# Collisions of positrons and positronium with atoms and molecules

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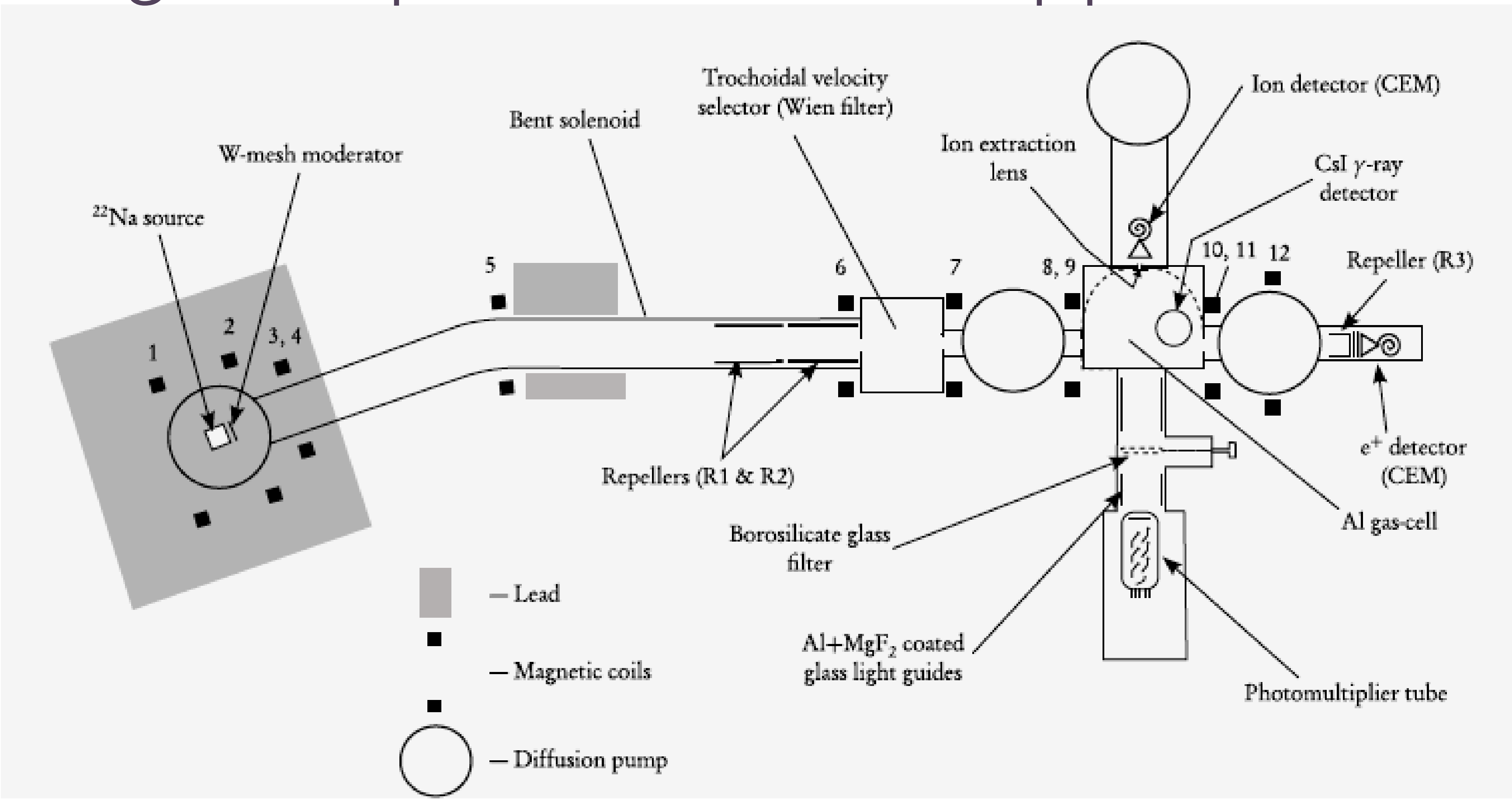
# Motivations

- To understand basic matter–antimatter interactions,
- to assist the development of accurate scattering theories,
- to support tests of QED bound–state problems and
- to provide input to positron–track simulations for quantifying and controlling positron–induced damage in biomedical applications (e.g. PET),
- to aid the analysis of astrophysical events?

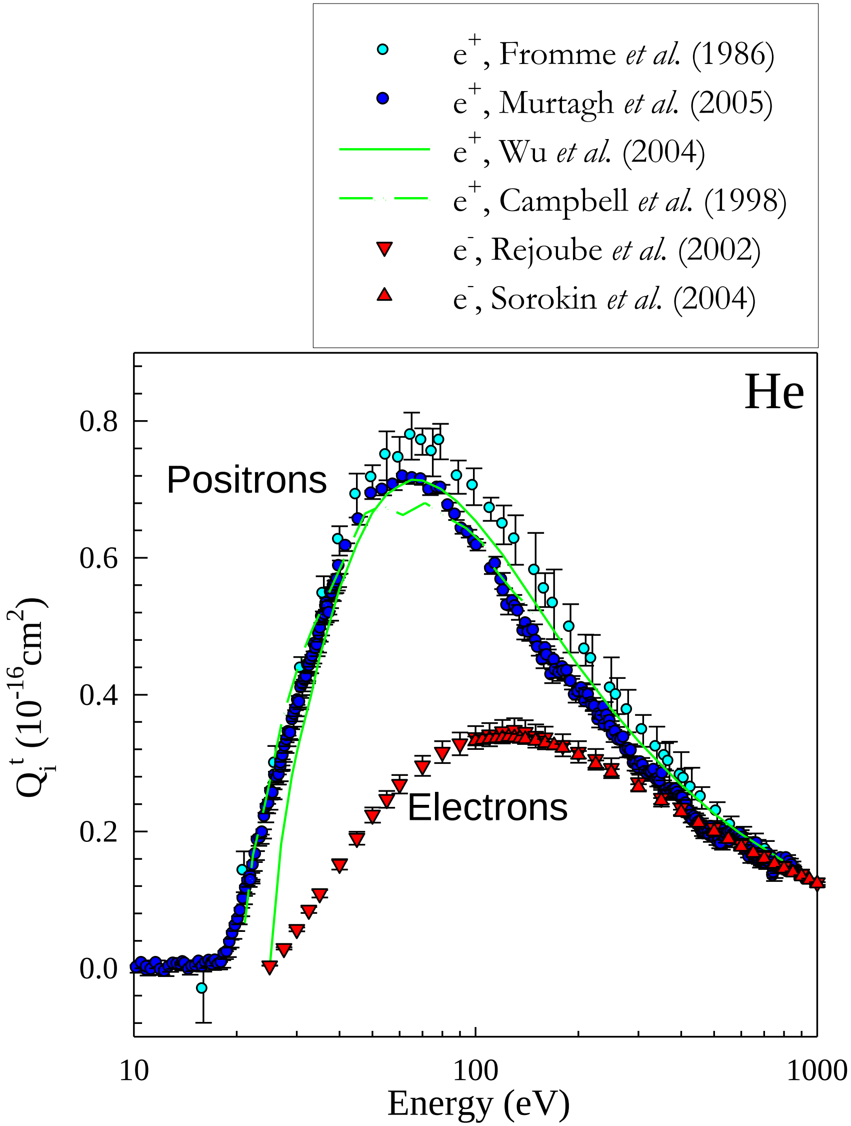
# Magnetic positron beam apparatus:

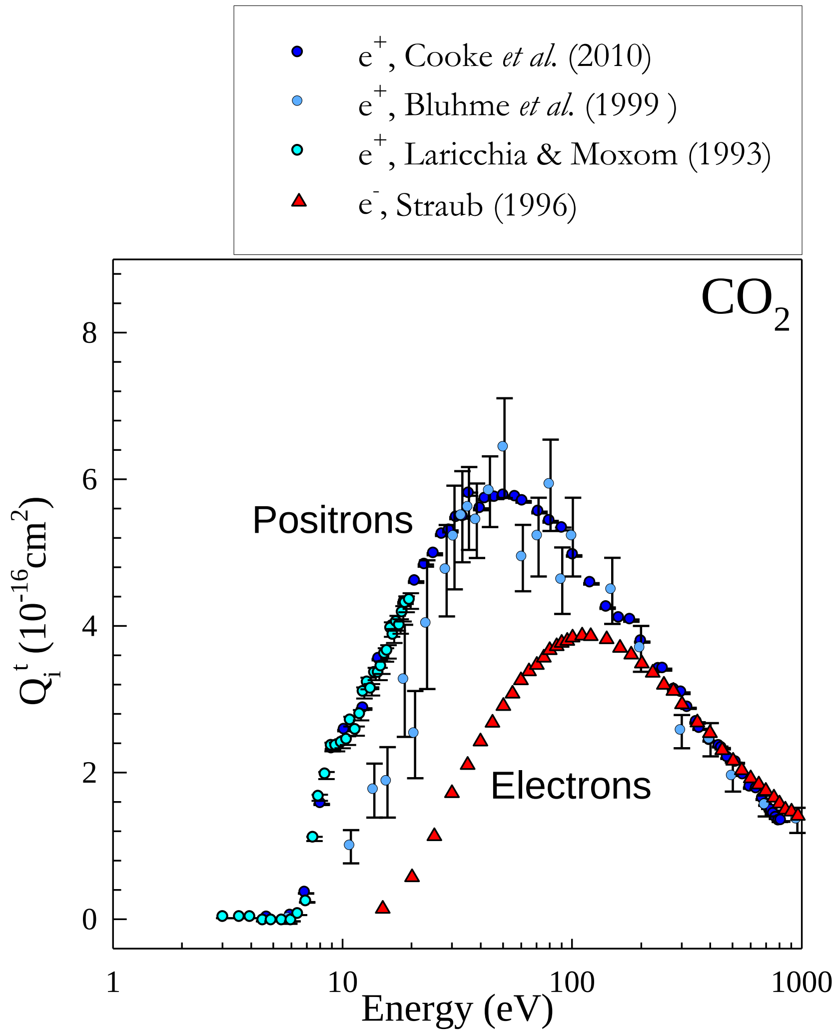



| | |
|---|---|
| $A^+ + e^+$ | direct ionization |
| $A^+ + \gamma$ | Ps formation or annihilation |
| $A^+ + h\nu$ | excitations of Ps or target |

Obtain absolute cross-sections at $E_{e+}$ ~ *1-1000 eV*.

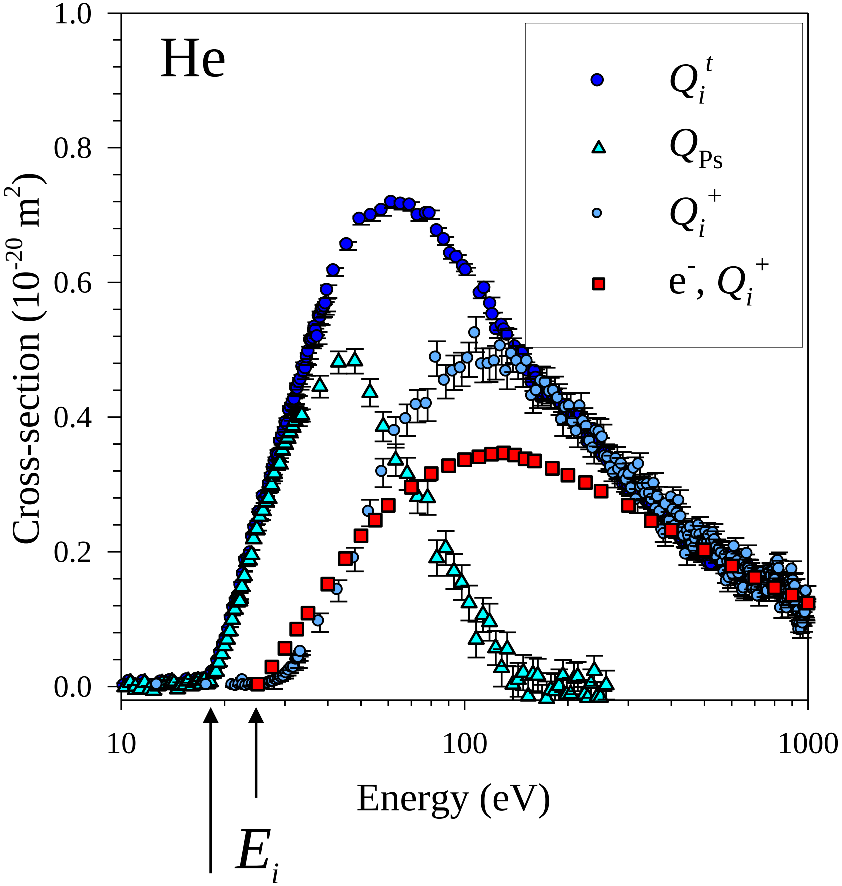
# Total ionisation cross-sections, $Q_i^T$:



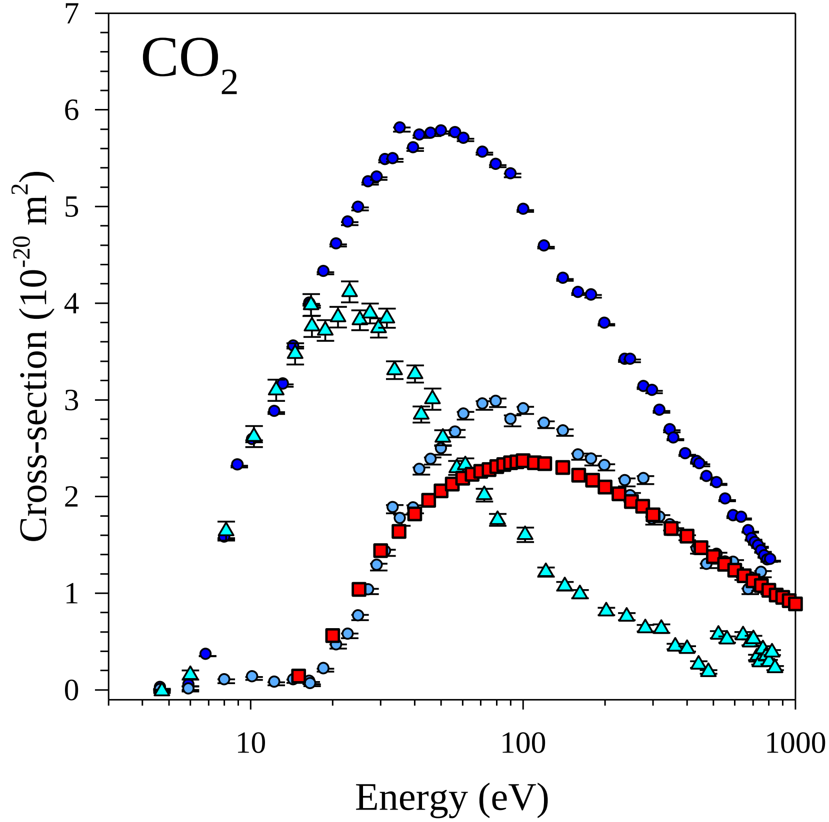




Laricchia *et al.*, *J. Phys. Conf. Ser.* **194** 012036 (2009)

# Ps formation, $Q_{Ps}$, and direct ionisation, $Q_i^+$:



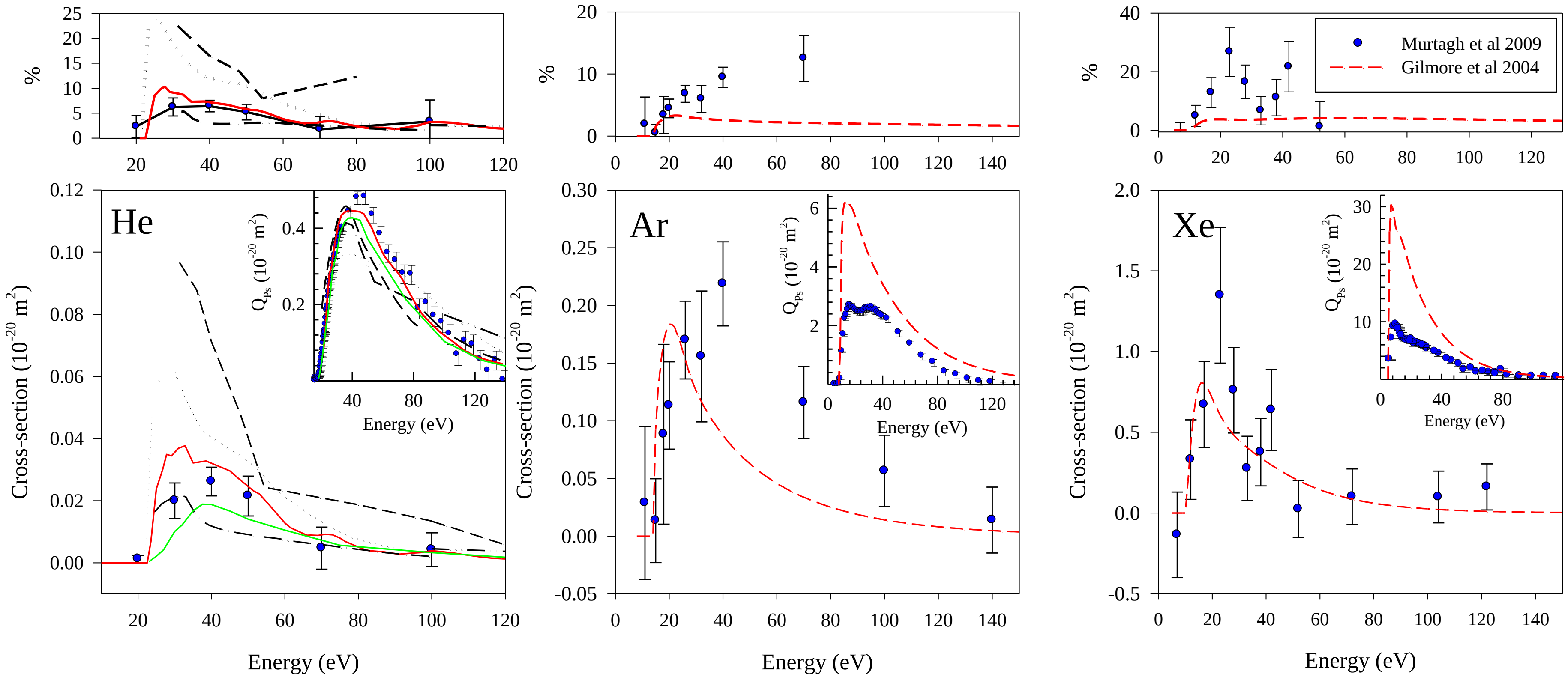

$$E_{Ps} = (E_i - 6.8)\text{eV}$$

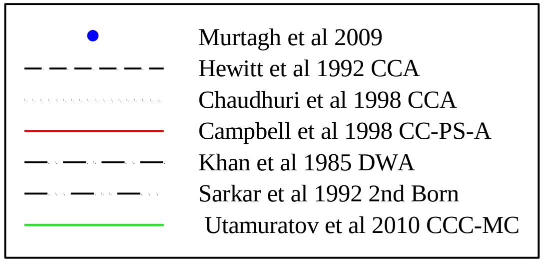



Murtagh *et al.*, *J.Phys. B* **38** 3857 (2005)

Cooke *et al.*, *J. Phys. Conf. Ser.* **199** 012006 (2010)

# $Q_{Ps}$(2P) for He, Ar and Xe



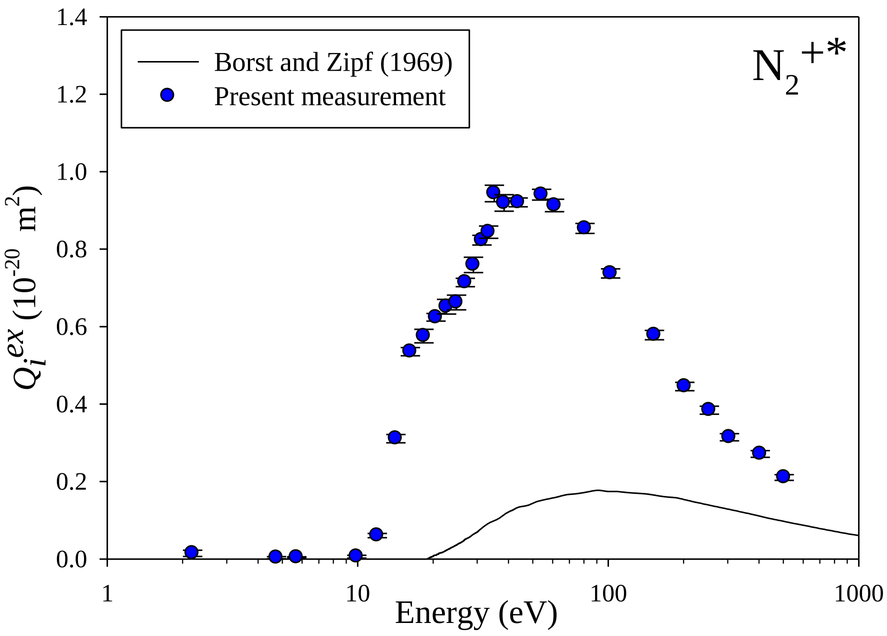

$$\left[\frac{Q_{Ps}(2P)}{Q_{Ps}(\text{all n})}\right]_{max} = 6\%, 12\%, 23\%$$

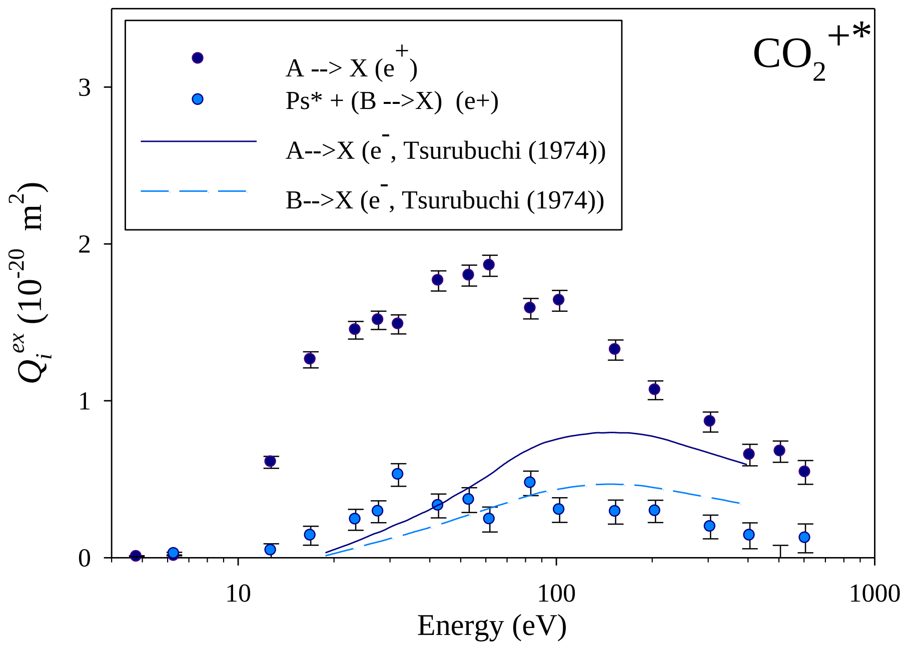
Murtagh *et al.*, *Phys. Rev. Lett.* **102** 133202 (2009)

# Simultaneous ionisation–excitation $Q_i^{ex}$ for $N_2$, $CO_2$

$$e^+ + AB \rightarrow (AB^+)^* + Ps$$

$$e^+ + AB \rightarrow (AB^+)^* + e^- + e^+$$



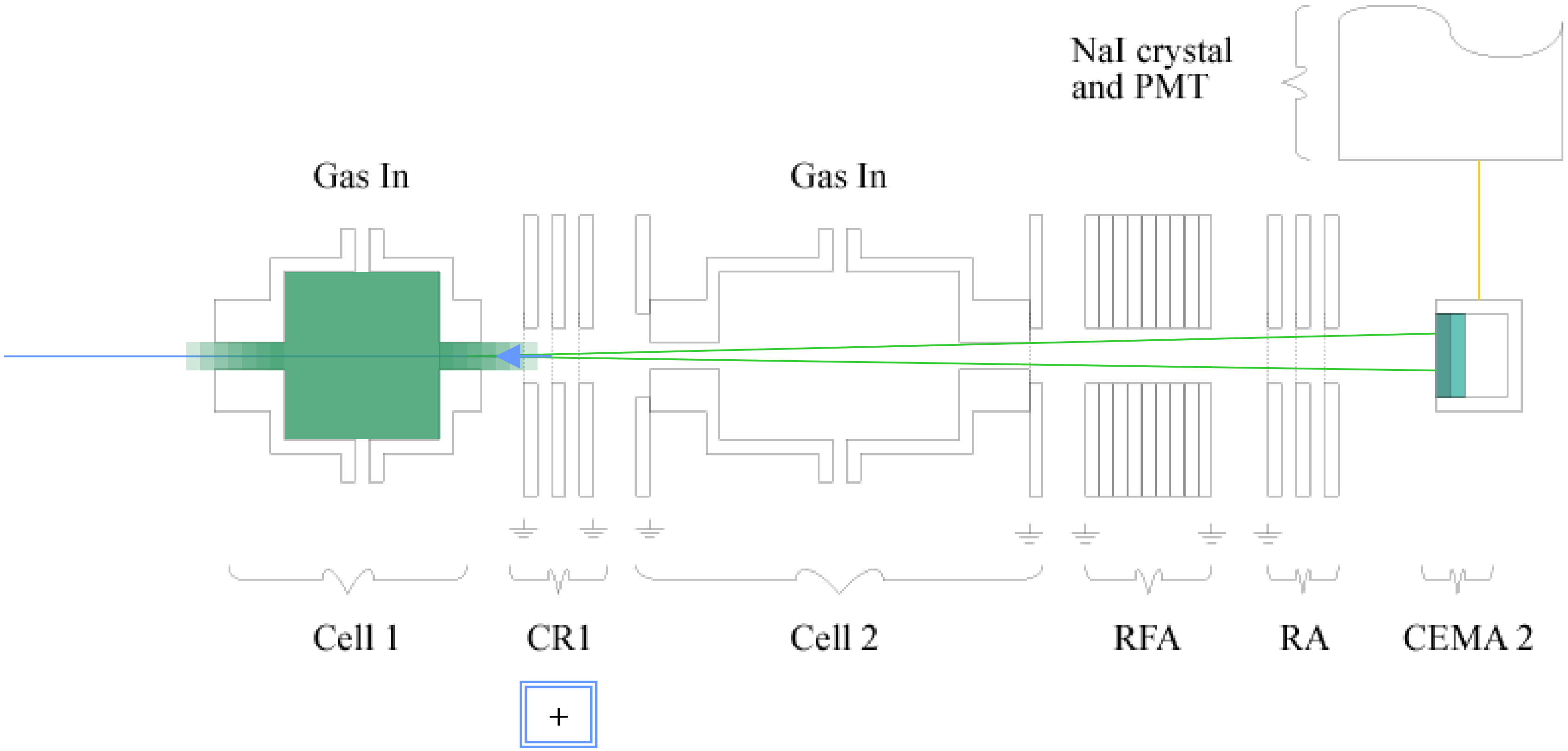

$B\ ^2\Sigma_u^+ \rightarrow X\ ^2\Sigma_g^+$ (391 nm)

$A\ ^2\Pi_u \rightarrow X\ ^2\Pi_g$ (271-434 nm)

$B\ ^2\Sigma_u^+ \rightarrow X\ ^2\Pi_g$ (288 nm)

Cooke *et al.*, *Phys. Rev. Lett* **104** 073201 (2010)

# Ps beam: production at UCL



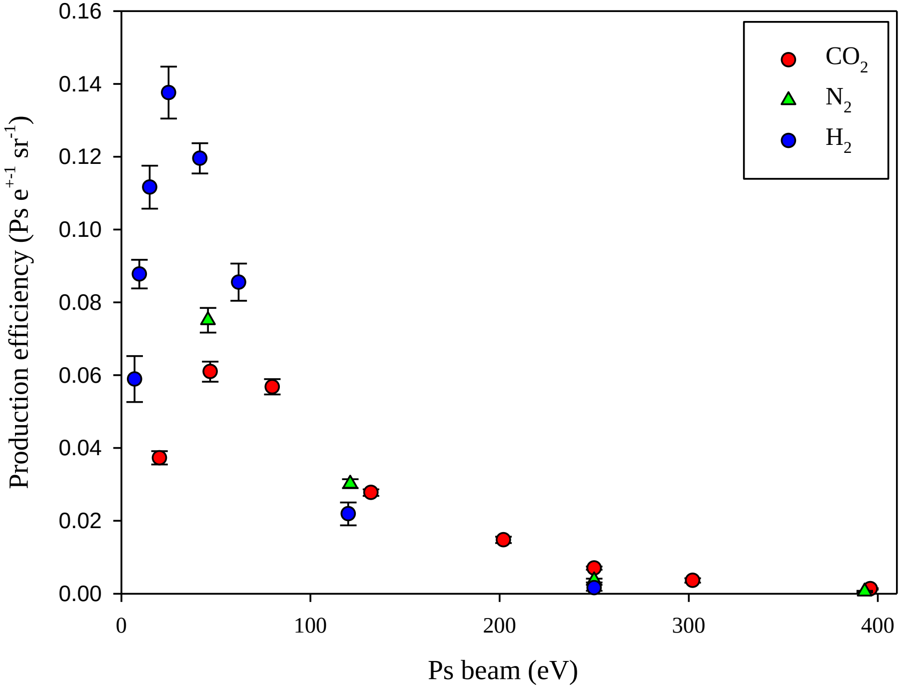

$$e^{+} + \mathrm{T} \rightarrow \mathrm{Ps} + \mathrm{T}^{+}$$

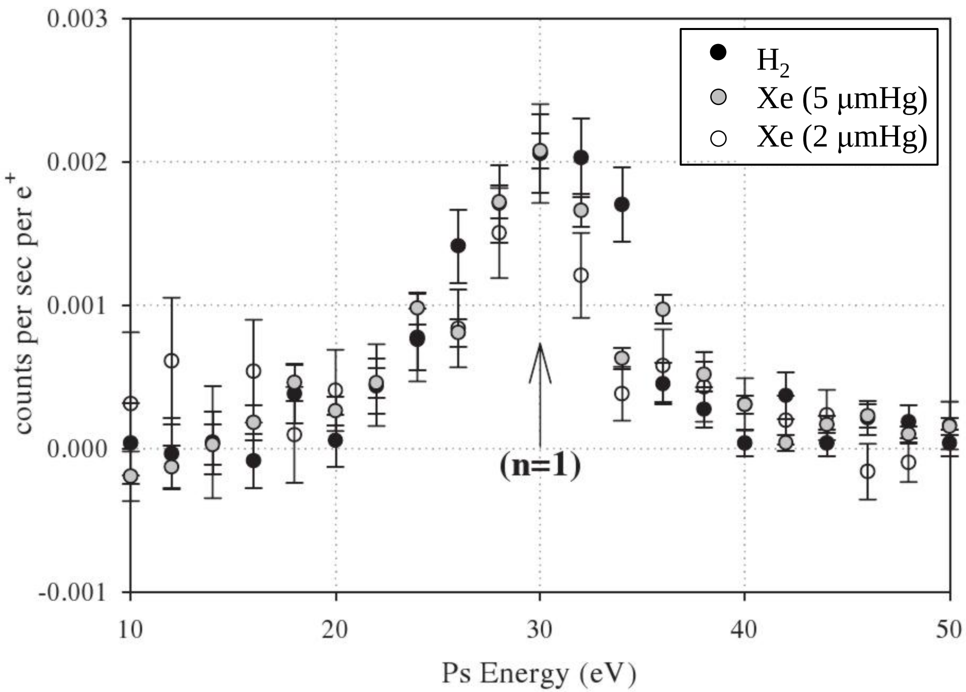
$$E_{\mathrm{Ps}} \approx E_{+} - E_{i}^{T} + \frac{6.8\mathrm{eV}}{n^{2}}$$

Key: e$^{+}$ Ps

Ps produced in Cell 1 and scattered in Cell 2

# Ps beam: production at UCL




$$e^+ + T \rightarrow Ps + T^+$$

$$E_{Ps} \approx E_+ - E_i^T + \frac{6.8\text{eV}}{n^2}$$

Key: e+ Ps

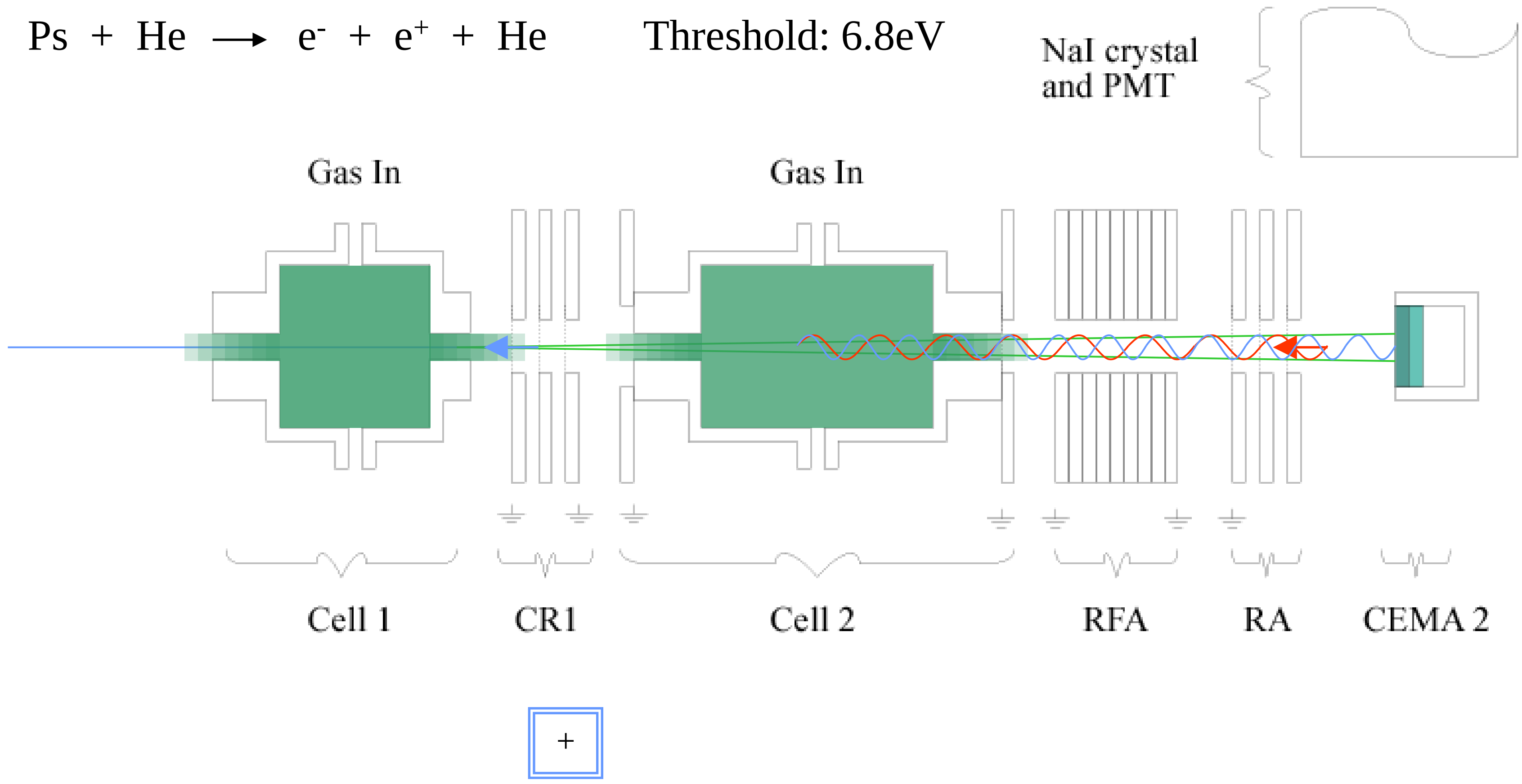
Ps produced in Cell 1 and scattered in Cell 2

Shipman *et al.*, *Eur. J. Phys.* (2012)

Laricchia et al., *Nucl. Intrum. Method B* **221** 60 (2004)

# Ps fragmentation on He, $Q_f^+$:

$Ps + He \longrightarrow e^- + e^+ + He$ Threshold: 6.8eV




We can detect either the positron *or* the electron

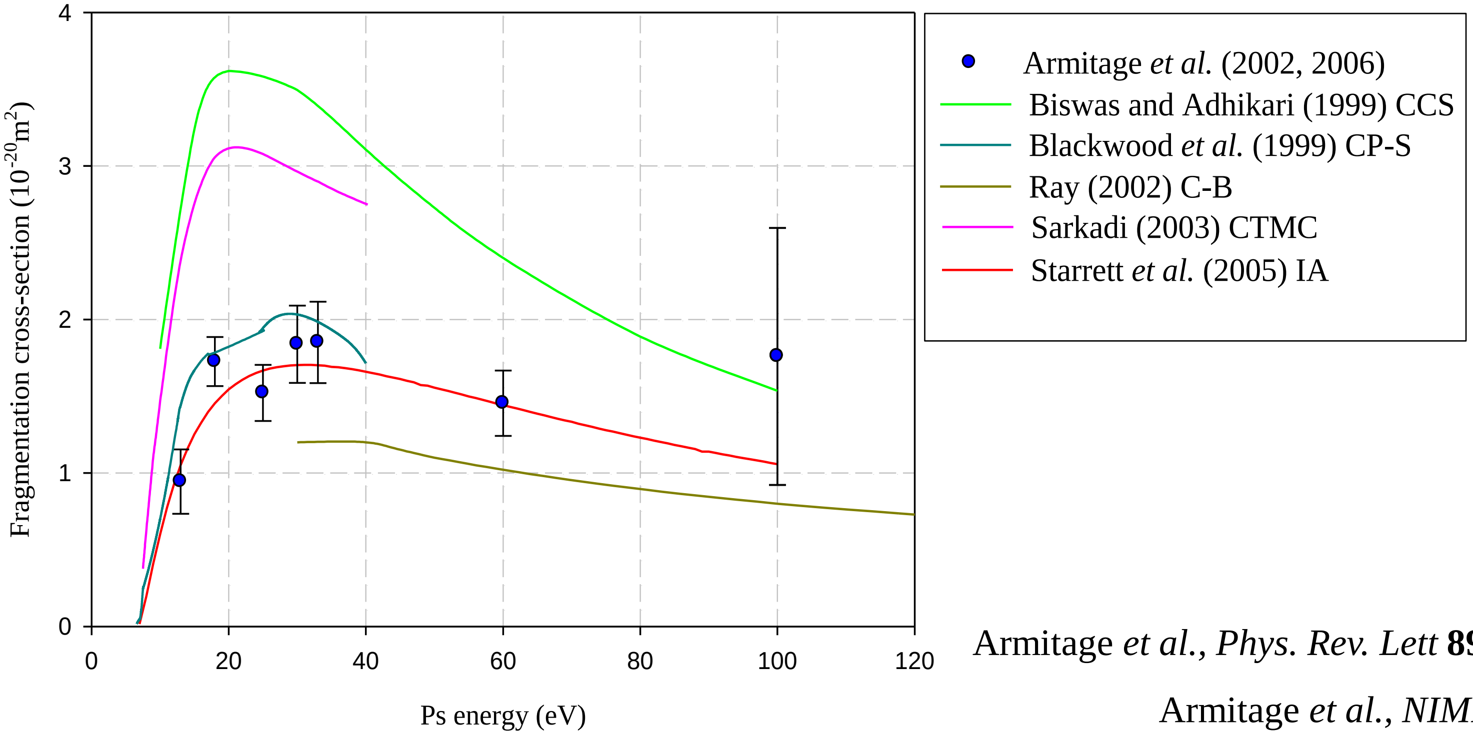
Key: $e^+$ Ps $e^-$

Armitage *et al.*, *Phys. Rev. Lett.* **89** 173402 (2002)

# $Q_f^+$: (Armitage *et al.* (2002, 2006))

| | |
|---|---|
| $Ps + He \longrightarrow e^- + e^+ + He$ | Threshold: 6.8eV |
| $Ps + He \longrightarrow Ps^- + He^+$ | Threshold: 24.2eV |
| $Ps + He \longrightarrow Ps + e^- + He^+$ | Threshold: 24.6eV |
| $Ps + He \longrightarrow e^- + e^+ + He^*$ | Threshold: 27.0eV |
| $Ps + He \longrightarrow Ps^* + e^- + He^+$ | Threshold: 29.7eV |
| $Ps + He \longrightarrow 2e^- + e^+ + He^+$ | Threshold: 31.4eV |

($I_{He}$ = 24.6eV)




Armitage *et al.*, *Phys. Rev. Lett* **89** 173402 (2002)

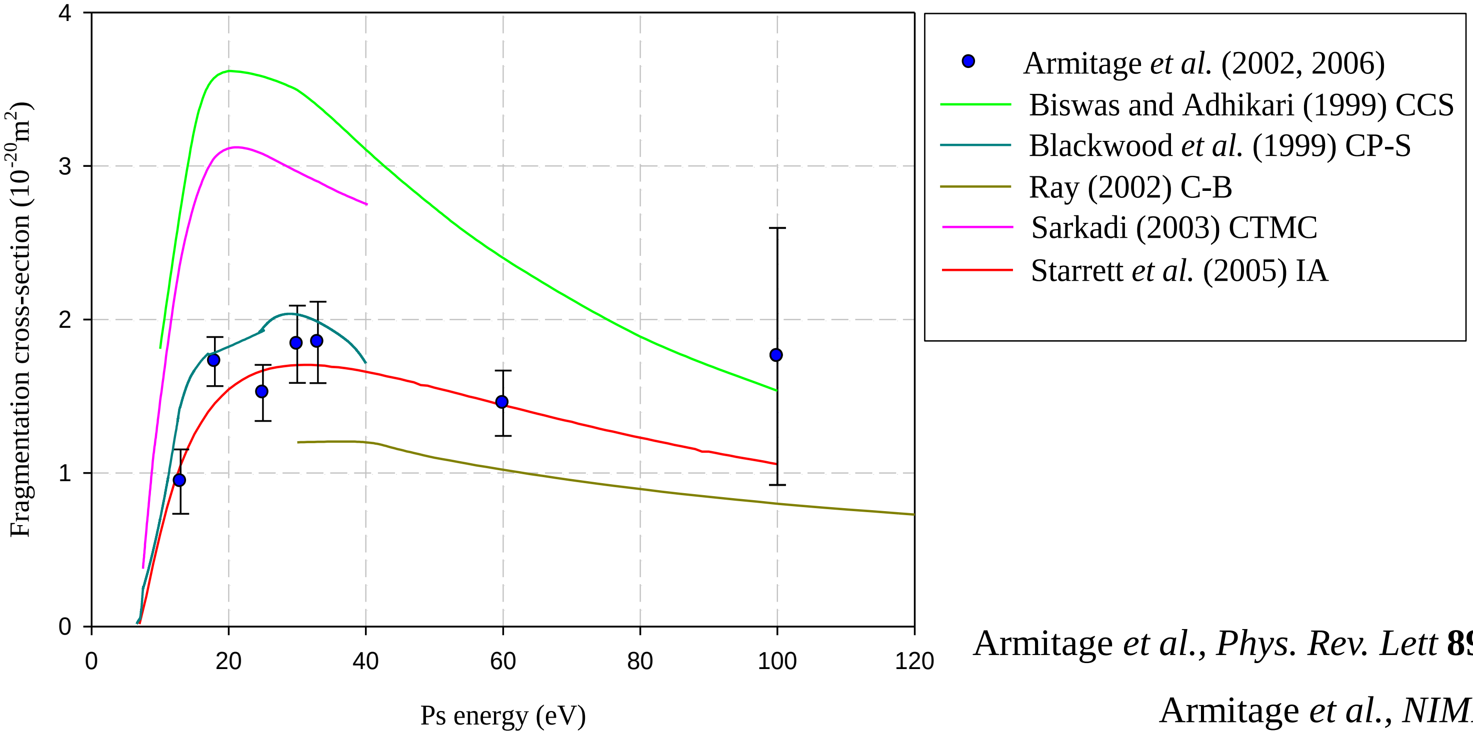
Armitage *et al.*, *NIMB* **247** 98 (2006)

Additional uncertainty of (+8, −(20−30))% on the absolute scale of experiment.

## $Q_f^+$: (Armitage *et al.* (2002, 2006))

| | |
|---|---|
| Ps + He ⟶ $e^-$ + $e^+$ + He | Threshold: 6.8eV |
| Ps + He ⟶ $Ps^-$ + $He^+$ | Threshold: 24.2eV |
| Ps + He ⟶ Ps + $e^-$ + $He^+$ | Threshold: 24.6eV |
| Ps + He ⟶ $e^-$ + $e^+$ + He* | Threshold: 27.0eV |
| Ps + He ⟶ Ps* + $e^-$ + $He^+$ | Threshold: 29.7eV |
| Ps + He ⟶ $2e^-$ + $e^+$ + $He^+$ | Threshold: 31.4eV |

($I_{He}$ = 24.6eV)




Armitage *et al.*, *Phys. Rev. Lett* **89** 173402 (2002)

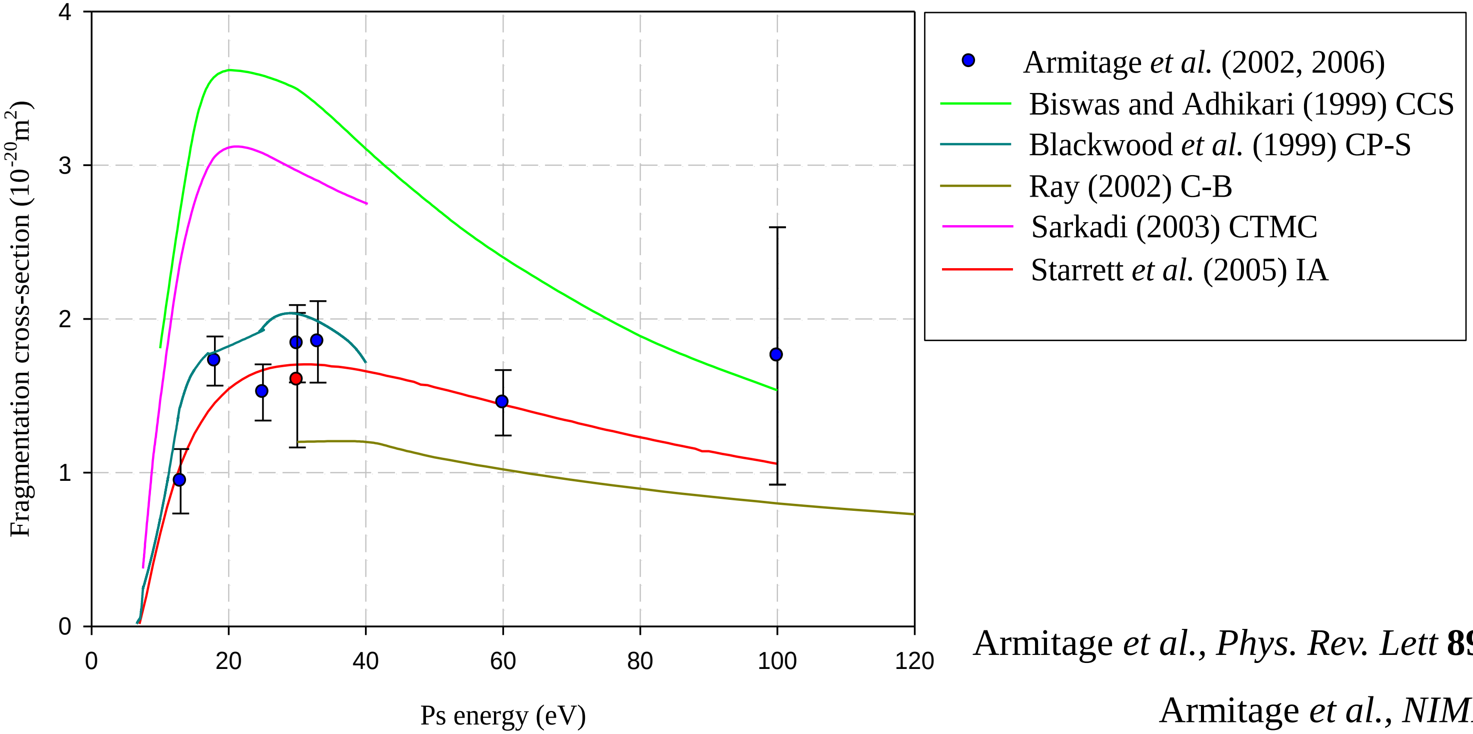
Armitage *et al.*, *NIMB* **247** 98 (2006)

Additional uncertainty of (+8, −(20−30))% on the absolute scale of experiment.

## $Q_f^-$: (Armitage *et al.* (2006))

| | |
|---|---|
| Ps + He → $e^-$ + $e^+$ + He | Threshold: 6.8eV |
| Ps + He → $Ps^-$ + $He^+$ | Threshold: 24.2eV |
| Ps + He → Ps + $e^-$ + $He^+$ | Threshold: 24.6eV |
| Ps + He → $e^-$ + $e^+$ + He* | Threshold: 27.0eV |
| Ps + He → Ps* + $e^-$ + $He^+$ | Threshold: 29.7eV |
| Ps + He → $2e^-$ + $e^+$ + $He^+$ | Threshold: 31.4eV |

($I_{He}$ = 24.6eV)

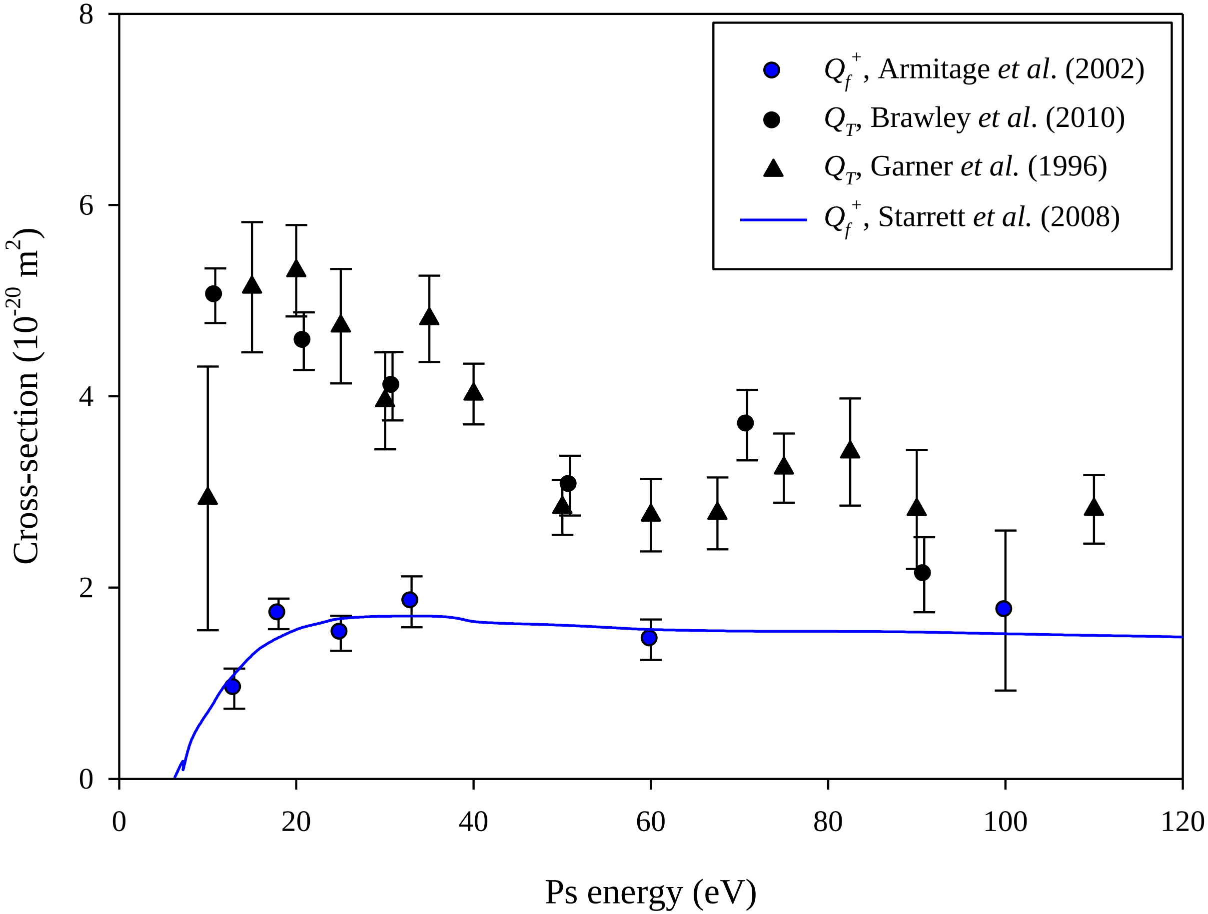



Armitage *et al.*, *Phys. Rev. Lett* **89** 173402 (2002)

Armitage *et al.*, *NIMB* **247** 98 (2006)

Additional uncertainty of (+8, −(20−30))% on the absolute scale of experiment.

# $Q_f^+$ compared to $Q_T$:

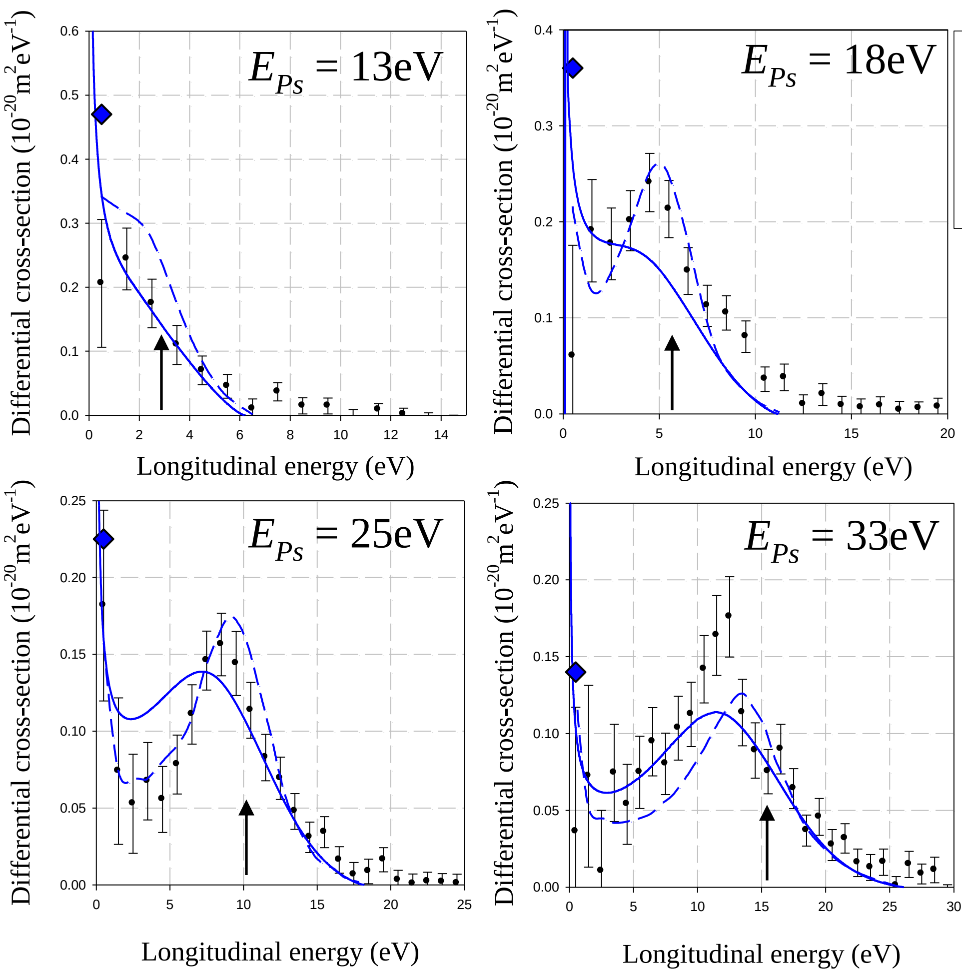


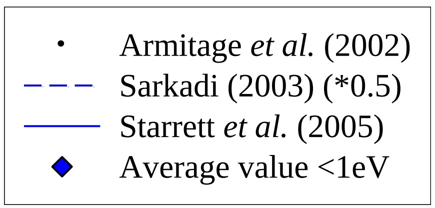

Additional uncertainty of (+8, −(20−30))% on the absolute scale for $Q_f^+$.

# $dQ_f^+/dE_\ell$ (Armitage *et al.* (2002)):

| | |
|---|---|
| Ps + He ⟶ $e^-$ + $e^+$ + He | Threshold: 6.8eV |
| Ps + He ⟶ $e^-$ + $e^+$ + He* | Threshold: 27.0eV |
| Ps + He ⟶ $e^-$ + $e^+$ + $He^+$ + $e^-$ | Threshold: 31.4eV |

($I_{He}$ = 24.6eV)




↑ denotes $E_r / 2 = (E_{Ps} - 6.8eV)/2$

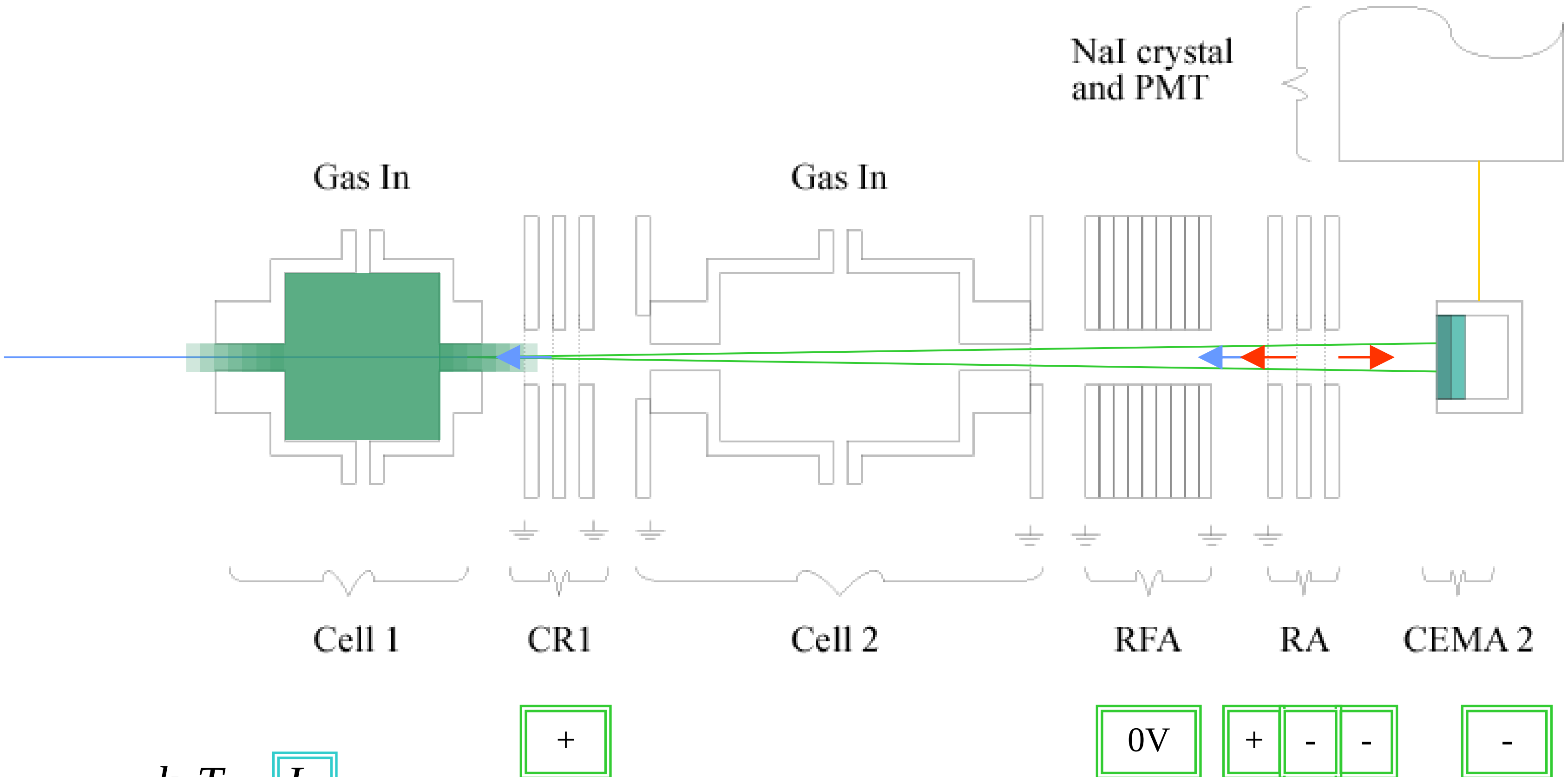
- Peaks at Er / 2 suggests ELC
- Shift from $E_r/2$ due partly to:

1) *angular* distribution (around ~20$^o$)

2) *energy* distribution of Ps beam (~2-3eV).

Armitage *et al.*, *Phys. Rev. Lett.* **89** 173402 (2002)

# $Q_T$: method (incident Ps beam):



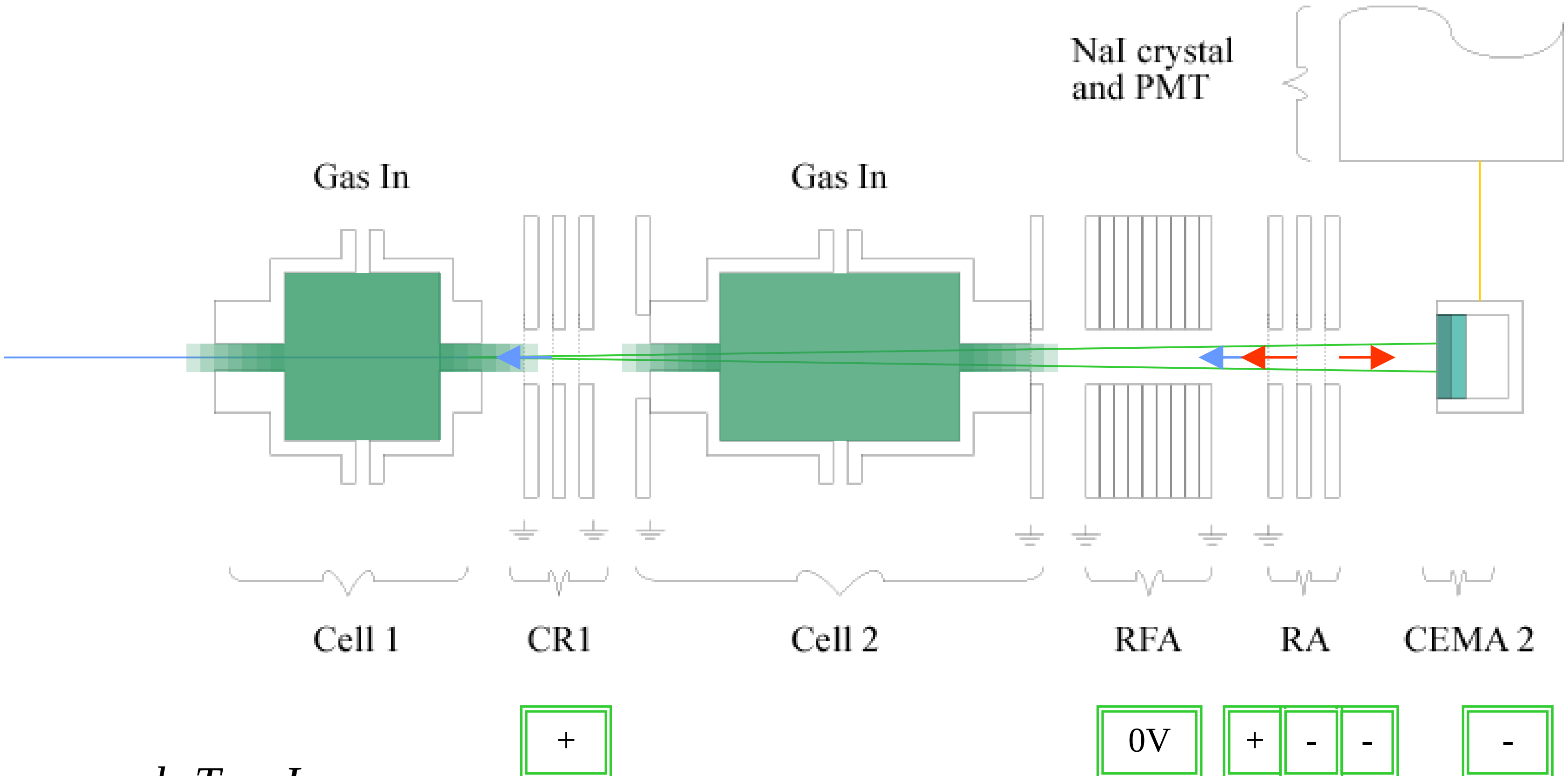

$$Q_T = \frac{k_B T}{P\ell} \ln \frac{I_o}{I}$$

Key: $e^+$ Ps $e^-$

Zafar *et al.*, *Phys. Rev. Lett.* **76** 1595 (1996)

Garner *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **33** 1149 (2000)

# $Q_T$: method (transmitted Ps beam):



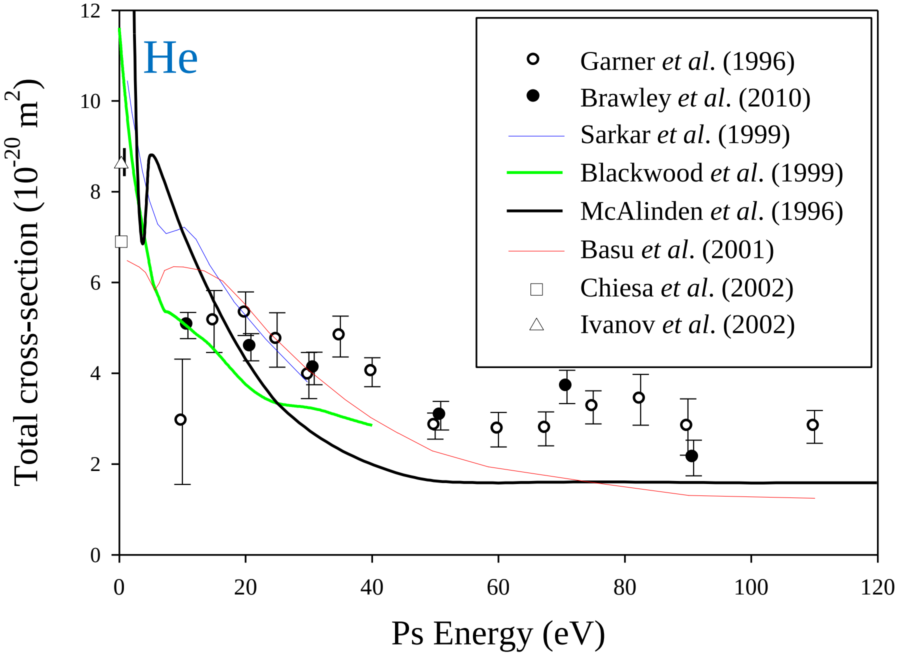

$$Q_T = \frac{k_B T}{P\ell} \ln \frac{I_o}{I}$$

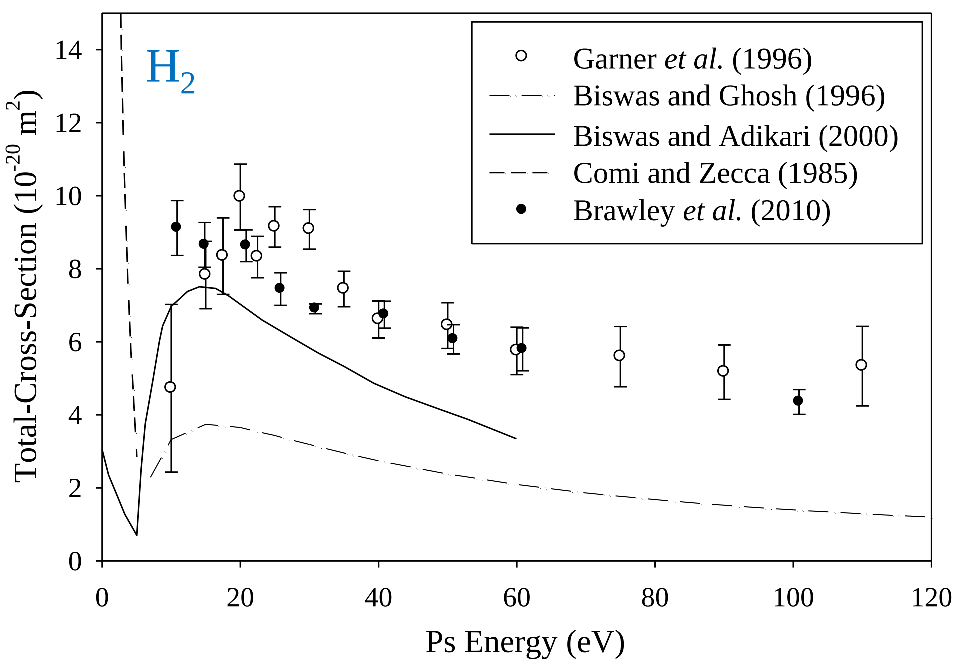
Key: $e^+$ Ps $e^-$

Zafar *et al.*, *Phys. Rev. Lett.* **76** 1595 (1996)

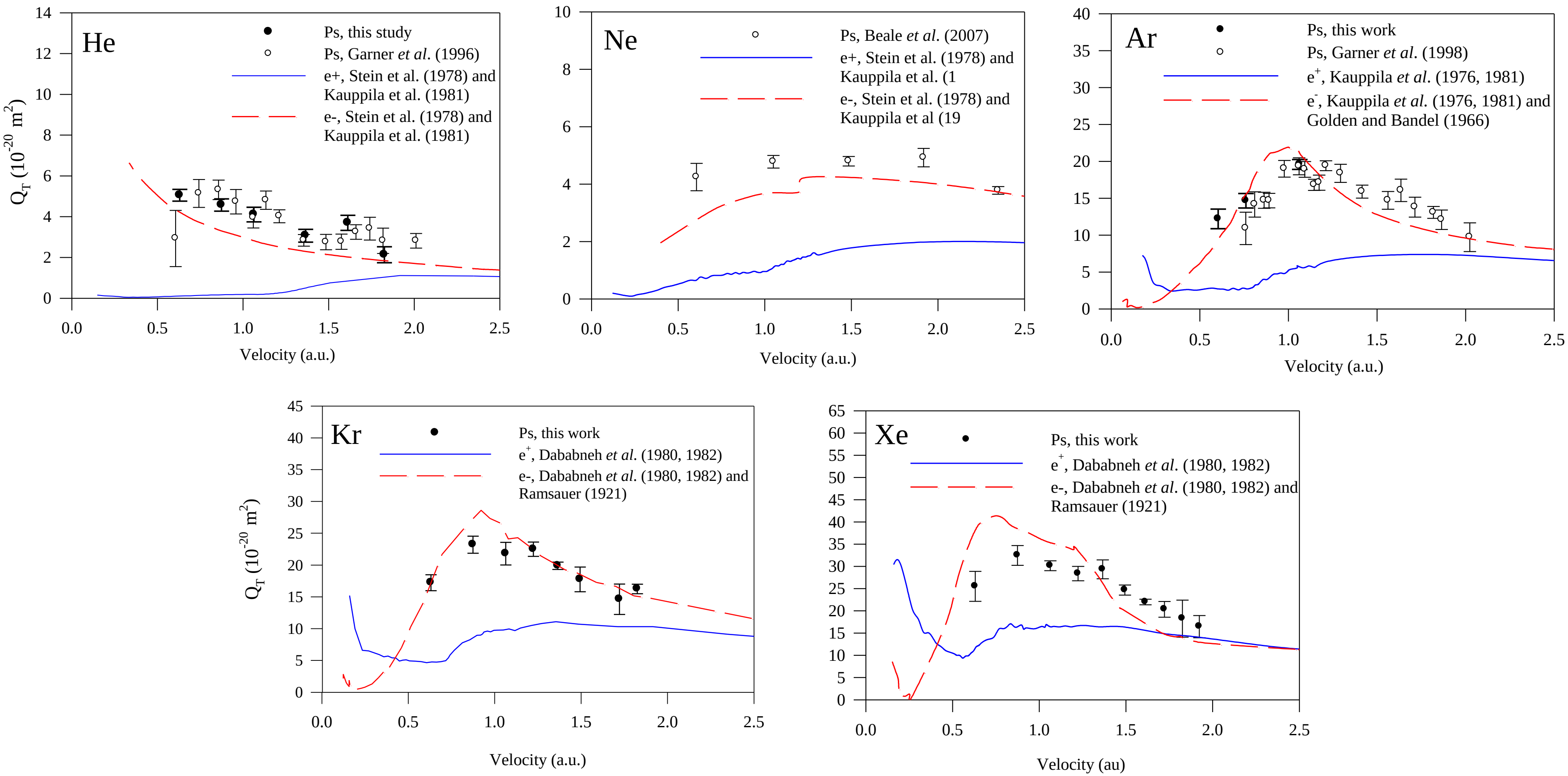
Garner *et al.*, *J. Phys. B: At. Mol. Opt. Phys.* **33** 1149 (2000)

# $Q_T$: comparison between UCL data and theory



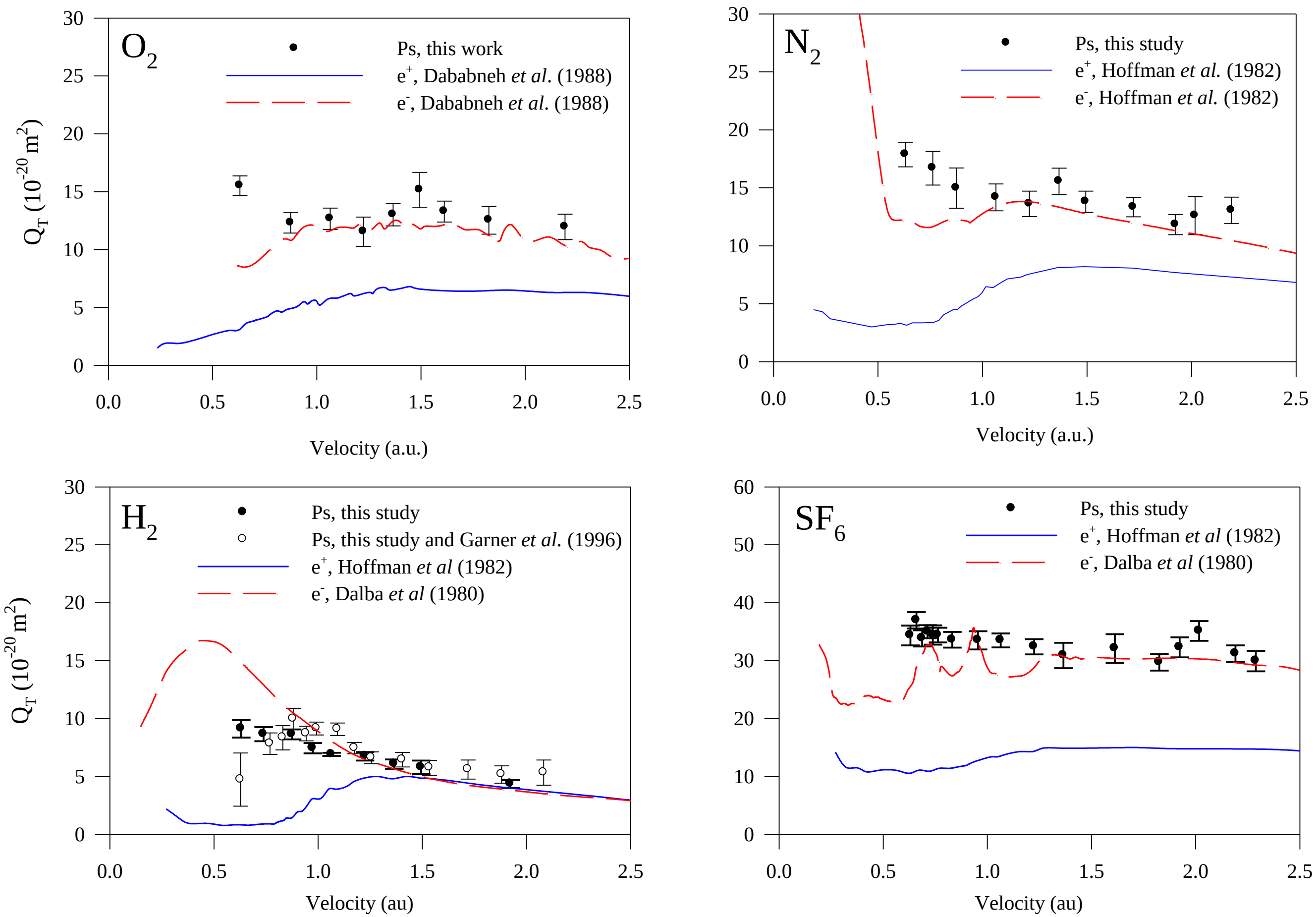



# $Q_T$: comparison of *equivelocity* $e^-$, $e^+$ and Ps scattering: **atoms**



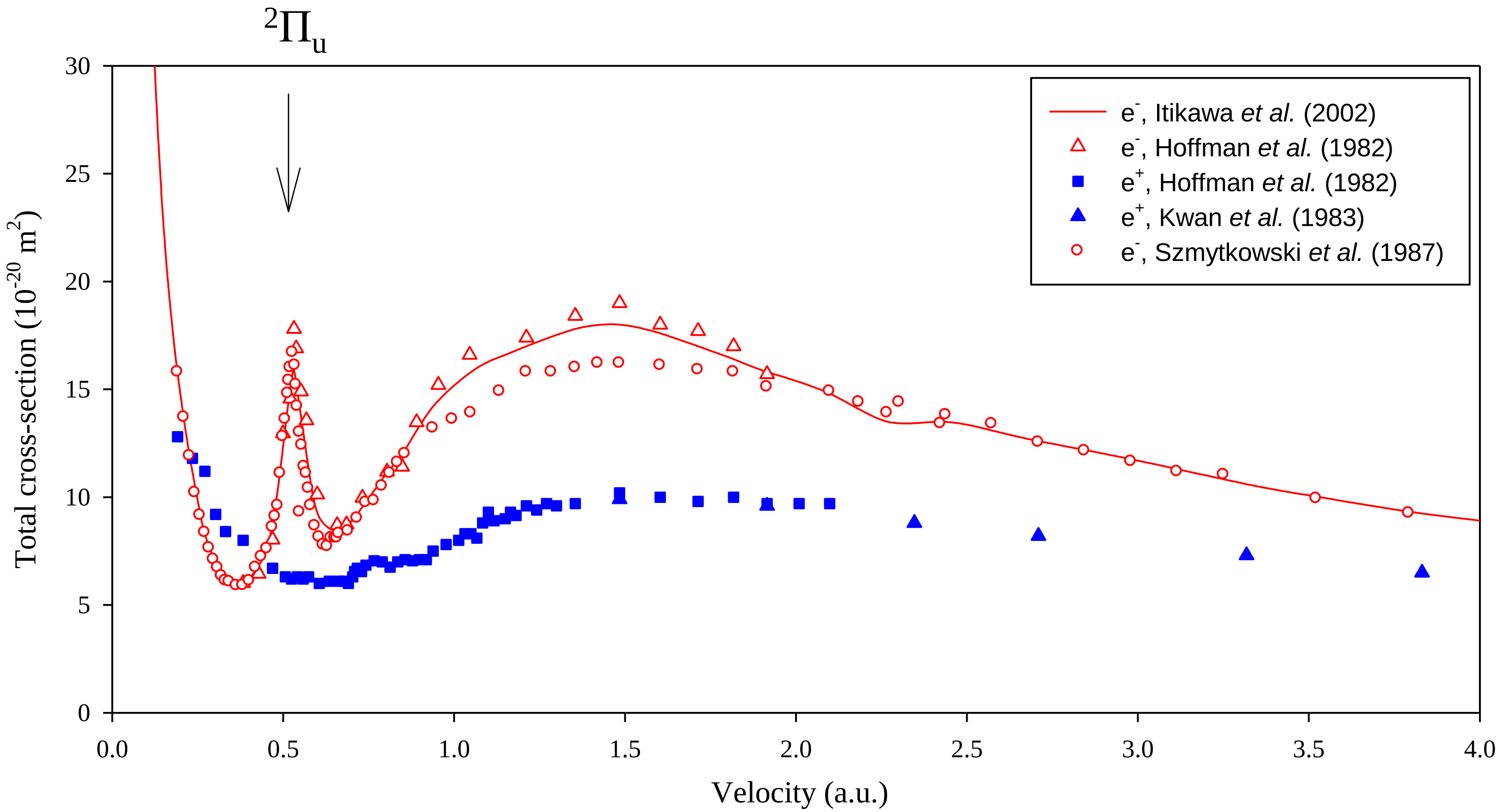

Brawley *et al.* Science **330** (2010). Key: – – –, electrons; ——, positrons; •, Ps.

# $Q_T$: comparison of *equivelocity* $e^-$, $e^+$ and Ps scattering: **molecules**



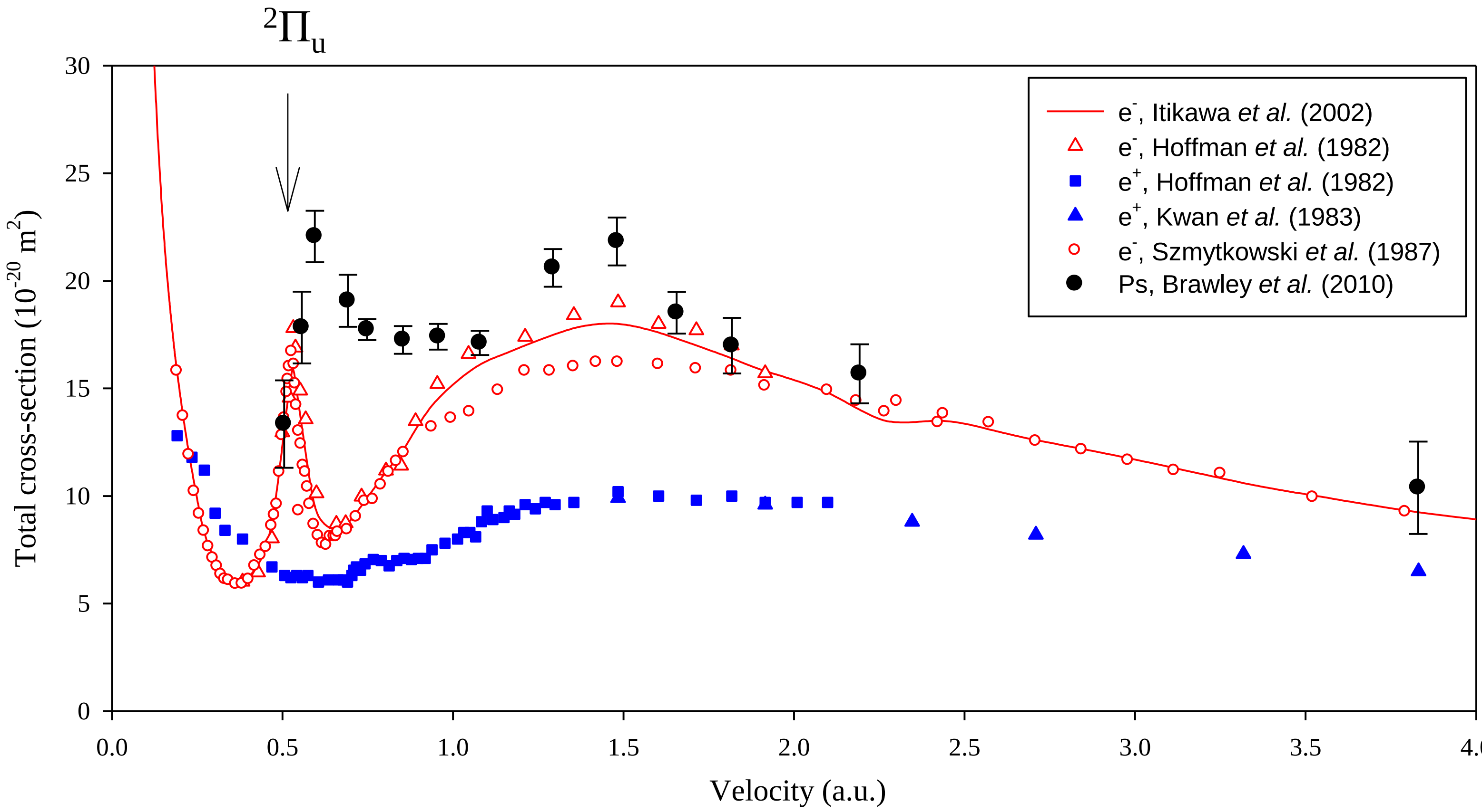

Brawley *et al.* Science **330** (2010). Key: – – –, electrons; ——, positrons; •, Ps.

# $Q_T$ ($e^-$, $e^+$ + $CO_2$)



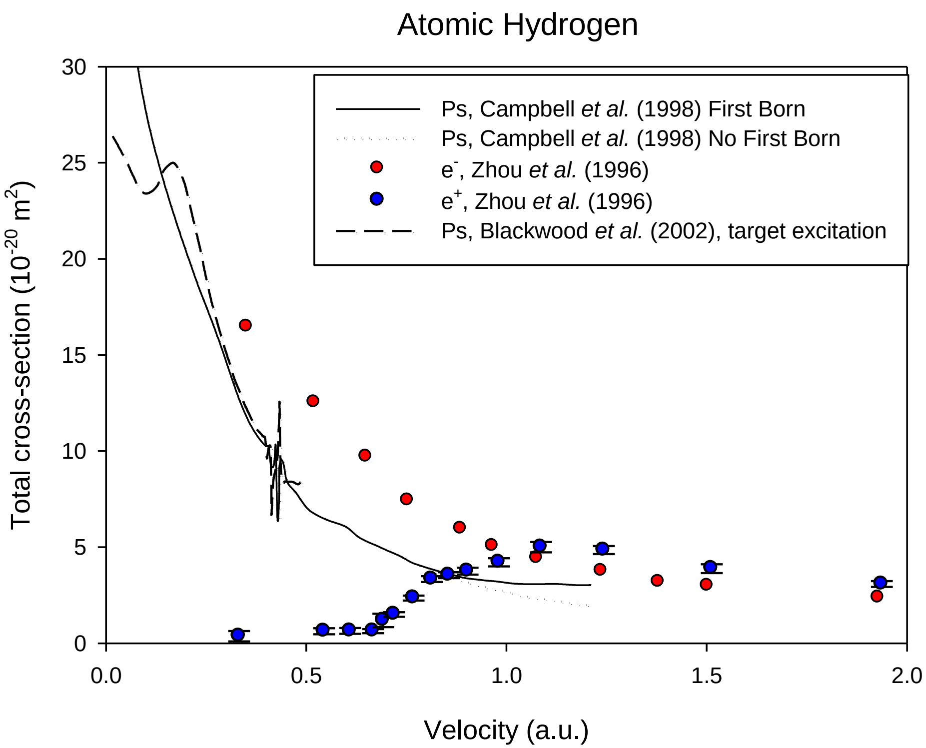
$^2\Pi_u$
30
25
20
15
10
5
0
Total cross-section ($10^{-20}$ m$^2$)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Velocity (a.u.)
e$^-$, Itikawa *et al.* (2002)
e$^-$, Hoffman *et al.* (1982)
e$^+$, Hoffman *et al.* (1982)
e$^+$, Kwan *et al.* (1983)
e$^-$, Szmytkowski *et al.* (1987)

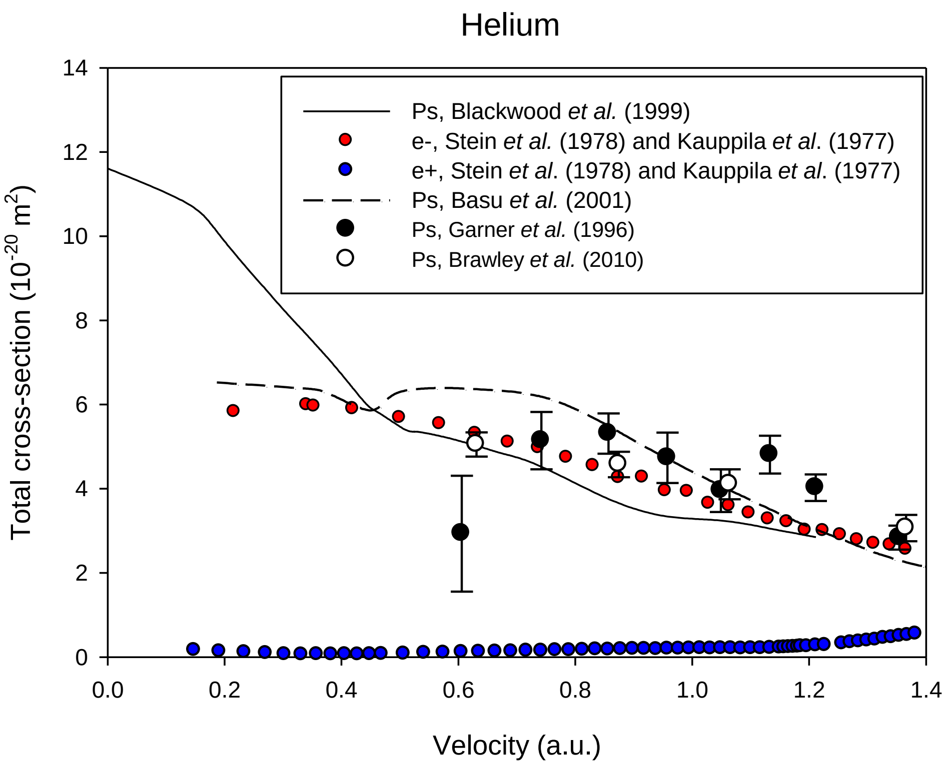
# $Q_T$ ($e^-$, $e^+$ + $CO_2$)




Brawley *et al. Phys. Rev. Lett.* **105** (2010)

# $Q_T$: comparison of $e^-$, $e^+$ measurements and Ps theory:




Brawley *et al. J. Phys. Conf. Ser.* (2012)

# Conclusion: positrons

## atoms:

- $\dfrac{(Q_{\mathrm{Ps}})_{\max}}{Q_T} \approx (30-60)\%$ ;
- $\dfrac{Q_{Ps}(2\mathrm{P})}{Q_{\mathrm{Ps}}(\mathrm{all\ n})} \approx (6-20)\%$ increase from He to Xe.

## molecules:

- $Q_{\mathrm{Ps}}$ is significant up to several hundred eV;
- $\dfrac{(Q_i^{ex})_{\max}}{Q_T} \approx 20\%$ for $N_2$ and $CO_2$.

# Conclusion: positronium

- Ps appears to scatter like a heavy electron;
- Structure observed in total cross–section for Ps scattering from $CO_2$;
- $\frac{\left(Q_f^+\right)_{\max}}{Q_T} \approx 40\%$, i.e. a significant contribution to $Q_T$.

# Outlook

- Investigation of Ps $Q_T$ for other targets which display resonances for electron impact;
- Extend measurements of $Q_i^{ex}$ to other molecules;
- Look at reaction products, including ions, at resonant velocities for Ps.

# Acknowledgements

We would like to thank:

Mr. John Dumper and

Mr. Rafid Jawad

for their technical support, EPSRC for supporting this work (under grant number EP/J003980/1), and the organisers of this conference.