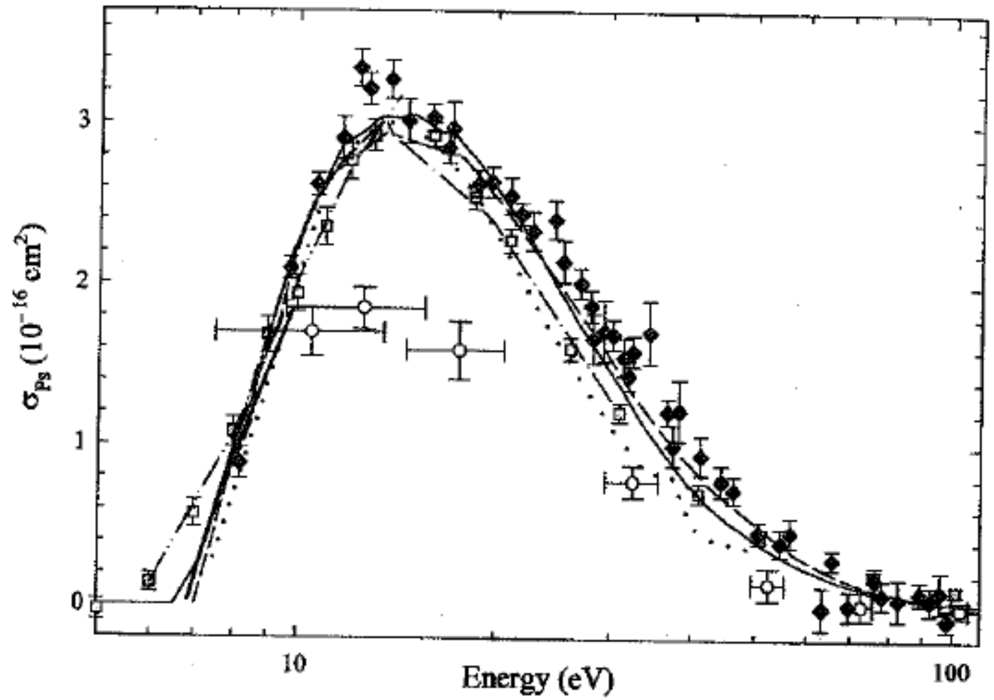


Fig. 4.20. Positronium formation in positron–hydrogen scattering. Experiment: □, Zhou *et al.* (1997); ○, Hofmann *et al.* (1997); •, Kara (1999). Theory: ——, Brown and Humberston (1985); -·——, Kernoghan *et al.* (1996); — —, Mitroy (1996); — · —, Igarishi and Toshima (1994); · · · · ·, Higgins and Burke (1993); — · · —, Janev and Solov'ev (1998).

Ionization in e^+-H collisions

L486 *Letter to the Editor*

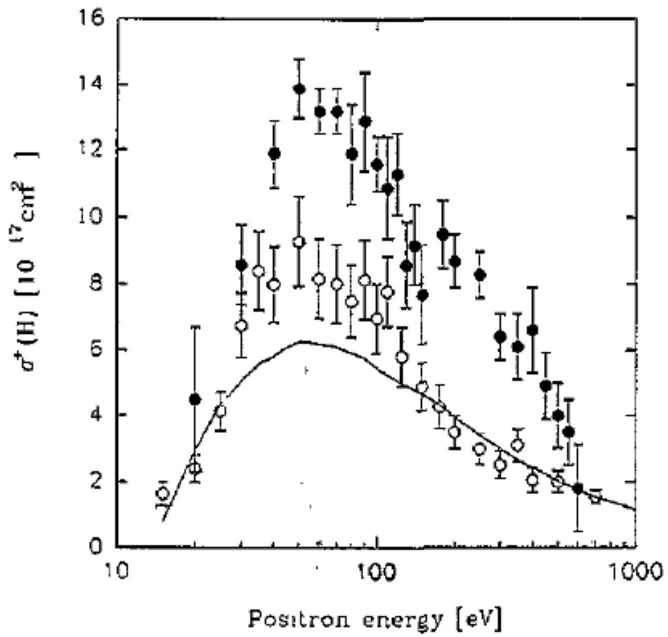


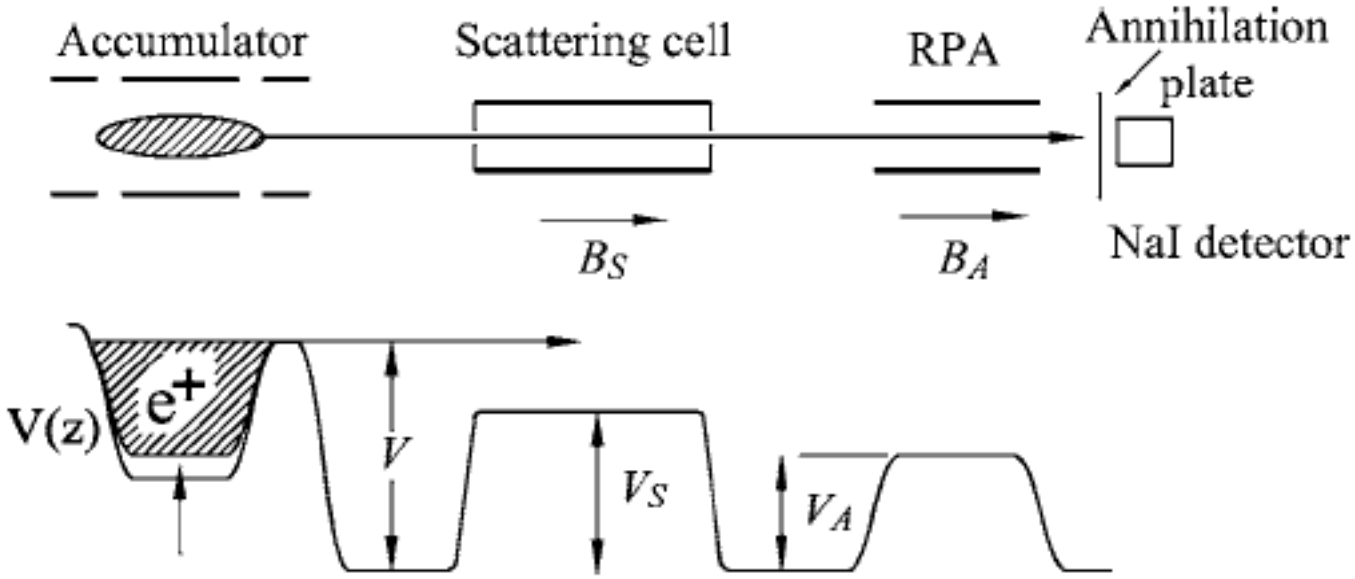
Figure 3. Positron impact ionization cross sections for aromic hydrogen: ○, present results; ●, Spicher *et al* (1990). The line shows the e⁻ data of Shah *et al* (1987) for comparison.

Measurements and Results - Beam and Trap

PHYSICAL REVIEW A **72**, 062713 (2005)

Positron-impact ionization, positronium formation, and electronic excitation cross sections for diatomic molecules

J. P. Marler and C. M. Surko
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093-0319, USA
(Received 1 September 2005; published 21 December 2005)



Measurements and Results - Beam and Trap

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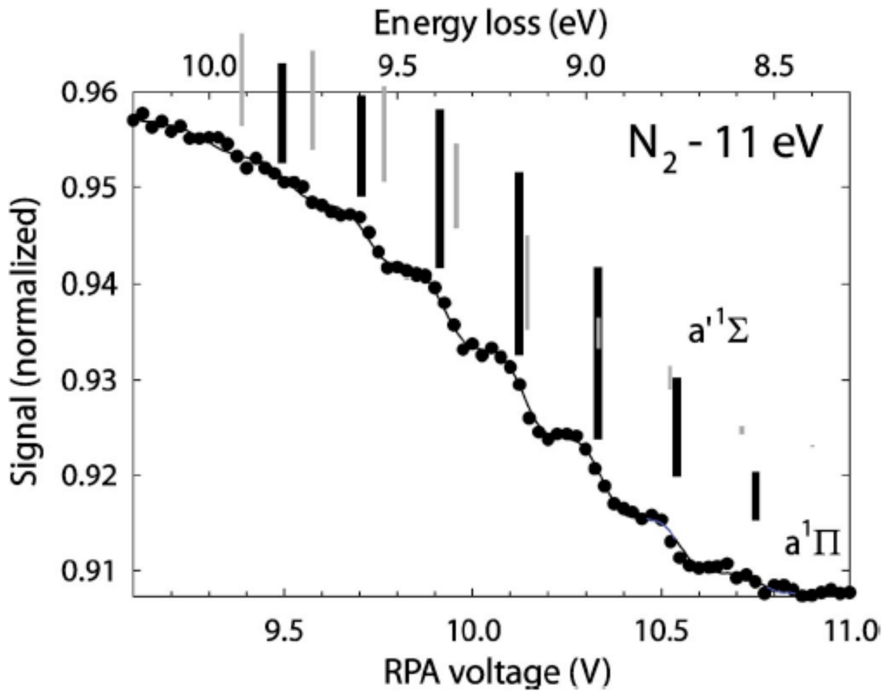

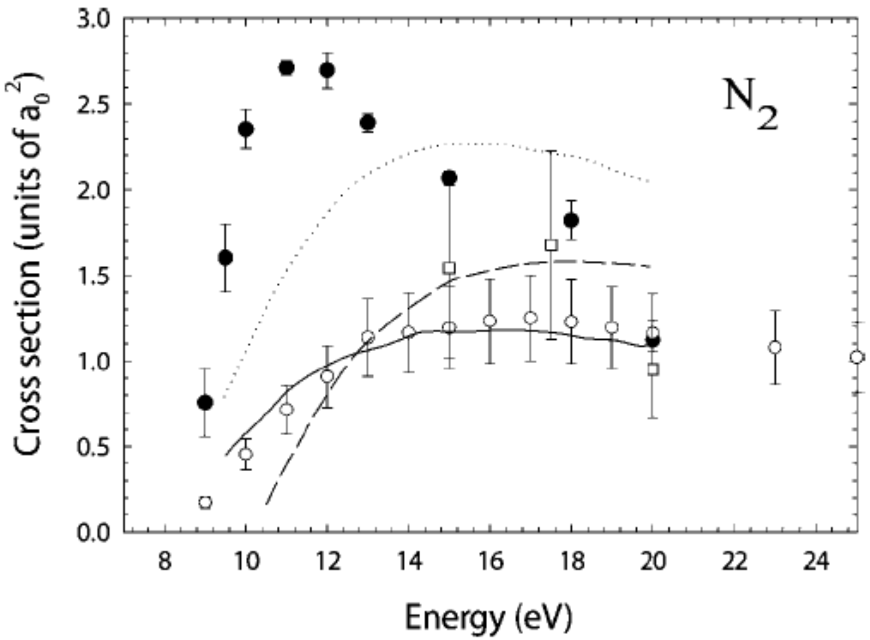

FIG. 11. Integral cross sections in N_2 for the excitation of the $a\,^1\Pi$ states by (●) positrons and (○, □) [24,25] electrons. Also

Measurements and Results - Beam and Trap

PRL 102, 133202 (2009) PHYSICAL REVIEW LETTERS week ending 3 APRIL 2009

Excited-State Positronium Formation from Helium, Argon, and Xenon

D. J. Murtagh, D. A. Cooke, and G. Laricchia
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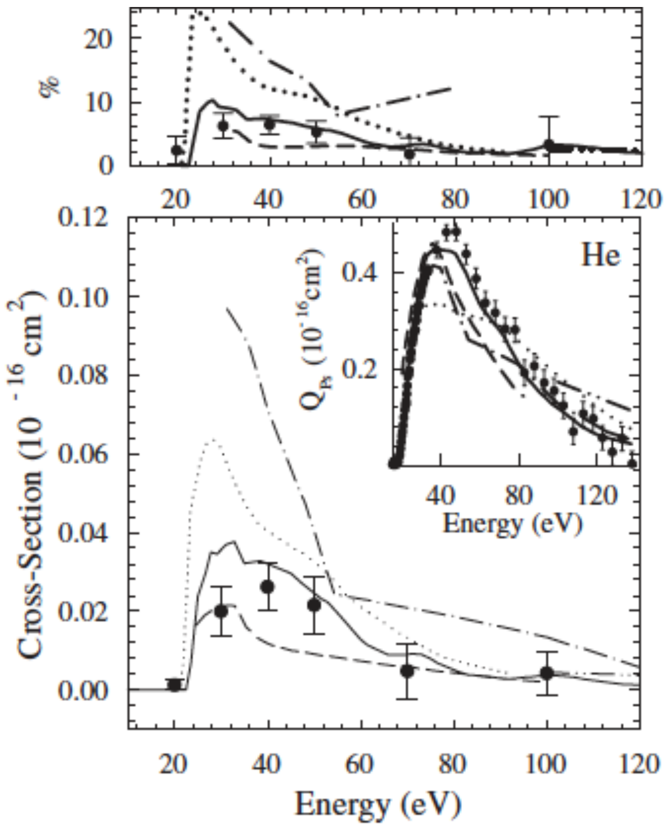
(Received 19 December 2008; published 1 April 2009)



J. Phys. B: At. Mol. Opt. Phys. 29 (1996) 3971–3987. Printed in the UK

Positron scattering by rubidium and caesium

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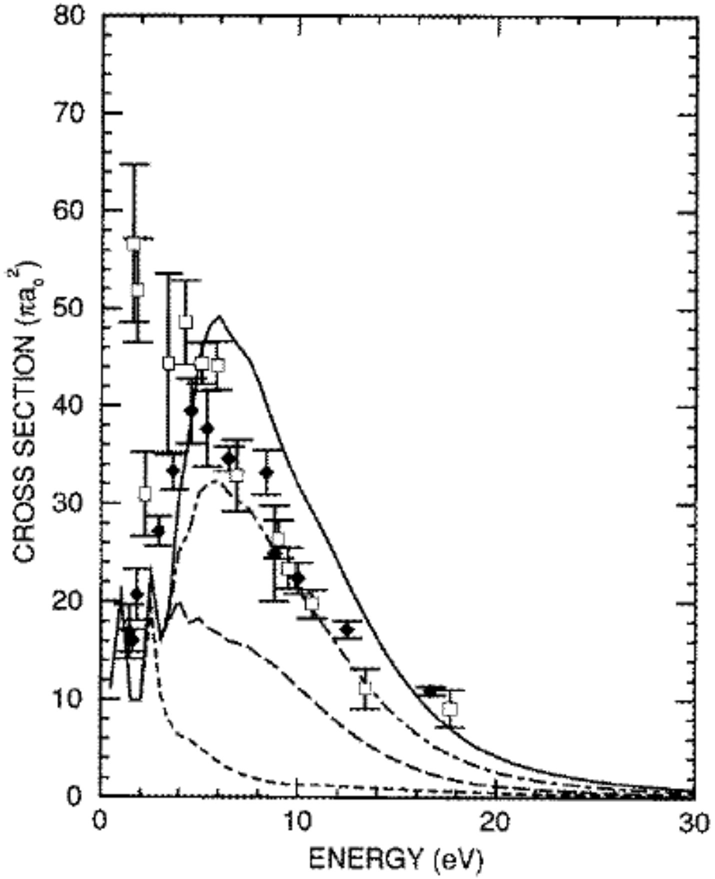
Key: short dash, n = 1 Ps formation; long dash n = (1 + 2); dot dash n = (1 + 2 + 3); full, total as n = (1 + 2 + 3) + n^3 addition for n ≥ 4. Experimental data from Detroit group; Surdutovitch *et al*. Phys. Rev A 53 (1996) 2861



Measurements and Results - Positronium

VOLUME 89, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 2002

Fragmentation of Positronium in Collision with He Atoms

S. Armitage, D. E. Leslie, A. J. Garner, and G. Laricchia*
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(Received 29 June 2002; published 3 October 2002)

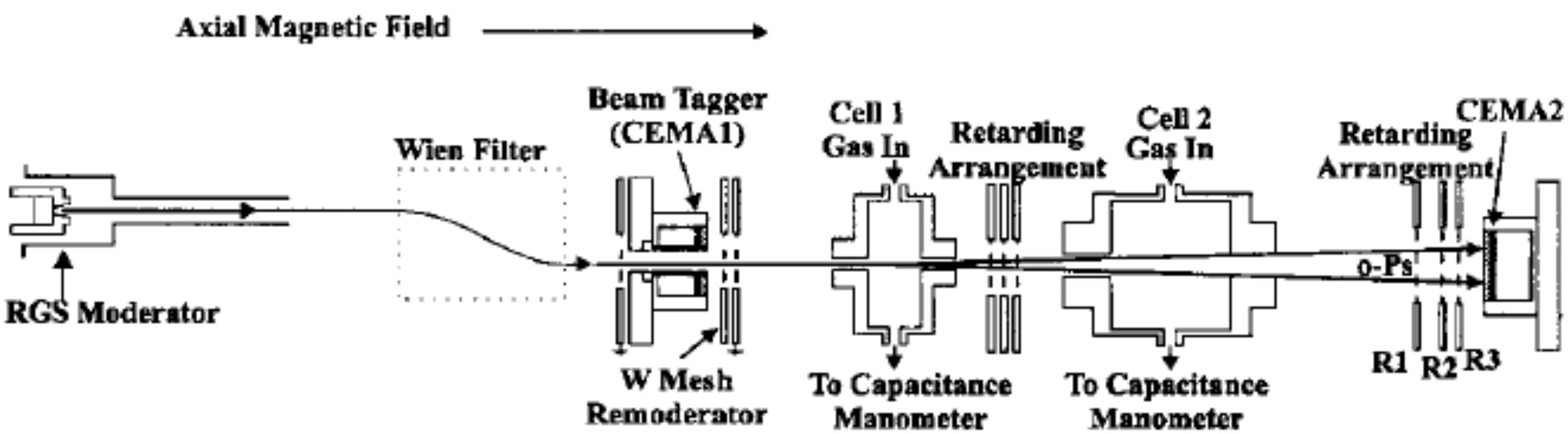
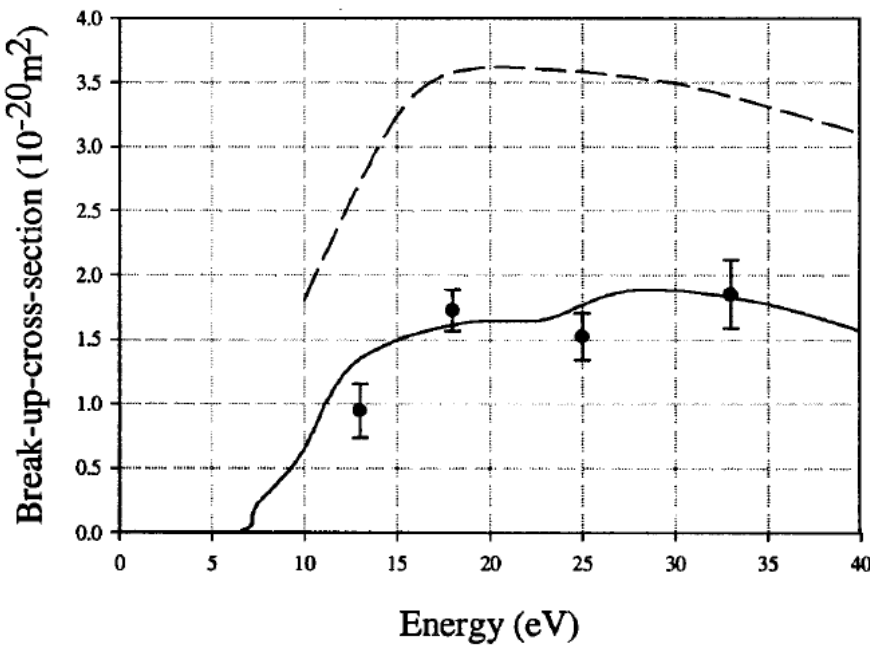


FIG. 1. Schematic diagram of the Ps beam.

Measurements and Results - Positronium



Break-up cross section in Ps-He scattering versus two theories; line - Blackwood *et al*. Phys Rev A 60 (1999) 4454 and dash – Biswas and Adhikari, Phys Rev A 59 (1999) 363

$$\mathrm{Ps} + \mathrm{He} \longrightarrow e^{+} + e^{-} + \mathrm{He}$$

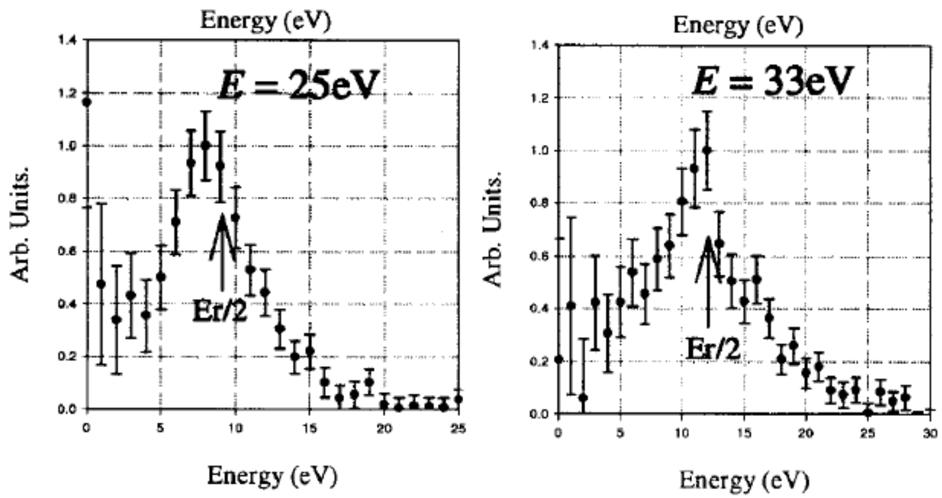


FIG. 3. Longitudinal energy spreads of the positrons released from Ps breakup.

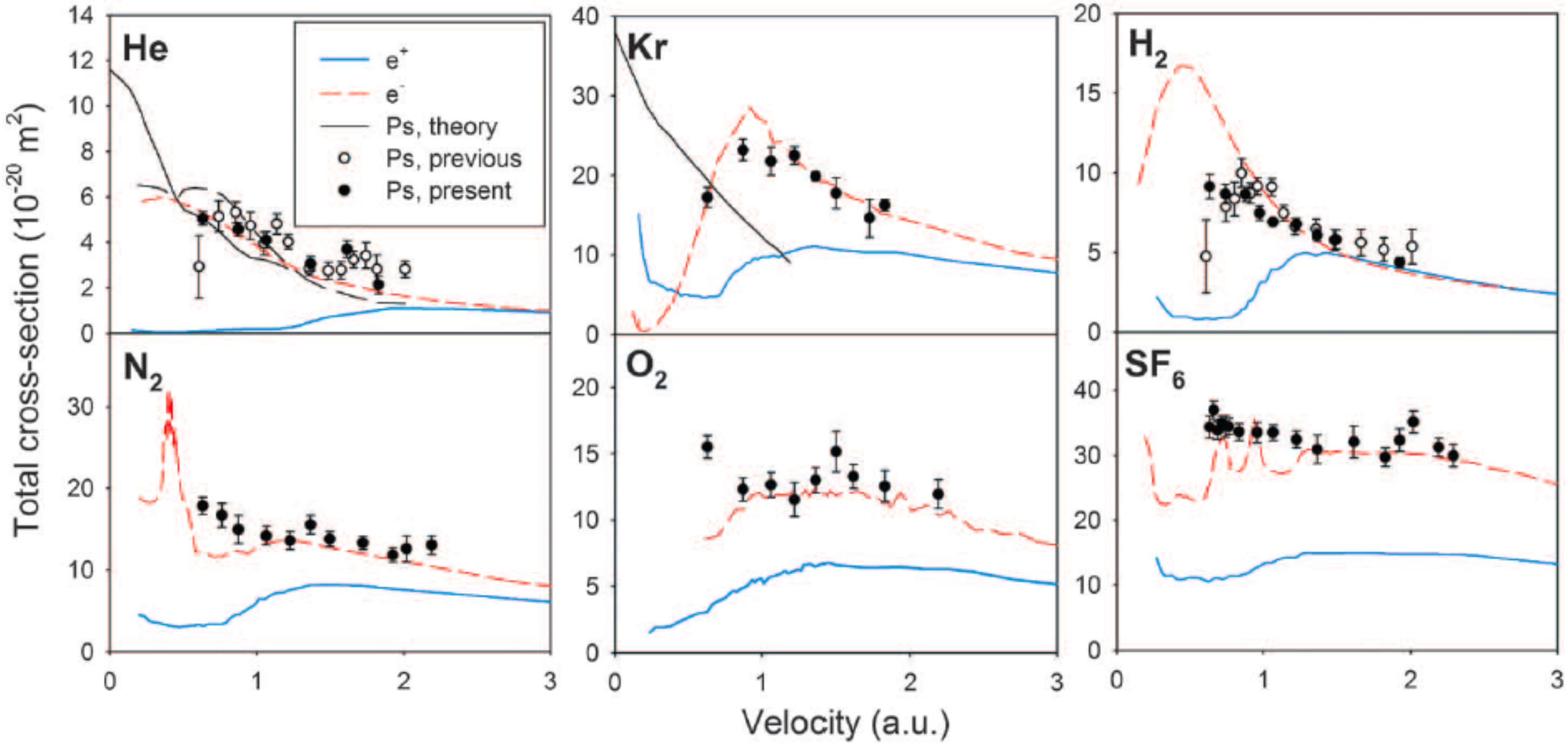
Measurements and Results - Positronium

Swansea University Prifysgol Abertawe

Electron-Like Scattering of Positronium

S. J. Brawley, S. Armitage,* J. Beale,† D. E. Leslie,‡ A. I. Williams, G. Laricchia§

SCIENCE VOL 330 5 NOVEMBER 2010 789



Measurements and Results - Positronium

PHYSICAL REVIEW A 81, 012715 (2010)

Positronium cooling in porous silica measured via Doppler spectroscopy

D. B. Cassidy,[1] P. Crivelli,[2] T. H. Hisakado,[1] L. Liszkay,[3,*] V. E. Meligne,[1] P. Perez,[3] H. W. K. Tom,[1] and A. P. Mills Jr.[1]
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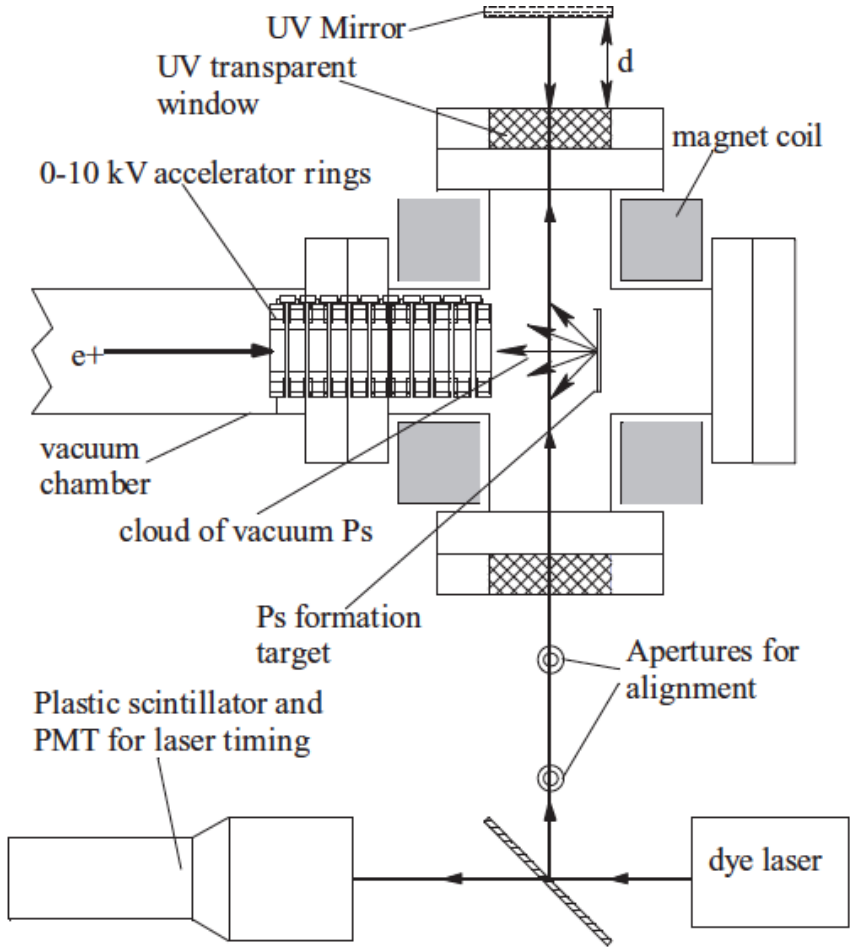
[3]*CEA, Saclay, IRFU, F-91191 Gif-sur-Yvette Cedex, France*
(Received 10 November 2009; published 29 January 2010; corrected 2 March 2010)



Measurements and Results - Positronium

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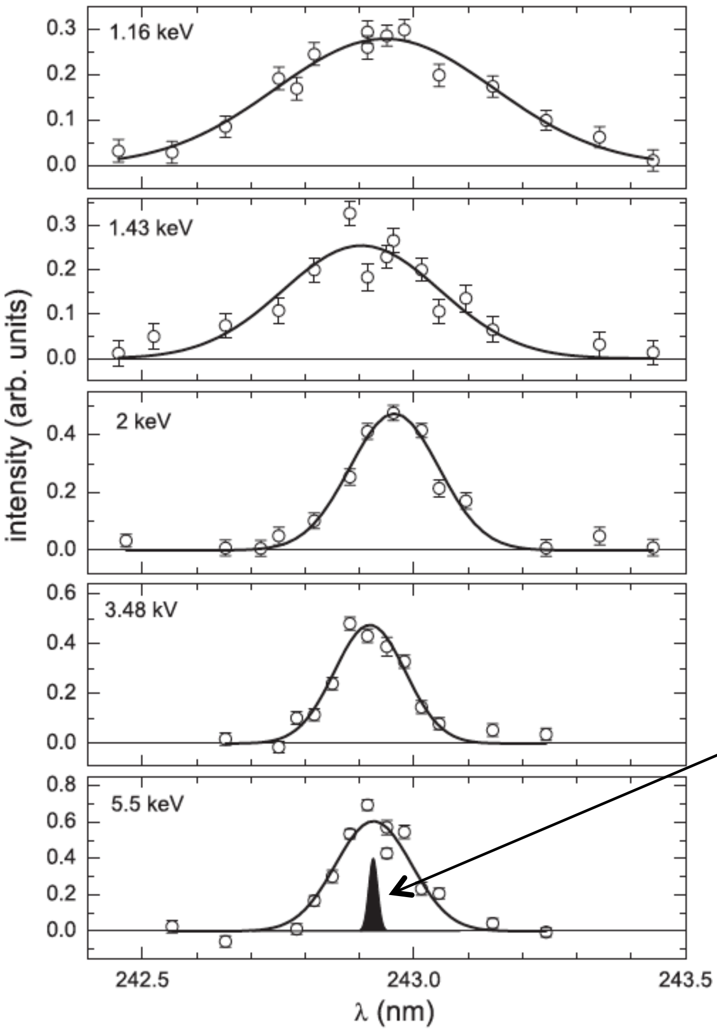

243 nm linewidths versus positron implantation energy into a porous sample.

Gaussian fits are shown

Probe laser bandwidth (0.02 nm)

Measurements and Results - Positronium

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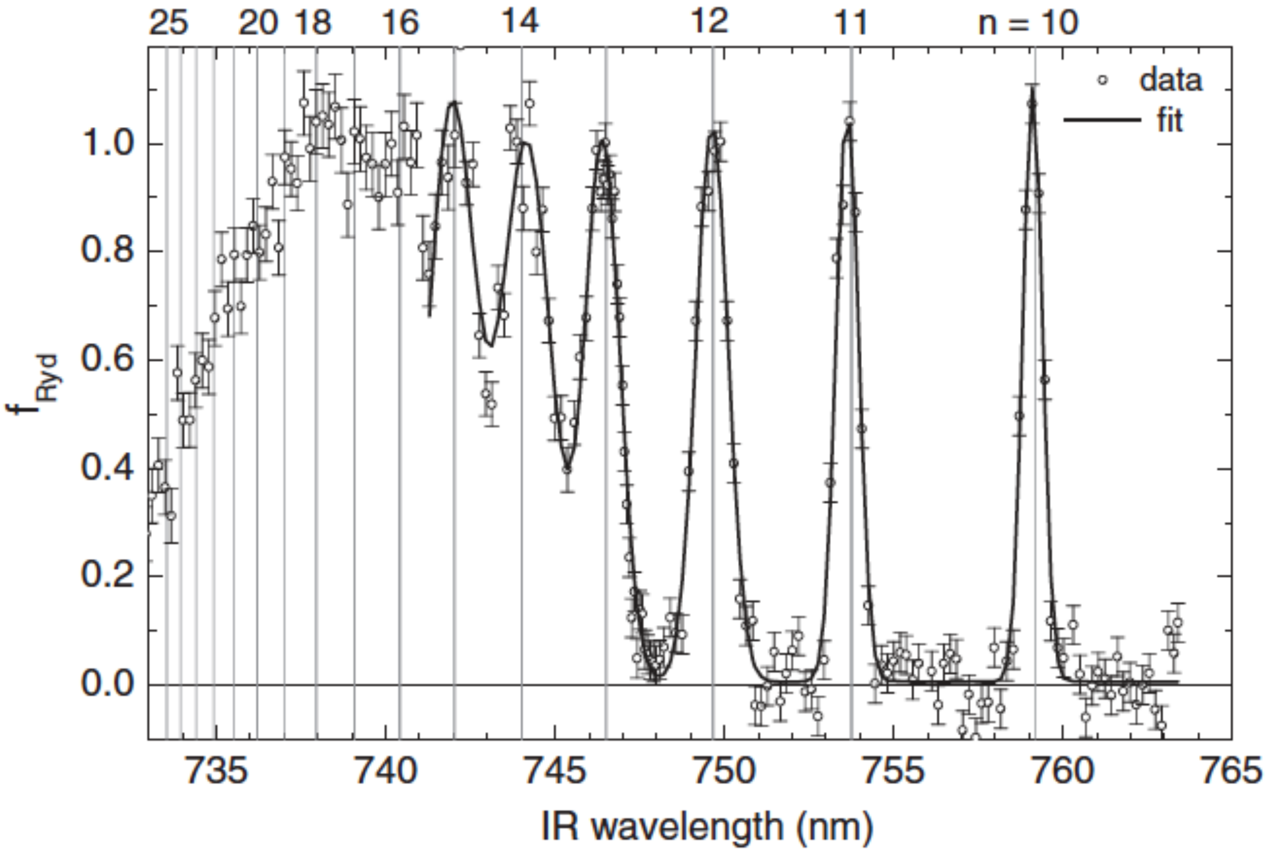
PRL **108**, 043401 (2012) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 2012

Efficient Production of Rydberg Positronium

D. B. Cassidy, T. H. Hisakado, H. W. K. Tom, and A. P. Mills, Jr.
Department of Physics and Astronomy, University of California, Riverside, California 92521-0413, USA

(Received 14 October 2011; published 26 January 2012)



Measurements and Results - Positronium

Swansea University Prifysgol Abertawe

PRL **106,** 153401 (2011) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2011

Photodetachment of Positronium Negative Ions

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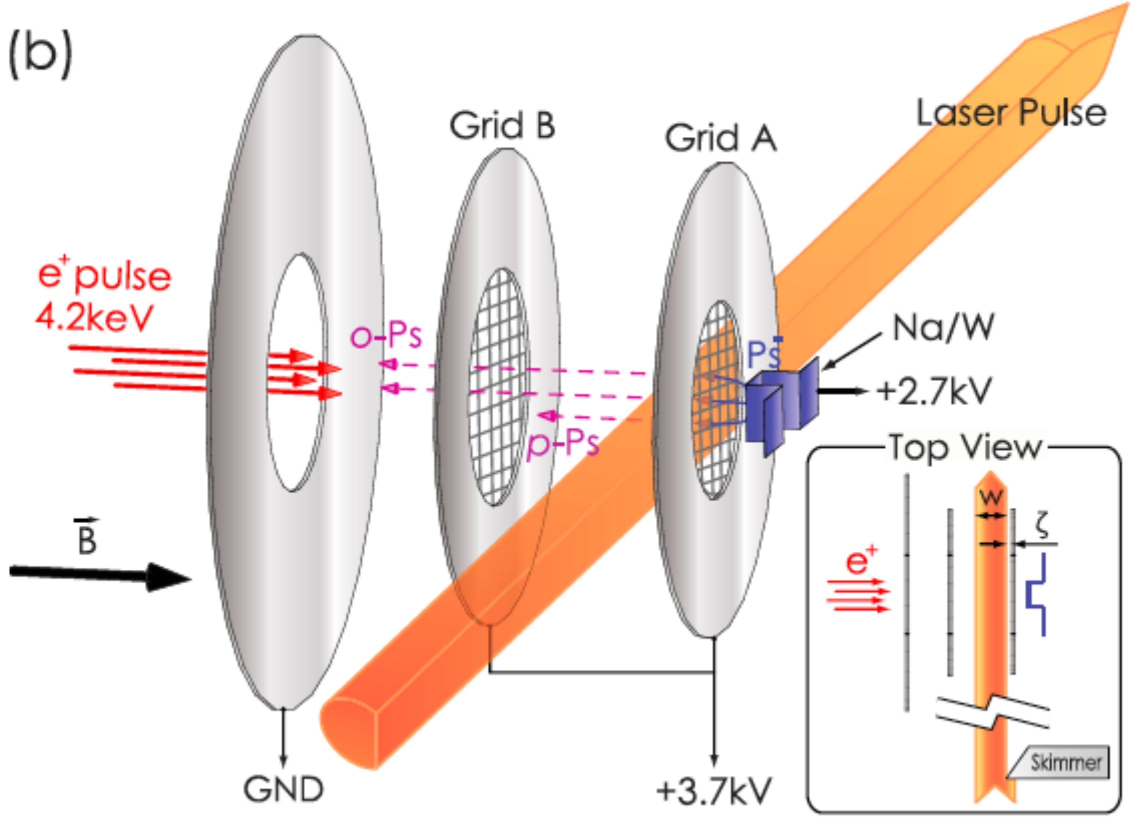
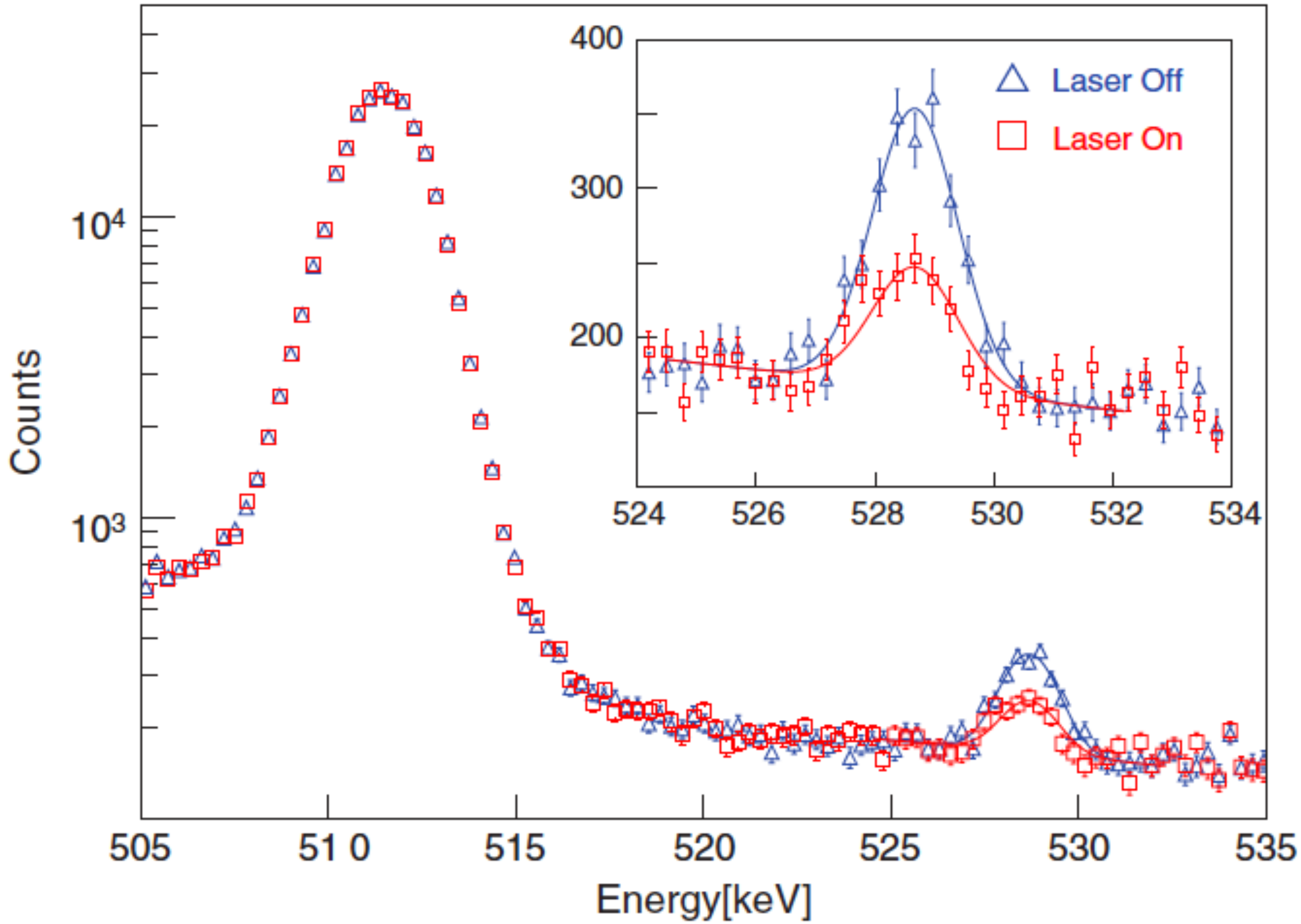
(Received 10 January 2011; published 11 April 2011)

BUT now its negative ion …



Measurements and Results - Positronium



Conclusions …

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Most processes of interest have cross sections that are reasonably well-known, or better.

If you need anything, ask …

Experimenters and theorists in the positron and positronium field have well-developed sets of tools to hand!