First Observation of long–lived $\mu p(\mathbf{2s})$

Lifetime and population of $\mu p(\mathbf{2s})$

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PSI

- Why μp(2S)?
- Measurement of the initial kinetic energies of μp(1S)
- First observation of μp(2S),
  First observation of new quenching mechanism
- Outlook: Laser resonance experiment

F.J. Hartmann [1], P. Hauser [2], F. Kottmann [3], G. LLosá [2],
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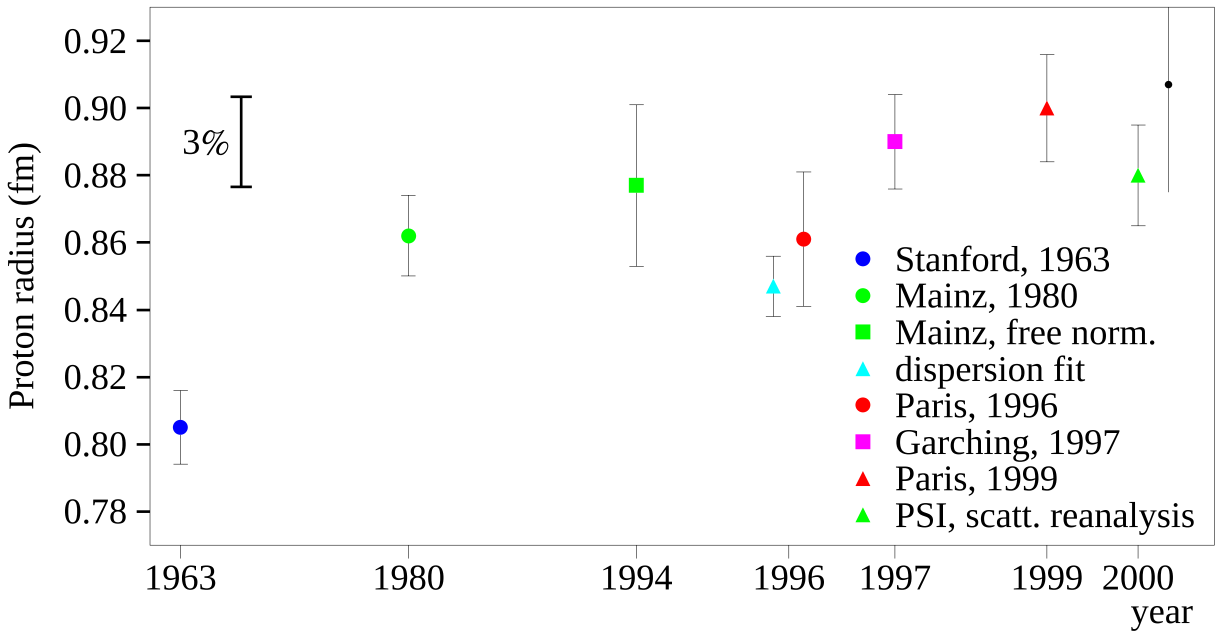
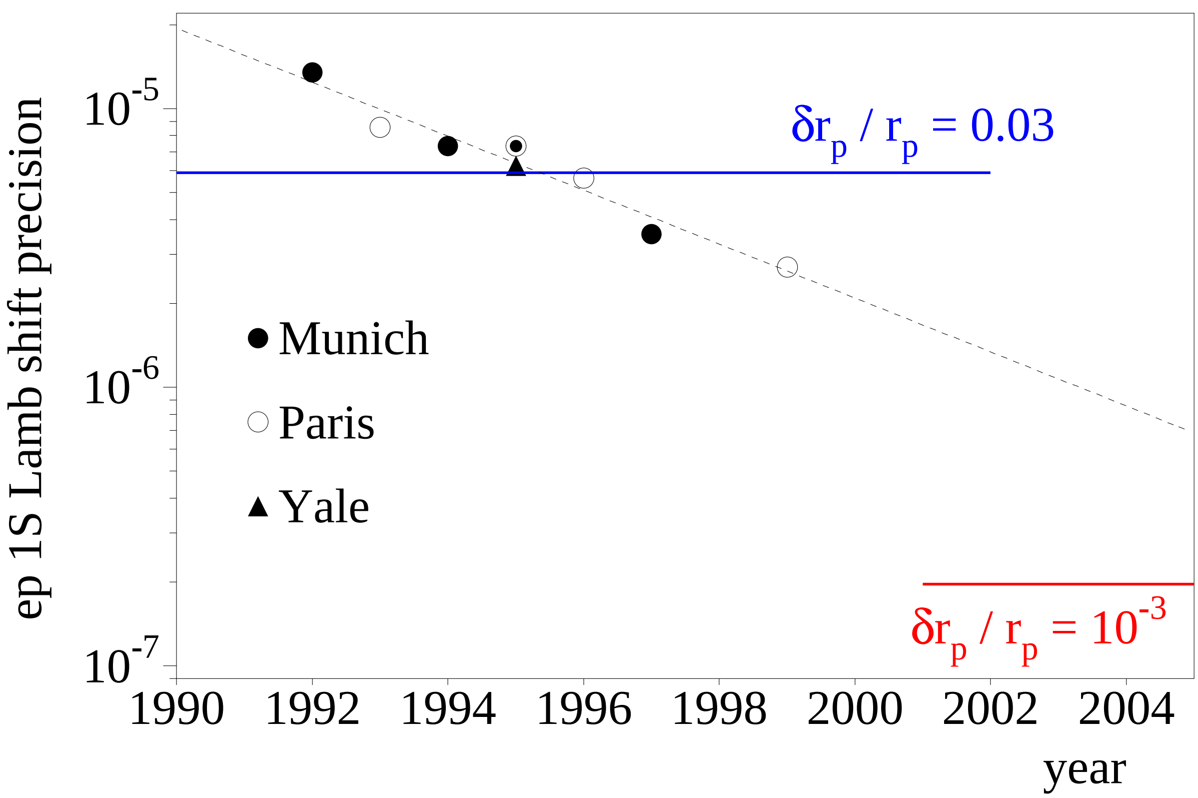
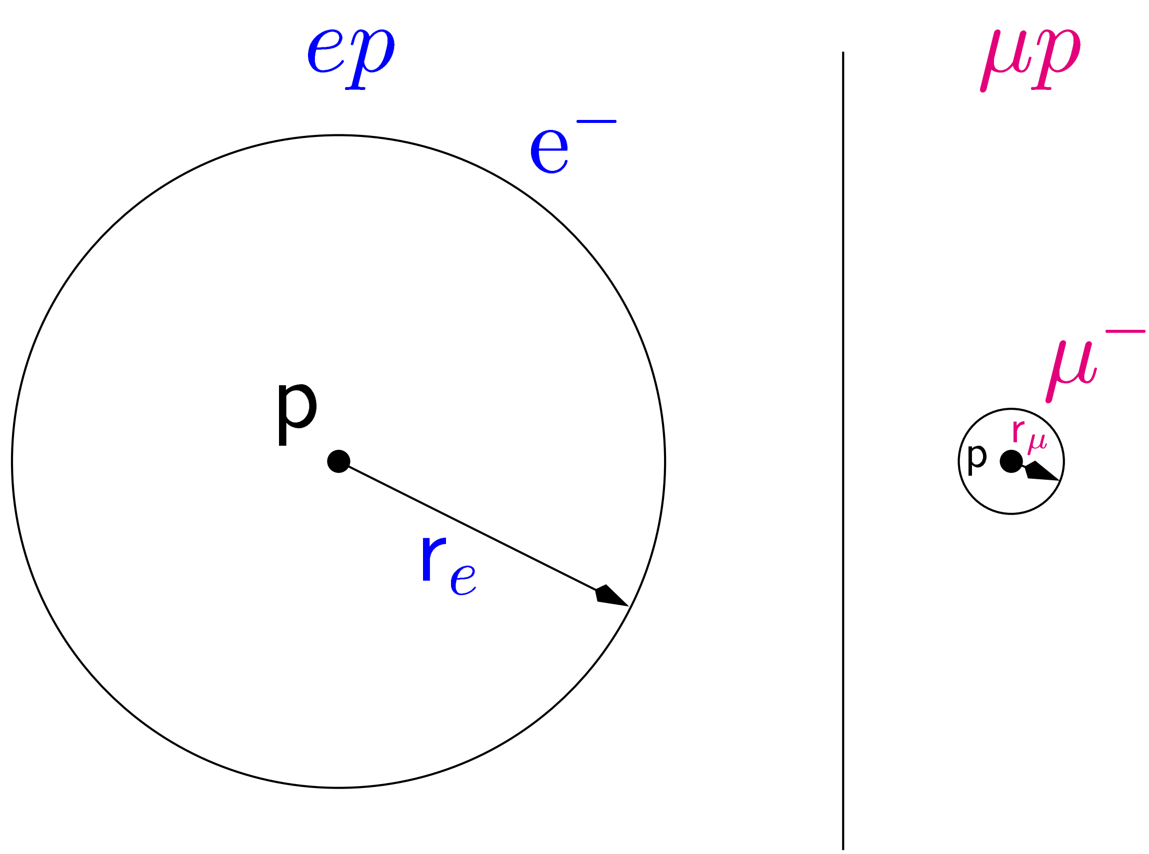
The Proton Radius





Electronic and Muonic Hydrogen

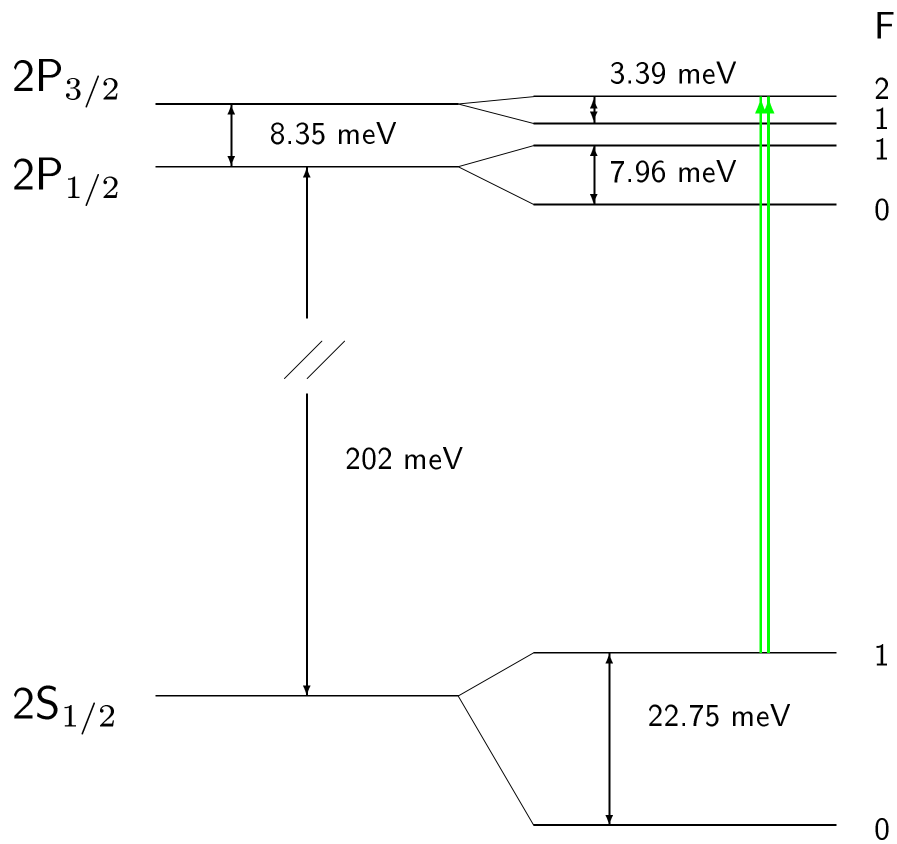


$$r_{ep} \sim 5{\cdot}10^{-11} \text{ m} \qquad r_{\mu p} \sim 3{\cdot}10^{-13} \text{ m}$$

$$r_p \sim 10^{-15} \text{ m}$$

$$m_\mu \cong 200 \cdot m_e \quad \Longrightarrow \quad r_{\mu p} \cong \frac{r_{ep}}{200}$$

Lamb Shift in Muonic Hydrogen



$$\Delta E_{(2S-2P)} = 210.005(6)\,\text{meV} - 5.166\,\text{meV fm}^{-2} \cdot r_p^2$$

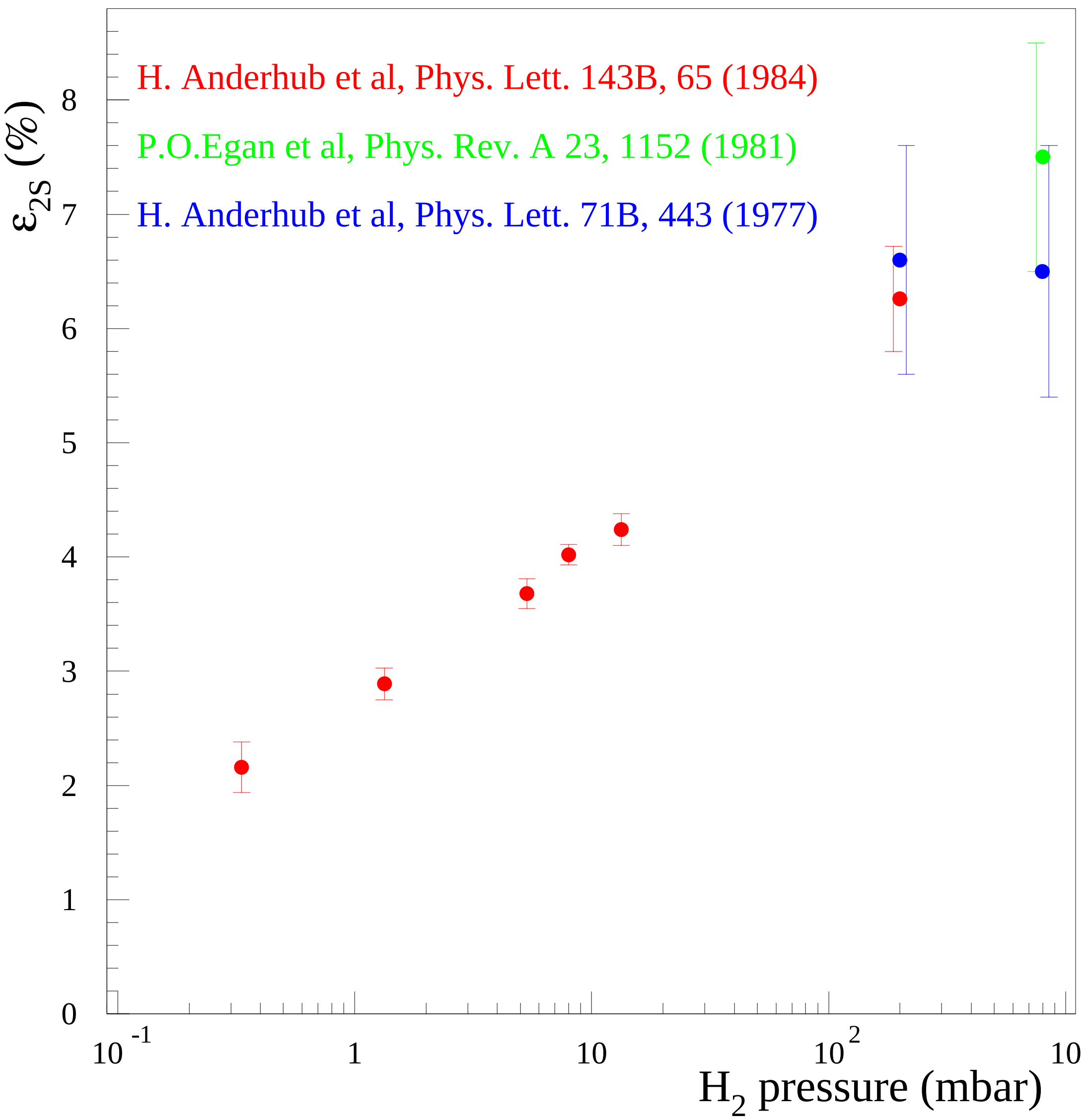
$$= 206.167(107)\,\text{meV}$$

$$\lambda = \frac{hc}{\Delta E} \sim 6.02\,\mu\text{m}$$

Initial μp(2S) population

The relative population ϵ_{2S} of the metastable 2S–state can be calculated from the measured K–line intensity ratios:

$$\epsilon_{2S} = 0.134\frac{I(K_\beta)}{I(K_{tot})} + 0.144\frac{I(K_{>\beta})}{I(K_{tot})}$$



Lifetime of the μp(2S) atom

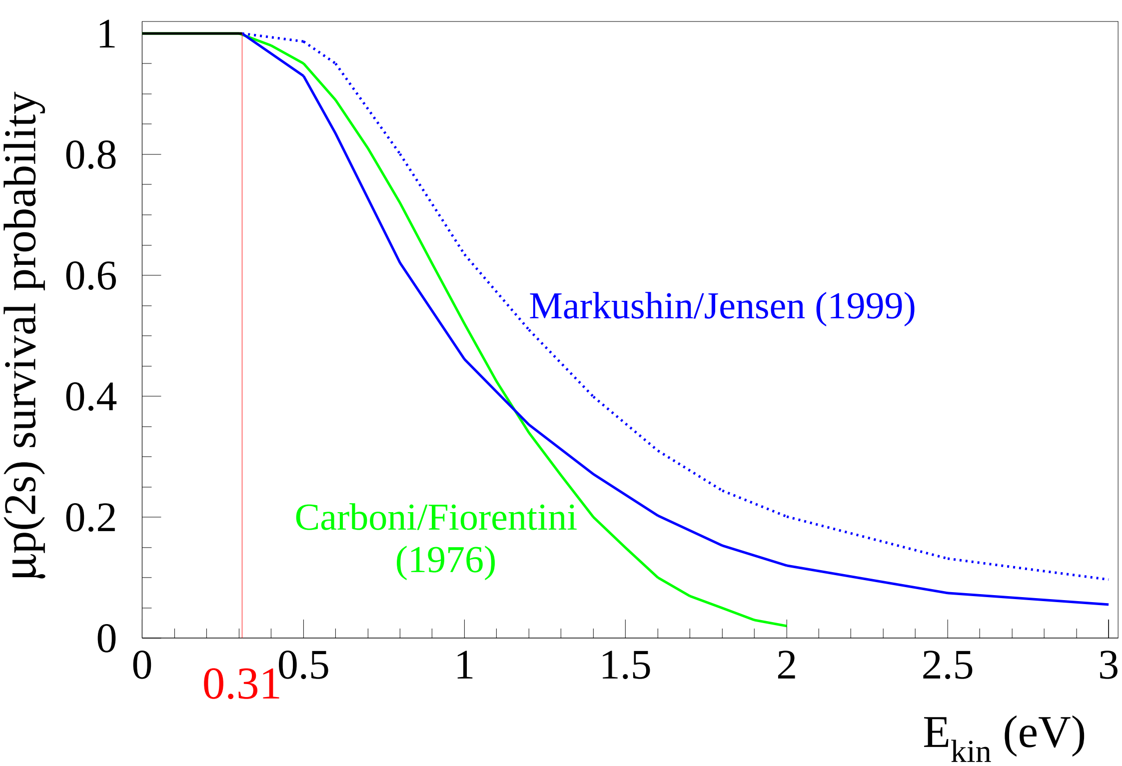
– μp(2S) in vacuum: $\tau \cong \tau_\mu = 2.2\ \mu s$

– μp(2S) in H_2 gas: collisional quenching

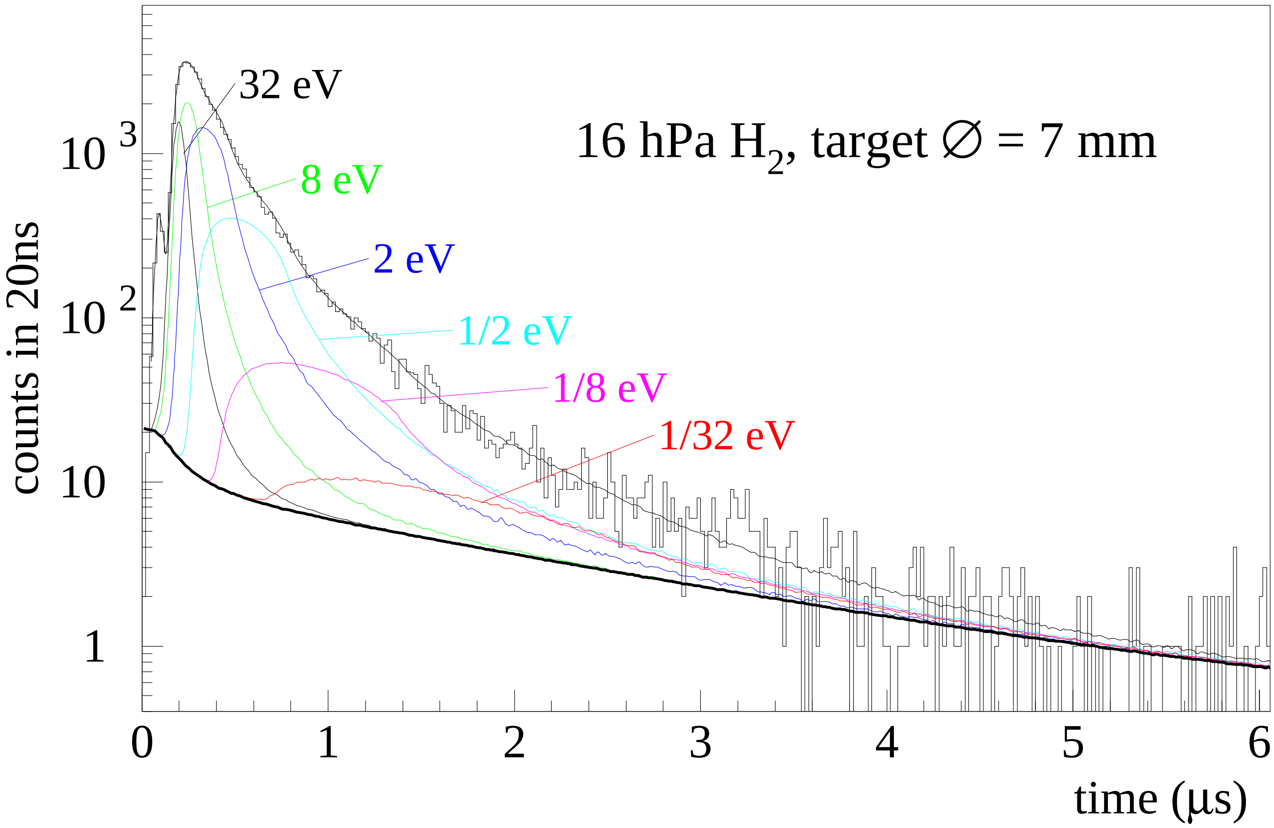
$$\mu p(2S) \quad + \quad H_2 \quad \rightarrow \quad \mu p(2P) \quad + \quad H_2$$
$$\Downarrow$$
$$\mu p(1S) \quad + \quad K_\alpha \text{ at 2 keV}$$

Energy threshold: $\Delta E^{lab}(2S \rightarrow 2P) = 0.31$ eV

Long–lived μp(2S) population: $\tau \geq 1\ \mu s$.



μp time–of–flight measurement



Stop muons on axis of cylindrical H_2 gas target

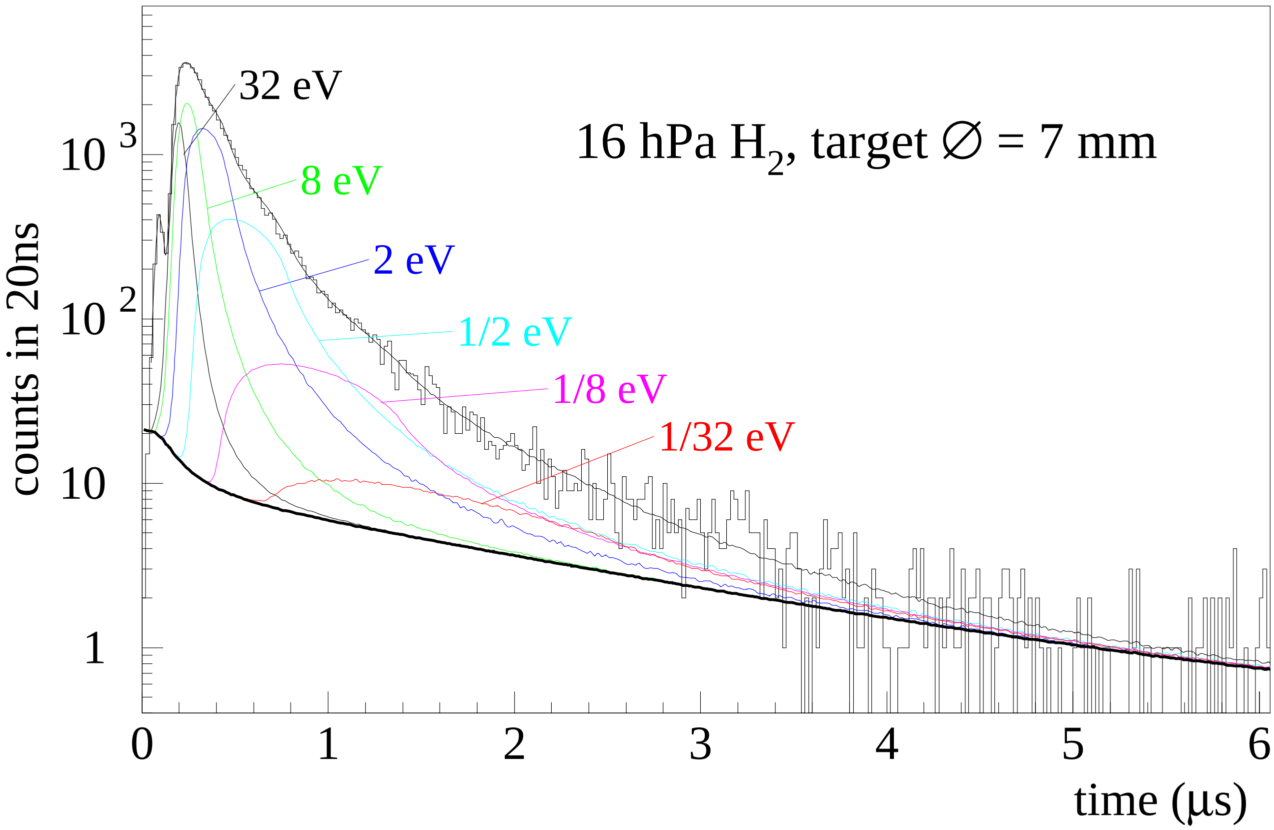
Time spectrum of μp arrival at walls (μAu)

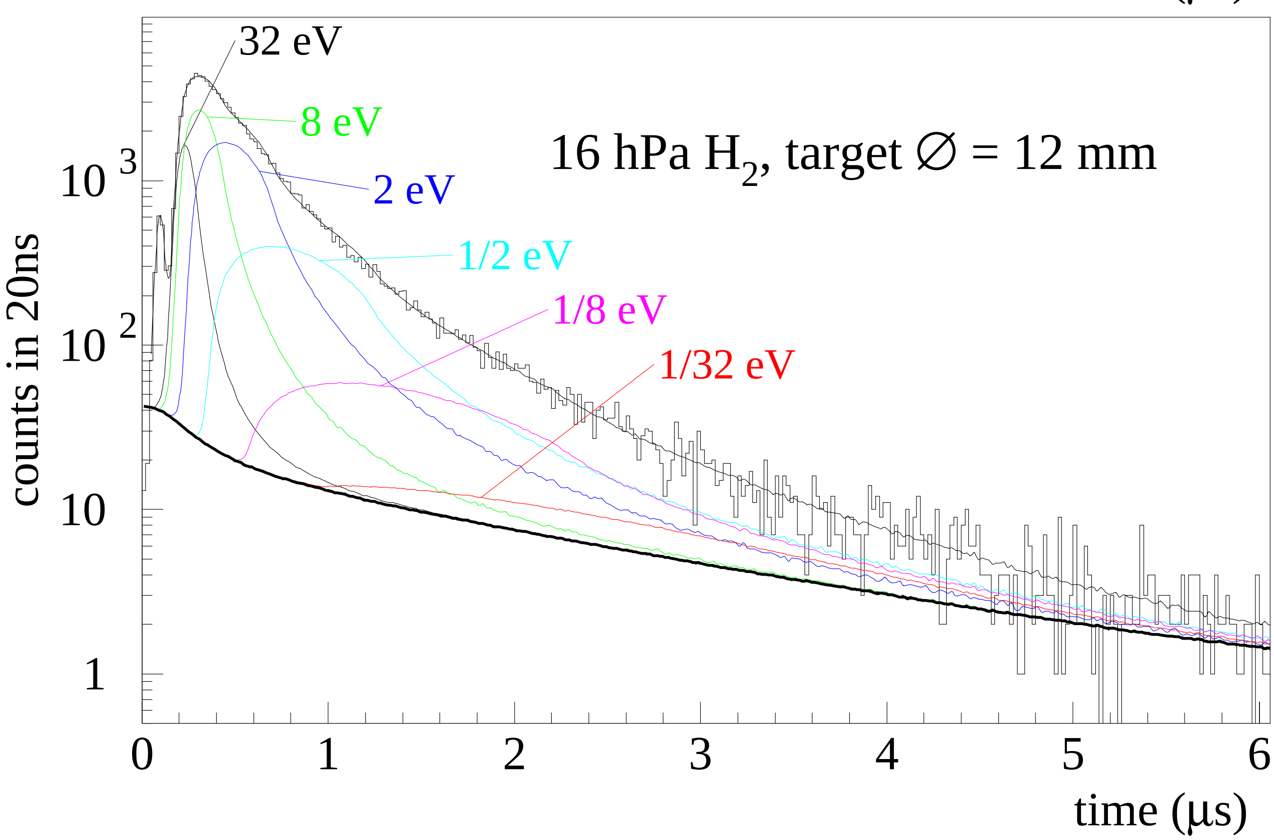
Monte Carlo simulations for single initial E_{kin}

Fit weights to measured spectra

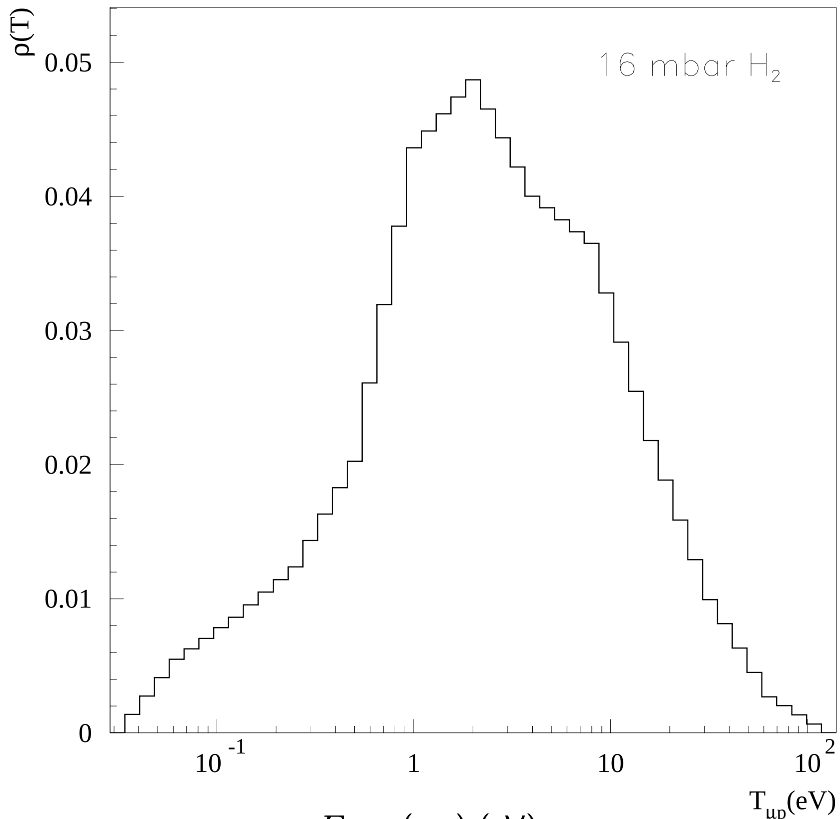
$\Rightarrow$ Initial kinetic energy distributions

μp time–of–flight measurement II





Kinetic Energy of μp atoms



$E_{kin}(\mu p)$ (eV)

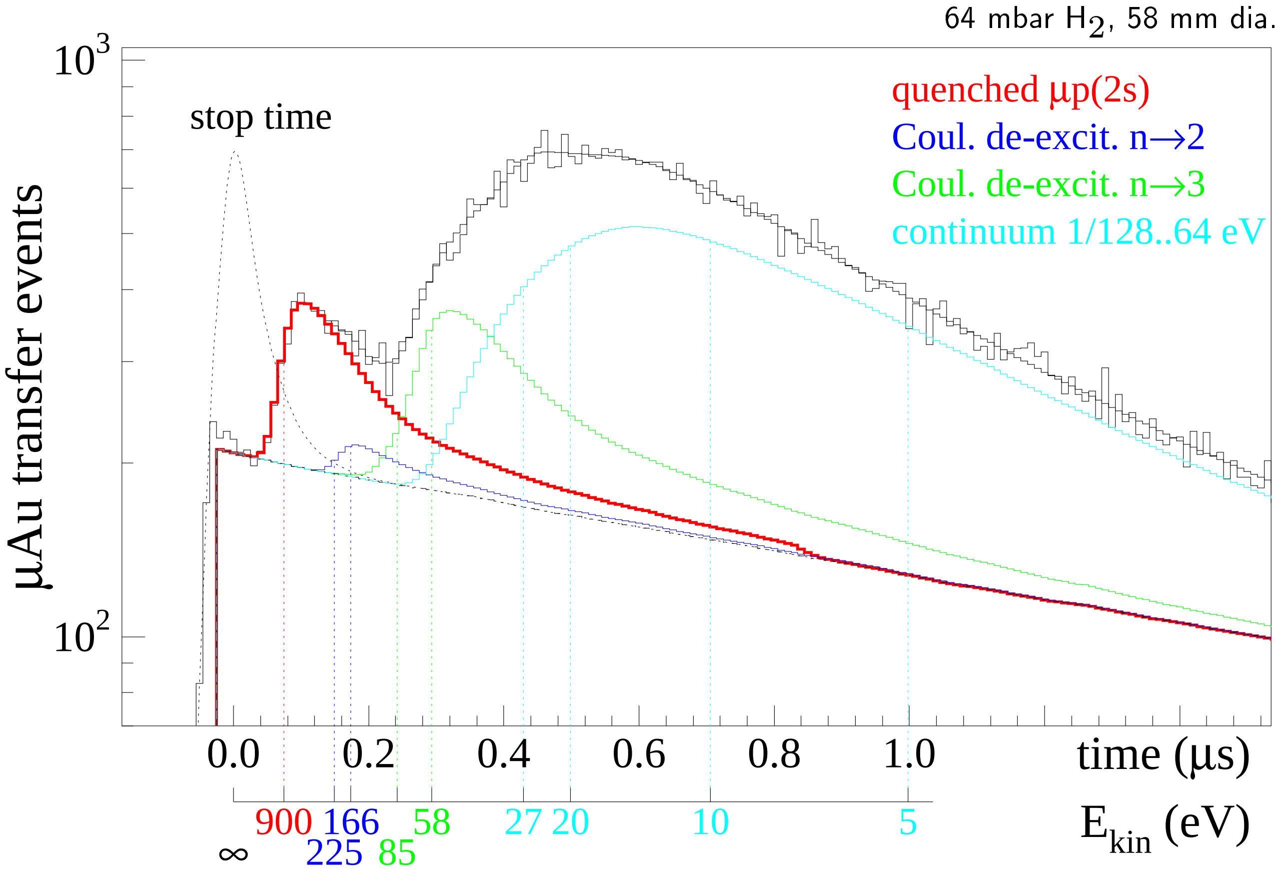
Pressure (mbar)	f_{2S} (%) ([1], m=H$_2$)	ϵ_{2S} (%) [2]	long-lived 2S (%)
0.25	67.8 ± 2.5	1.97 ± 0.12	1.34 ± 0.10
1.0	57.0 ± 3.4	2.78 ± 0.10	1.58 ± 0.11
4.0	45.5 ± 3.3	3.59 ± 0.12	1.63 ± 0.13
16.0$^{(1)}$	33.4 ± 6.8	4.40 ± 0.17	1.47 ± 0.31
16.0$^{(2)}$	32.1 ± 2.4	4.40 ± 0.17	1.41 ± 0.12

(1) 20 and 58 mm target diameter, (2) 7 and 12 mm target diameter.

[1] T. Jensen and V.E. Markushin, PSI-PR-99-32, nucl-th/0001009.

[2] H. Anderhub et al., Phys. Lett 143B (1984) 65.

Direct observation of μp(2s)



Early times: Fast μp(1s) with $E_{kin} \sim 1$ keV

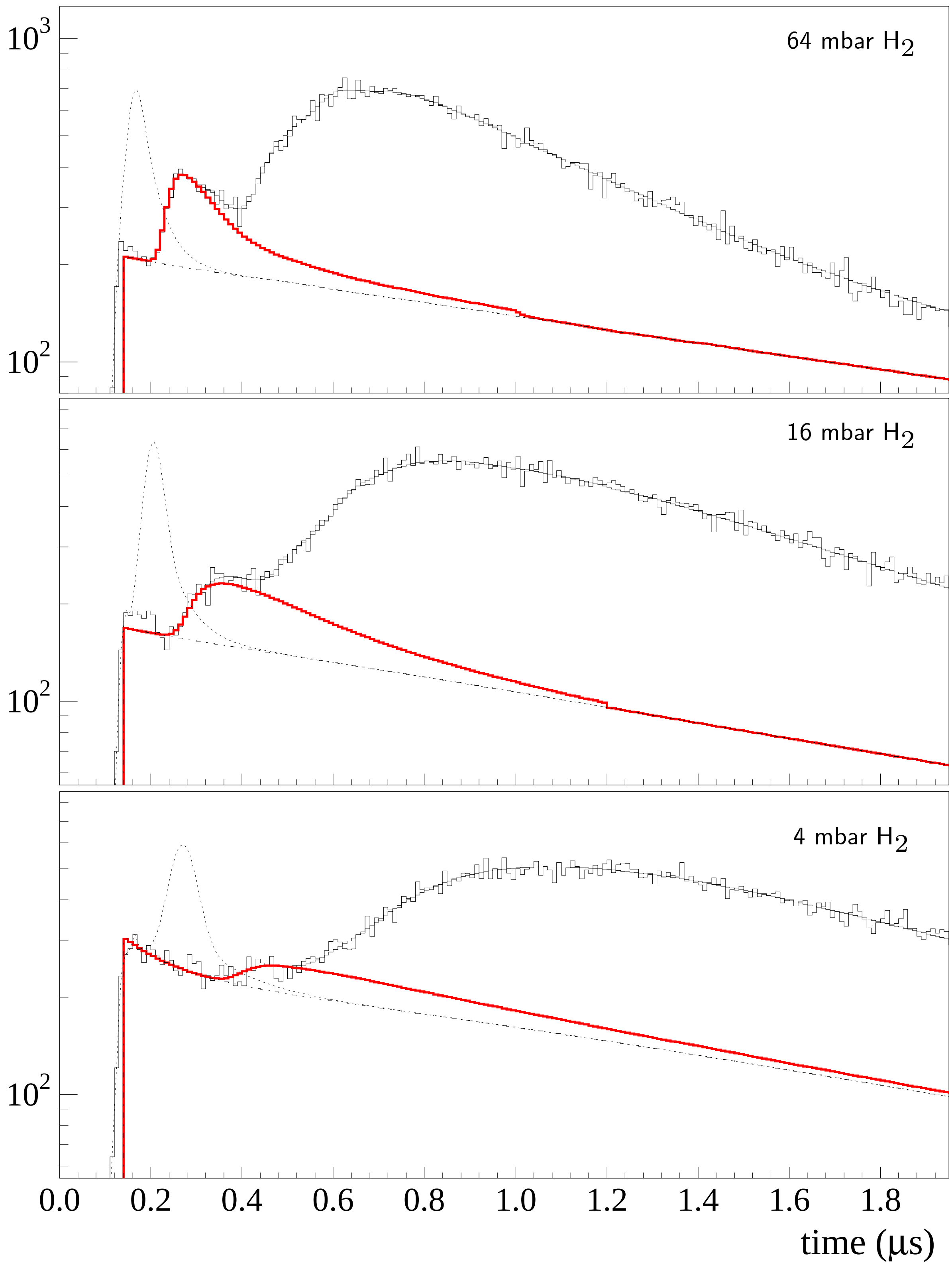
Origin: μp(2s) are quenched via the resonant process

$$\mu p(2s) + H_2 \quad \rightarrow \quad \{[(pp\mu)^+]^* \quad pee\}^*$$
$$\Downarrow$$
$$\mu p(1s) + p \quad + \ldots + 2 \text{ keV}$$

P.Froelich and A.Flores-Riveros, *Phys. Rev. Lett.* **70**, 1595 (1993)

Lifetime of μp(2s) shortened, proportional to pressure.

Lifetime of $\mu p(2s)$ vs. pressure



μp(2s) quenching mechanism

- Previously believed: $E_{\rm kin}(\mu p(2s)) \leq 0.31$ eV:

  radiative quenching (slow), only during a collision

- Well-known for μp(1s): Vesman mechanism:

  $\mu p(1s) + H_2 \rightarrow \{[(pp\mu)^+]^* pee\}^*$

E.A.Vesman, *Pis´ma Zh. Eksp. Teor. Fiz.* **5**, 113 (1967)
[*JETP Lett.* **5**, 91 (1967)]

- Now: Resonant molecule formation also for μp(2s)
  - Weakly bound states close to μp(n=2)
    $\Rightarrow$ excess energy efficiently absorbed by rotational/ vibrational motion of molecule
  - Final state is in continuum above dissociation limit $\mu p(n=1) + p \Rightarrow$ fast autodissociation

S.Hara, T.Ishihara, *Phys. Rev.* **A40**, 4232 (1989)
I.Shimamura, *Phys. Rev.* **A40**, 4863 (1989)
P.Froelich, A.Flores-Riveros, *Phys. Rev. Lett.* **70**, 1595 (1993)
P.Froelich, J.Wallenius, *Phys. Rev. Lett.* **75**, 2108 (1995)
J.Wallenius, P.Froelich, *Phys. Rev.* **A54**, 1171 (1996)
S.Jonsell, J.Wallenius, P.Froelich, *Phys. Rev.* **A59**, 3440 (1999)

Conclusions

– 1^{st} direct observation of metastable μp(2s)

– 1^{st} direct evidence for new cascade process

$$\begin{array}{lcl} \mu p(2s) + \mathrm{H}_2 & \rightarrow & \{[(pp\mu)^+]^* \quad pee\}^* \\ & & \quad\Downarrow \\ & & \mu p(1s) + p \quad + \ldots + 2\ \mathrm{keV} \end{array}$$

– consistent results on 2s population from

* Low–energy part of μp(1s) kinetic energy distribution and '2s survival probability'
* High–energy component from μp(2s) quenched via resonant molecule formation with H_2

– 2s population ($\sim 1.5\%$) and lifetime ($\sim 1\mu$s at low pressure) suitable for laser experiment.

– Technical developments underway, laser experiment to start next year.

Outlook

- Availability of long–lived metastable μp(2S)
  First direct observation!

- Technical advances in muon beam:
  higher μ^- stop rate in a small volume of a few mbar H_2
  Test run with electrons in June 2000: works.
  First pion/muon beam in Nov. 2000.

- 2 keV X–ray detector: MSGC based GPSC available
  Prototype # 1 tested in 5 Tesla field: works.
  # 2 waiting for muonic K–x-rays (Nov. 2000)
  Improved prototype # 3 under construction.

- Laser: all components realized already
  Dye laser under construction at PSI.
  Ti:Sa constructed in Paris: works.
  Raman cell on its way to Paris.

- Experiment to start in 2001:

  ◇ measure ΔE (2 $S_{1/2}$(F=1) - 2 $P_{3/2}$(F=2))
  ◇ event rate : 9 per hour on resonance
  ◇ split line to 1/10
  ◇ proton radius to 10^{-3}

Calculation of $\Delta E_{2S-2P}(\mu p)$

Contribution	Value (in meV)
Leading order VP	205.006
Relativistic correction to VP	0.059
Double VP	0.151
Two–loop VP	1.508
Three–loop VP	0.008
Hadronic VP	0.011
Muon self–energy and VP	-0.668
Muon self–energy with electron VP	-0.006
Recoil of order α^4	0.057
Recoil of order α^5	-0.045
Proton self energy	-0.010
VP with finite size	-0.021
Nuclear polarization	0.017(4)
$2S$ hyperfine structure: $-1/4 \cdot [22.745(15)]$	-5.686(4)
$2P_{3/2}$ hyperfine structure: $3.393 \cdot 3/8$	1.272
Fine structure	8.352
Lamb shift without r_p contribution	210.005(6)
Finite size effect $-5.166 \cdot r_p^2$	-3.838(107)
Total Lamb shift	206.167(107)

(values for the transition 2 $S_{1/2}$(F=1) – 2 $P_{3/2}$(F=2))

Finite size effect: $E = \frac{1}{12}\mu^3\alpha^4\langle r_p\rangle^2$