Laser spectroscopy of metastable pionic helium atoms at Paul Scherrer Institute

M. Hori[1,2], H. Aghai-Khozani[2], A. Sótér[2,3], D. Barna[4], A. Dax[5], L. Venturelli[6]
ASACUSA and PiHe collaborations

[1]Imperial College London
[2]Max-Planck Institute of Quantum Optics
[3]ETH Zurich
[4]CERN
[5]PSI
[6]INFN

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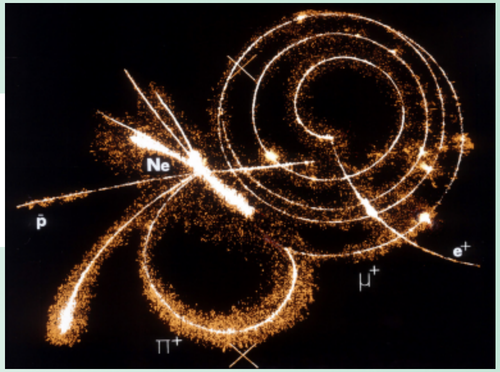
Fundamental three-body, long-lived Rydberg helium atoms

Antiprotons annihilate within 1 ps in normal matter except for the case of helium.

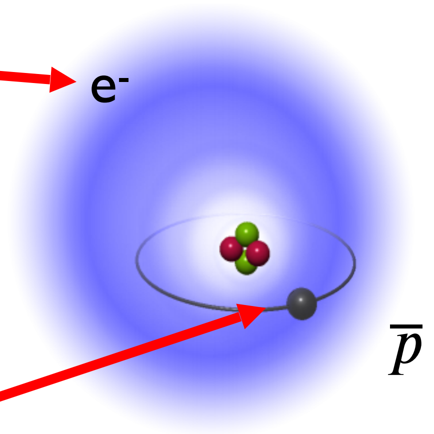
PS179 streamer chamber (1984)



Electron in 1s orbital. Attached with 25-eV ionization potential. Auger emission suppressed.

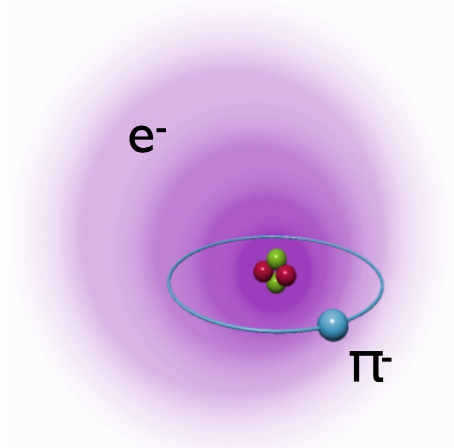
Antiproton in a circular Rydberg orbital n=38, l=n-1 with diameter of 100 pm.

- Localized away from the nucleus so that the antiproton escapes annihilation.
- The electron protects the antiproton during collisions with other helium atoms.
- Lifetime $\tau \approx 4$ to $10\ \mu$s, millions of times longer than other antiprotonic atoms.



$\bar{p}He^+$: metastable antiprotonic helium

CERN

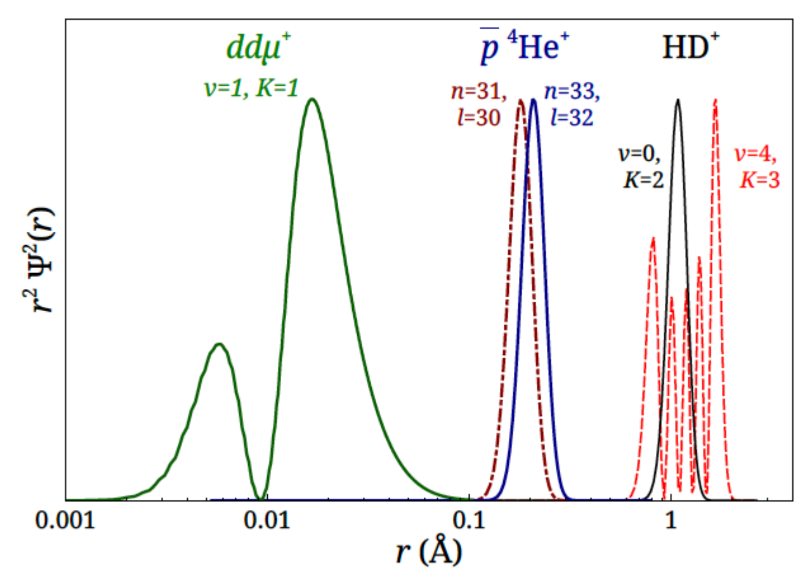


πHe^+: metastable pionic helium, Pion in n=17, l=16 orbital, $\tau \approx 7$ ns, 1000x longer than other atoms containing mesons

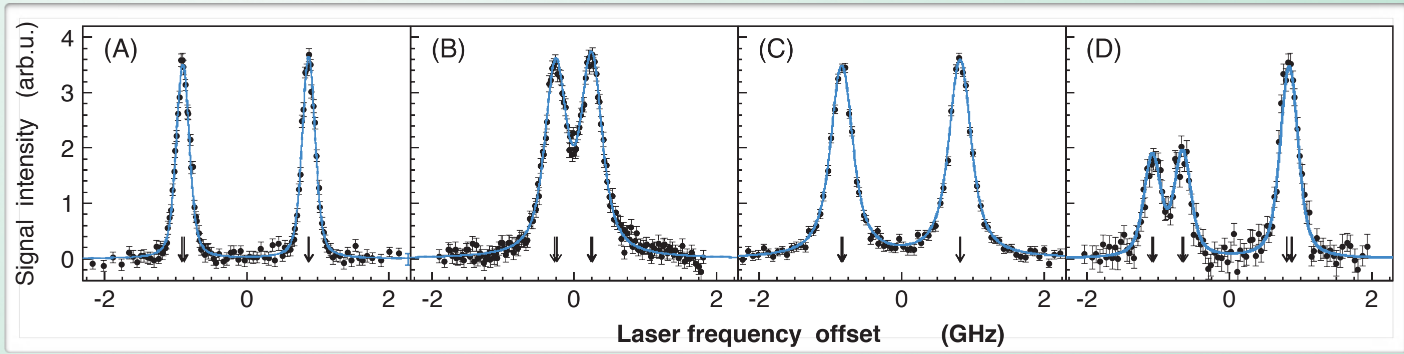
PSI

Antiprotonic helium atoms, the longest-living hadron-antihadron system known

- Laser spectroscopy probes the interaction V(r) at angstrom distances between antiproton, alpha particle, and electron.
- V(r) can be theoretically calculated to extraordinary precision 10^{-12} using the Standard Model of particle physics
- Same level of theoretical precision as two-body atoms like (anti)hydrogen (antihadron-antilepton system), but less sensitive to uncertainies due to the size of the nucleus.
- High sensitivity to physics: QED effects, antiproton-to-electron mass ratio, fifth forces, CPT symmetry

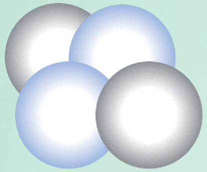


J. Mol. Phys. 300, 65 (2014)

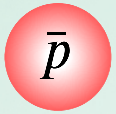


Science 354, 610 (2016)

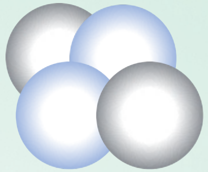
These exotic atoms are among the most precisely theoretically understood atoms/molecules



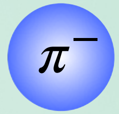
^{4}He
$s = 0$



$s = \frac{1}{2}$



^{4}He



$s = 0$

Energy levels of antiproton follows Dirac equation

$$\mathscr{L}_{QED} = \overline{\psi}\left(i\gamma^\mu\partial_\mu - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - q\overline{\psi}\gamma^\mu\psi A_\mu$$

No fine/hyperfine structure for pion, energy levels obey

Klein-Gordon equation $\mathscr{L} = \frac{1}{2}(\partial_\mu\phi)(\partial^\mu\phi) - \frac{1}{2}m^2\phi^2 +$

Antiproton two-photon transition (n,l)=(36,34)→(34,32)

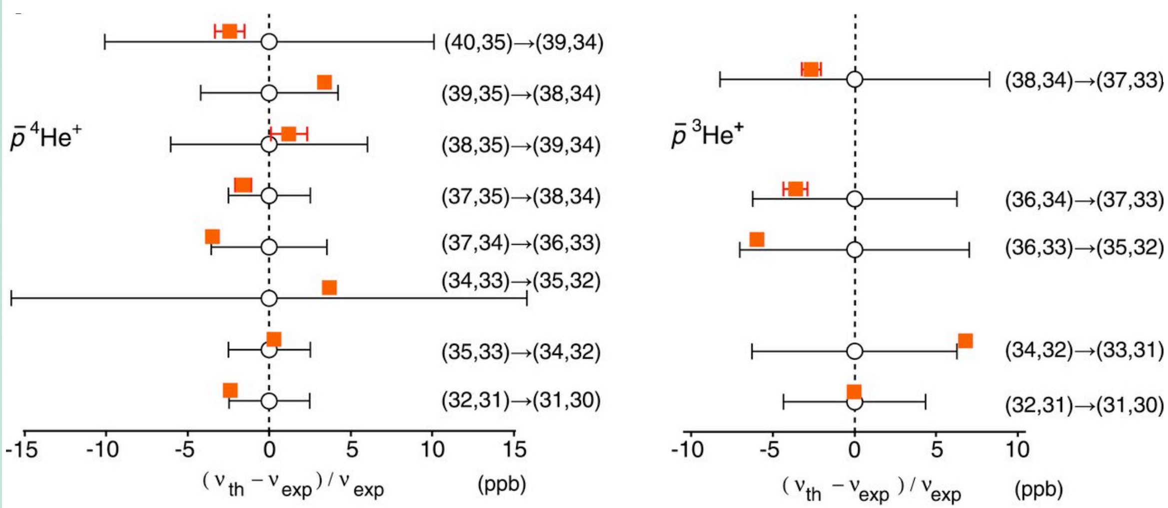
Non-relativistic energy	1 522 150 208.13 MHz
mα^4 order corrections	-50320.64
mα^5 order corrections	7070.28
mα^6 order corrections	113.11
mα^7 order corrections	-10.46(20)
mα^8 order corrections	-0.12(12)
Transition frequency	1 522 107 060.3(2)
Uncertainty alpha charge radius	+/-0.007
Uncertainty antiproton charge radius	$<$ 0.0007

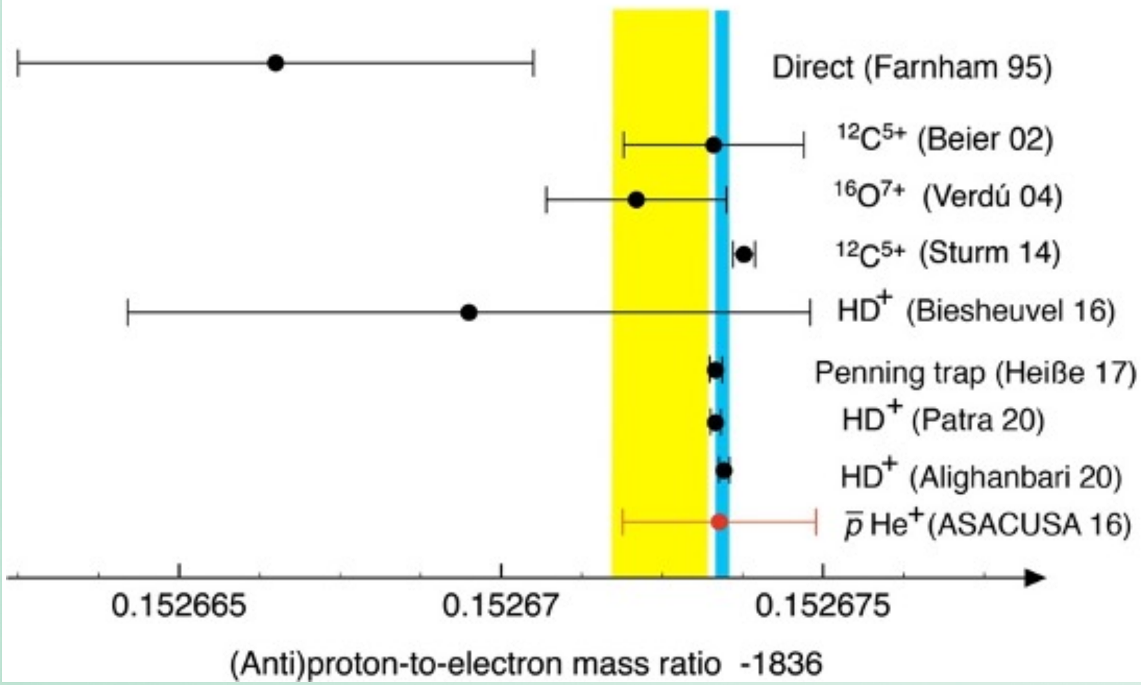
Korobov, Hilico, Karr, *Phys. Rev. Lett.* 112, 103003 (2014)

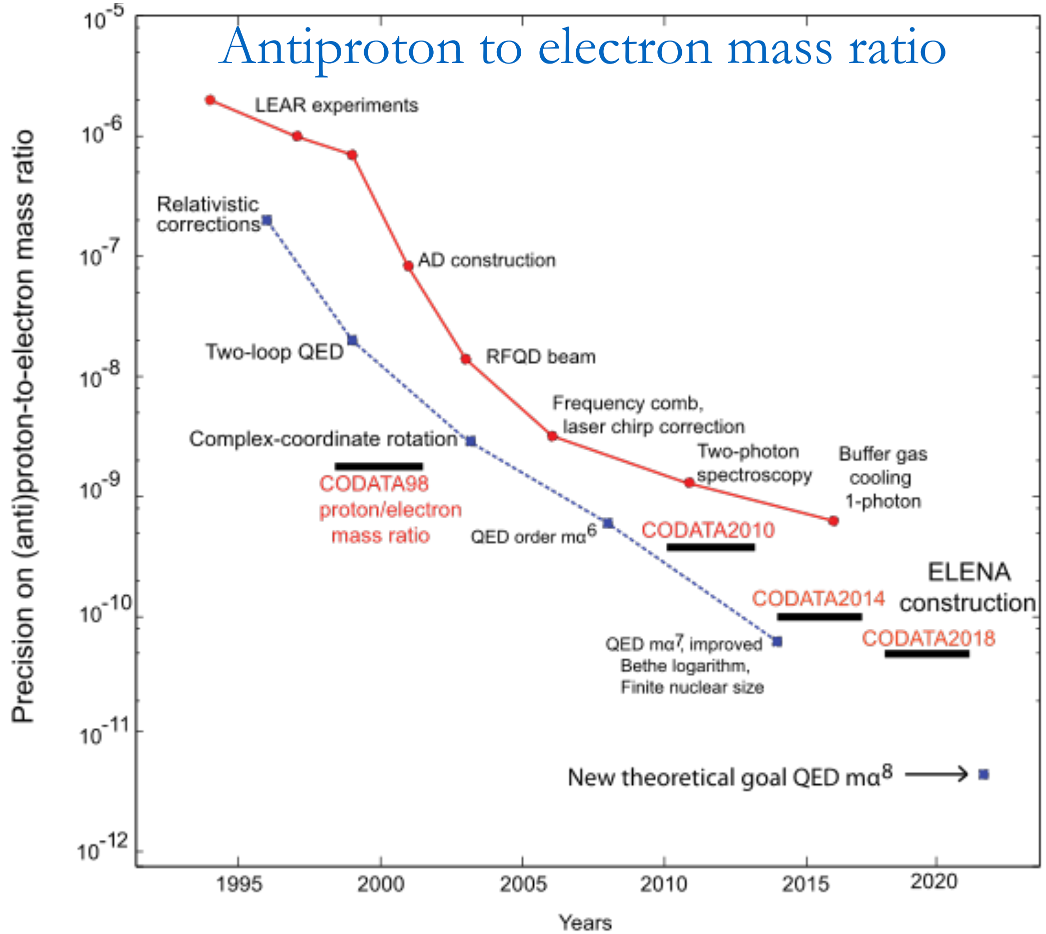
Pion transition (n,l)=(17,16)→(16,15)

Non-relativistic energy	1 125 369 104.121(7) MHz
mα^4 order corrections	-73281.2(9)
mα^5 order corrections	10376.5(5)
mα^6 order corrections	155.5(32)
mα^7 order corrections	-15.5(31)
Transition frequency	1 125 306 339.4(45)
Uncertainty from alpha charge radius	+/-0.006
Uncertainty from pion charge radius	$<$ 0.001

Z.-Da. Bai et al., *Phys. Rev. Lett.* 128, 183001 (2022)

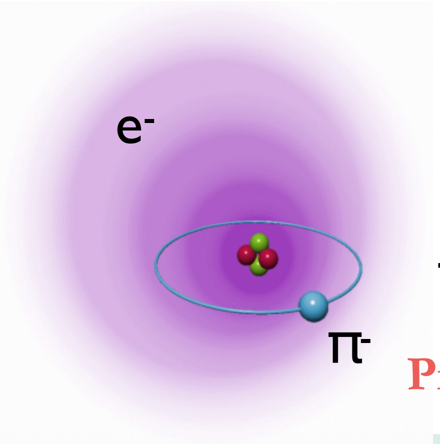


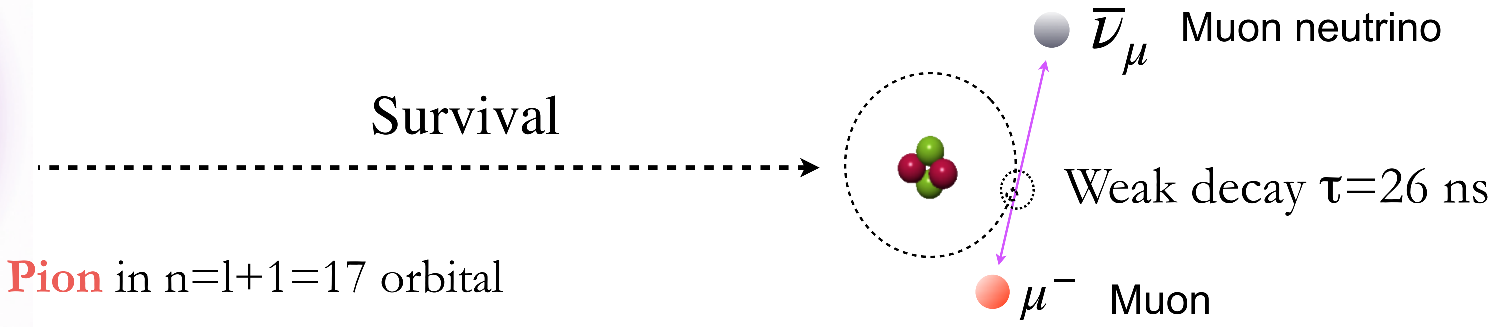




- 13 transitions precisely measured.
- Antiproton-to-electron mass ratio 1836.1526734 (15), Science 354, 610 (2016).
- We improved the precision from 2×10^{-6} to 8×10^{-10}. Further aim to improve to 10^{-12}

Physics motivation for pionic helium laser spectroscopy





- 1960's: Bubble chamber (Nobel prize 1960) experiments show π^- in helium survive for >0.3 ns.
- 1969: J.E. Russell suggest πHe^+ is too unstable to explain the experimental results: "The rate for atom with n=16 would make a direct experimental detection of pions trapped in these circular orbits exceedingly difficult".
- 2020: We achieved the first laser excitation and spectroscopy of an atom containing a meson.
- Constitutes definitive evidence for existence of three-body metastable πHe^+
- Energies obey Klein-Gordon equation (different kind of QED from normal atoms)
- Determination of the π^- mass at a level of $\leq 10^{-8}$ precision may in principle become possible.
- Upper limits on exotic forces coupling to mesons.
- Improvement on the direct laboratory limit of muon antineutrino ν_μ mass.
- Best value <1 eV obtained from neutrino oscillation.

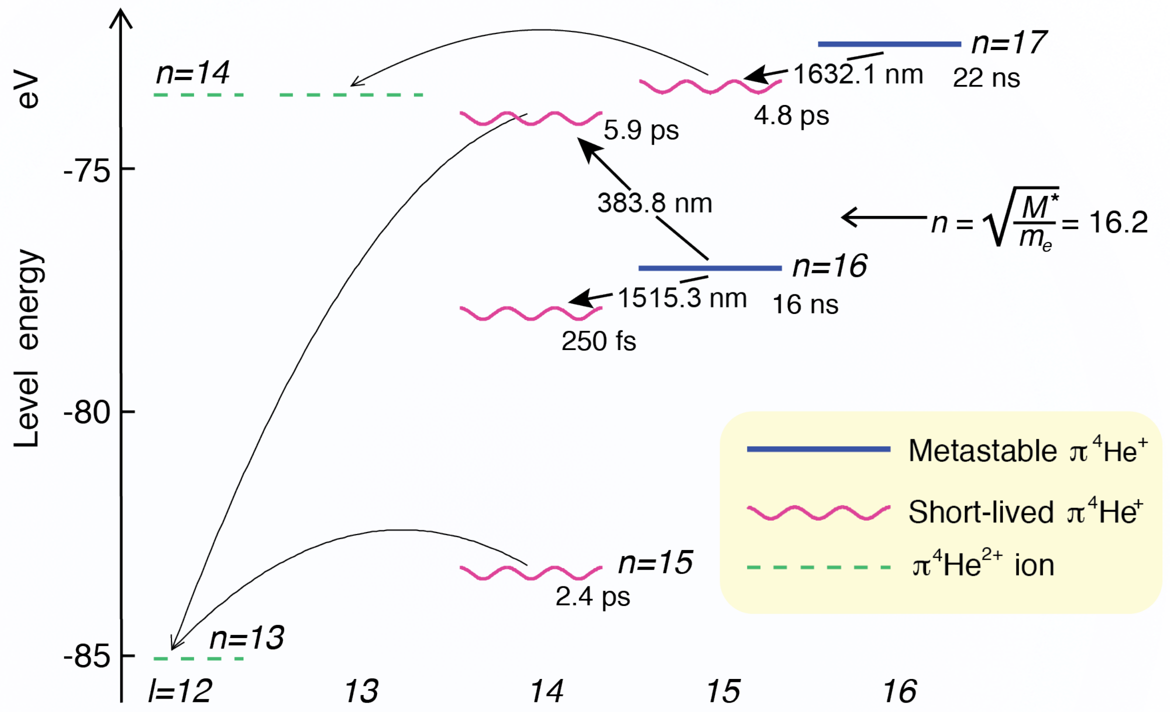
PRD 53, 6065 (1996).

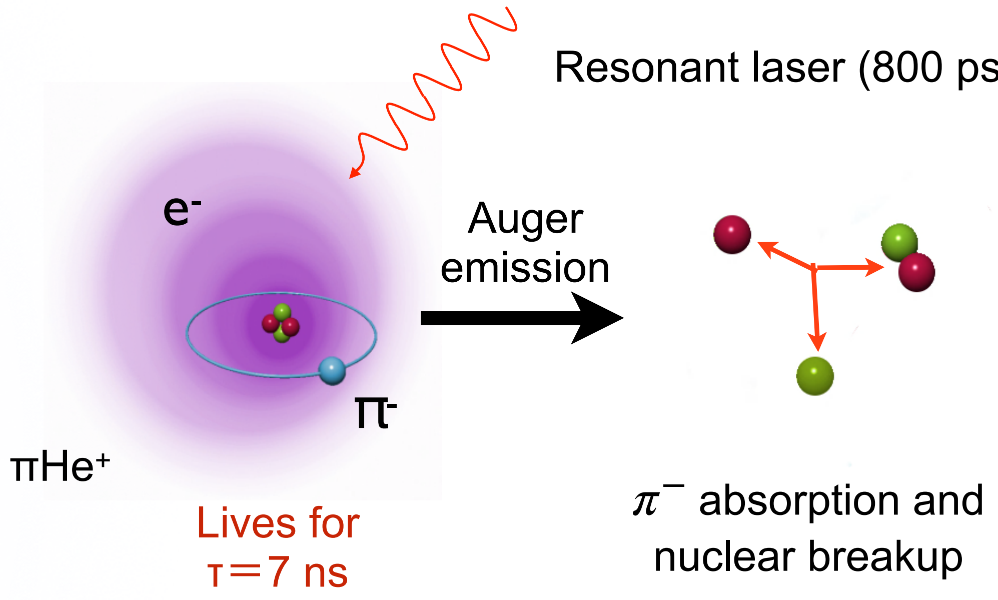
$$p_\mu^2 + m_\mu^2 = \left(m_\pi^2 + m_\mu^2 - m_{\nu\mu}^2\right)^2 / 4m_\pi^2$$

29.79200(11) MeV/c

105.6583668(38) MeV/c

Laser spectroscopy of πHe^+



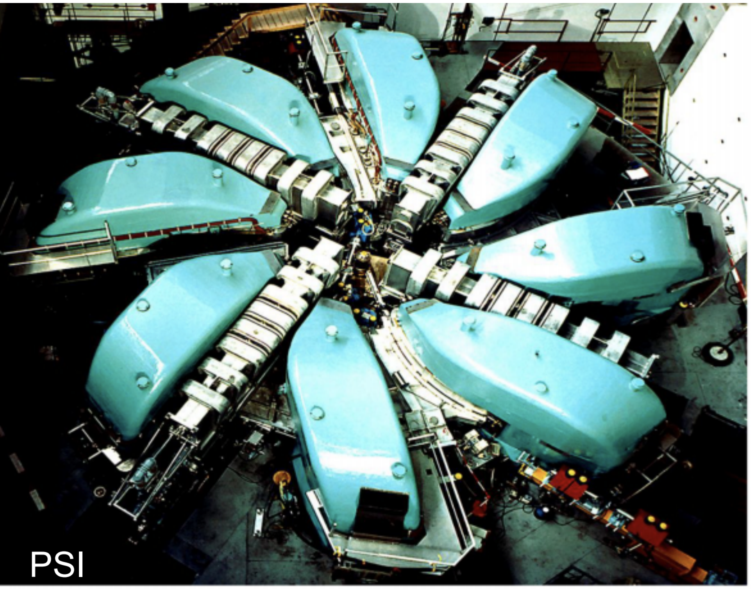


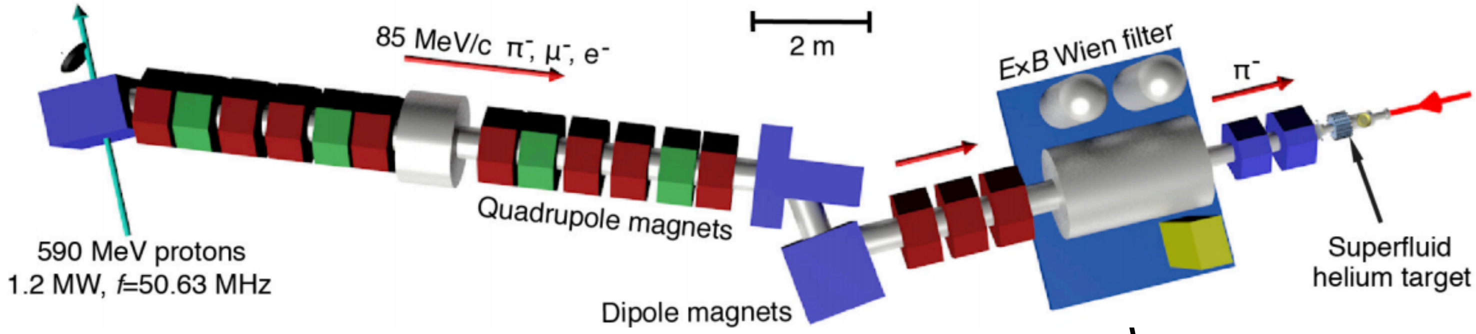
- When the laser is in resonance with the atom, the nucleus absorbs the pion and breaks up.

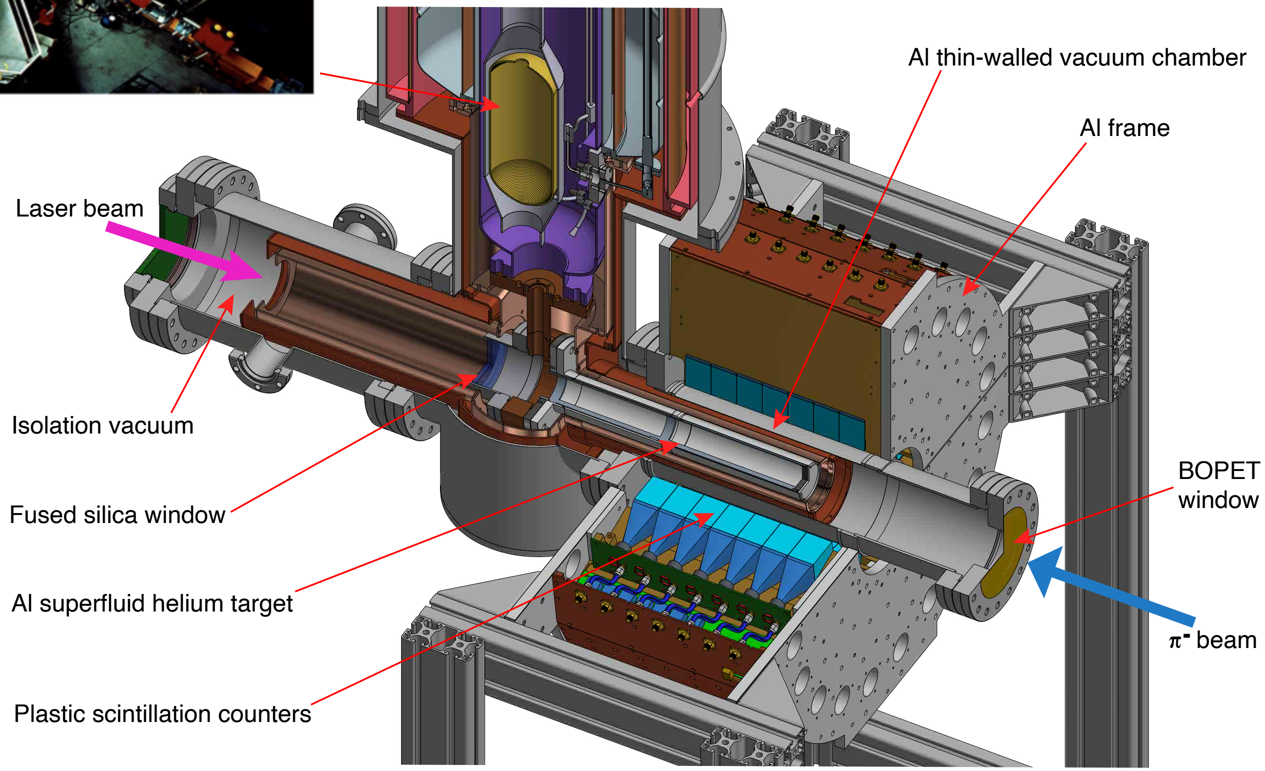
πHe^+ + laser $\rightarrow p+n+n+n, \quad d+n+n,$ or $t+n$ detect these fission products.

- High backgrounds (relative yield >10^3) from decay electrons, nuclear fission, and contamination in the particle beam.
- Ultra low-rate experiment: 2-3 events per hour. Must accumulate data for months.

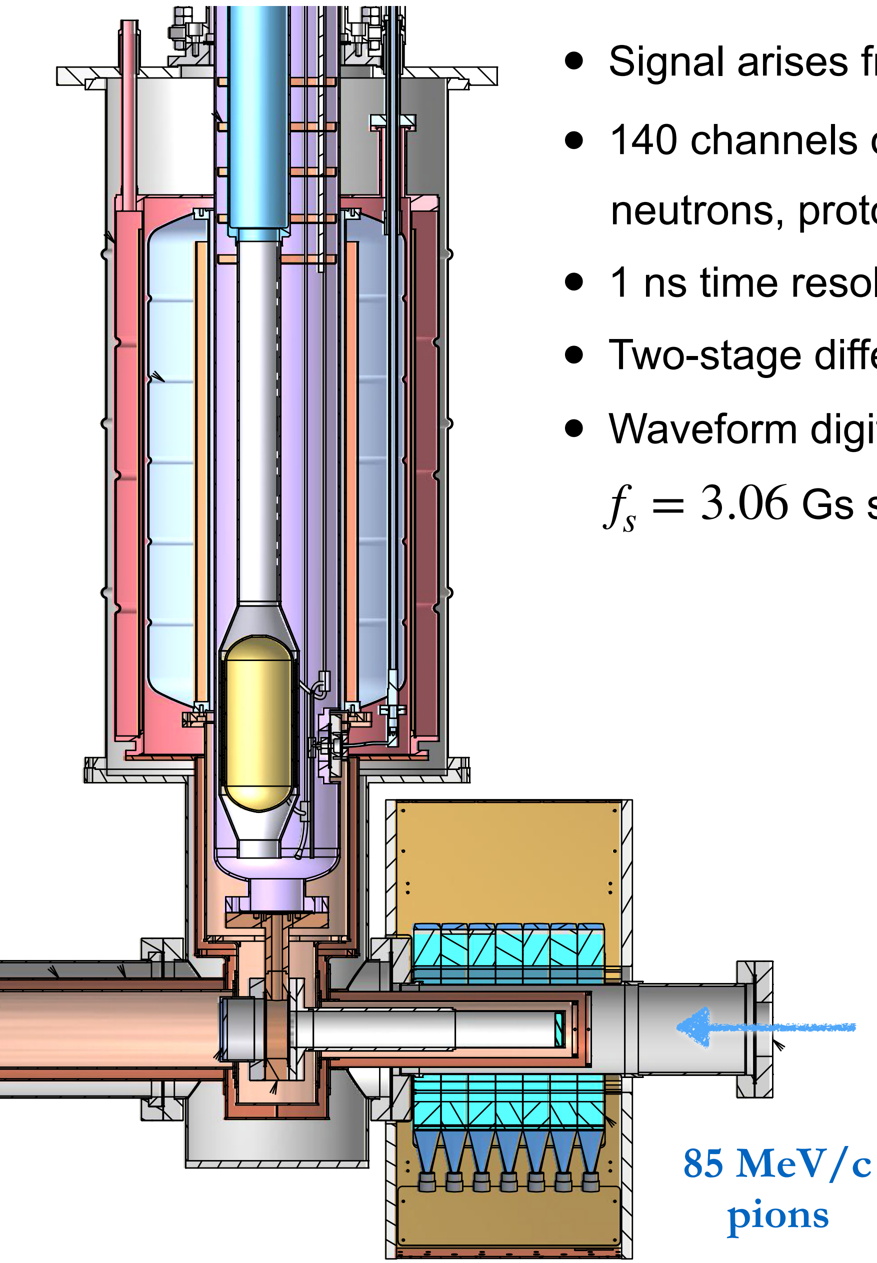
Experimental setup



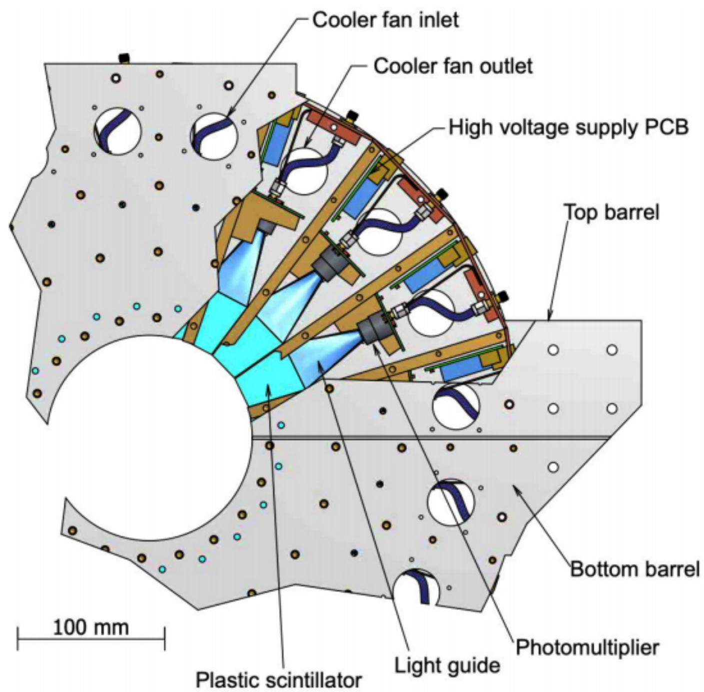




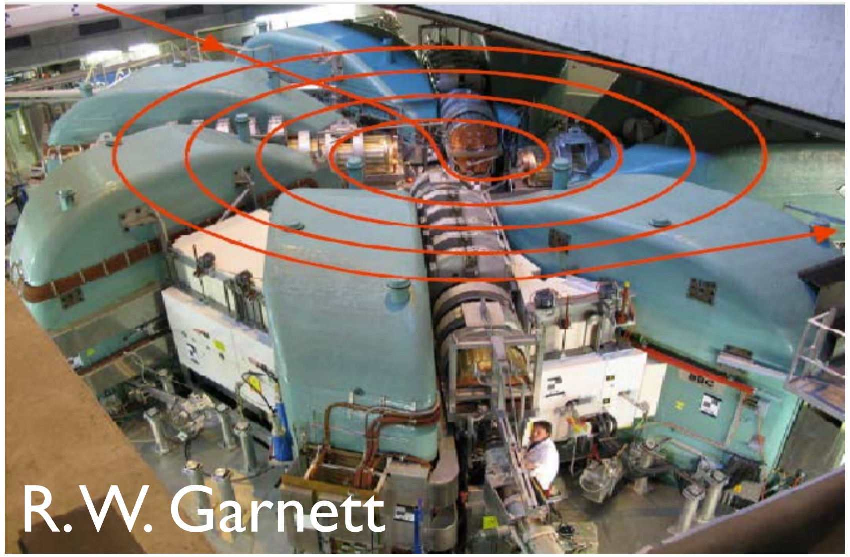
Wien filter ΔV=550 kV

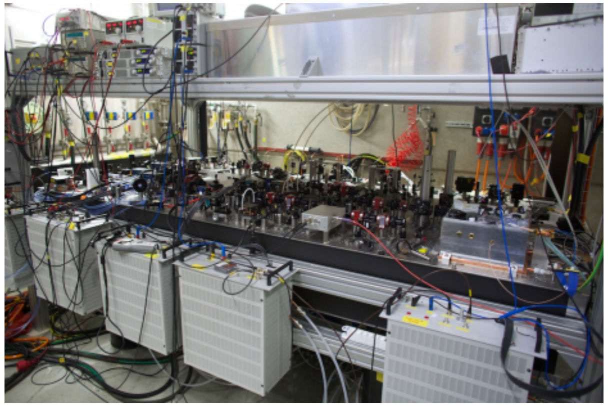


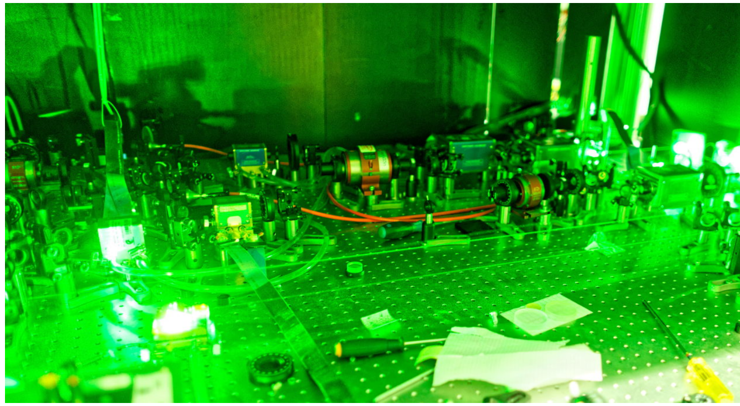
- Signal arises from the quasi-free nuclear absorption of pions.
- 140 channels of $40 \times 30 \times 34$ mm³ Elijen EJ-200 plastic scintillators sensitive to neutrons, protons, and deuterons.
- 1 ns time resolution metal-channel dynode photomultipliers.
- Two-stage differential preamplifier bandwidth $f_b = 400$ MHz
- Waveform digitization using Domino Ring Sampler DRS4 ASIC of sampling $f_s = 3.06$ Gs s^{-1}. Average transfer rate 13-15 GB h^{-1}



1515-1633 nm subpicosecond 10 mJ optical parametric generator + amplifier with low jitter



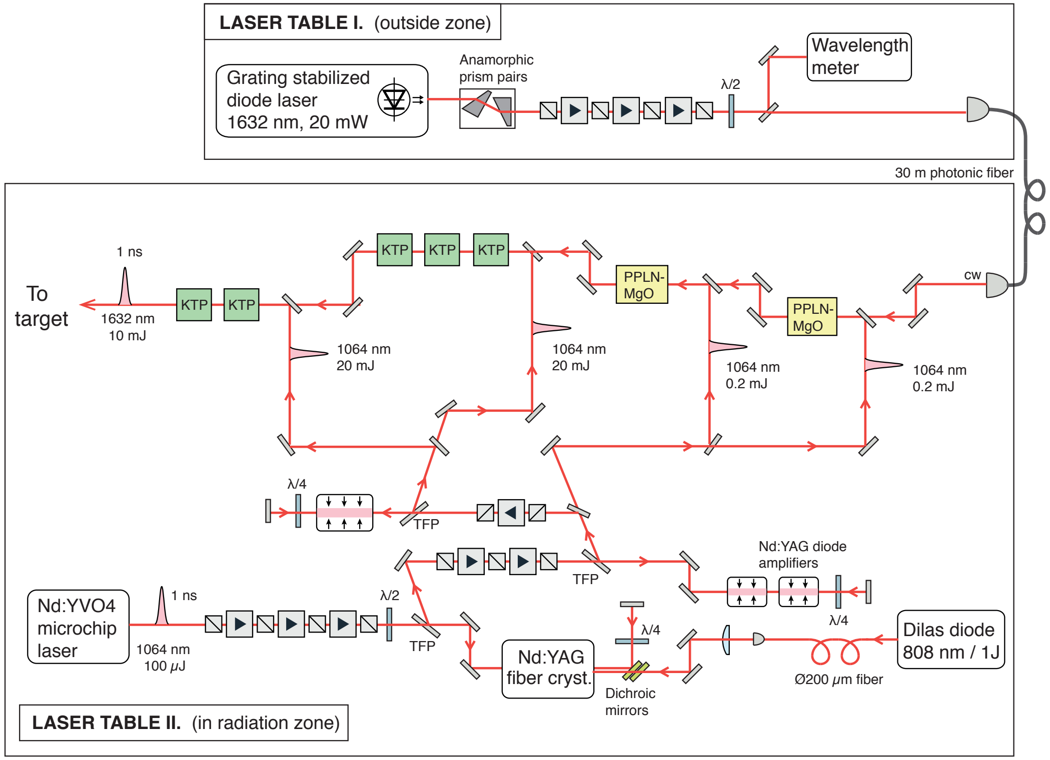




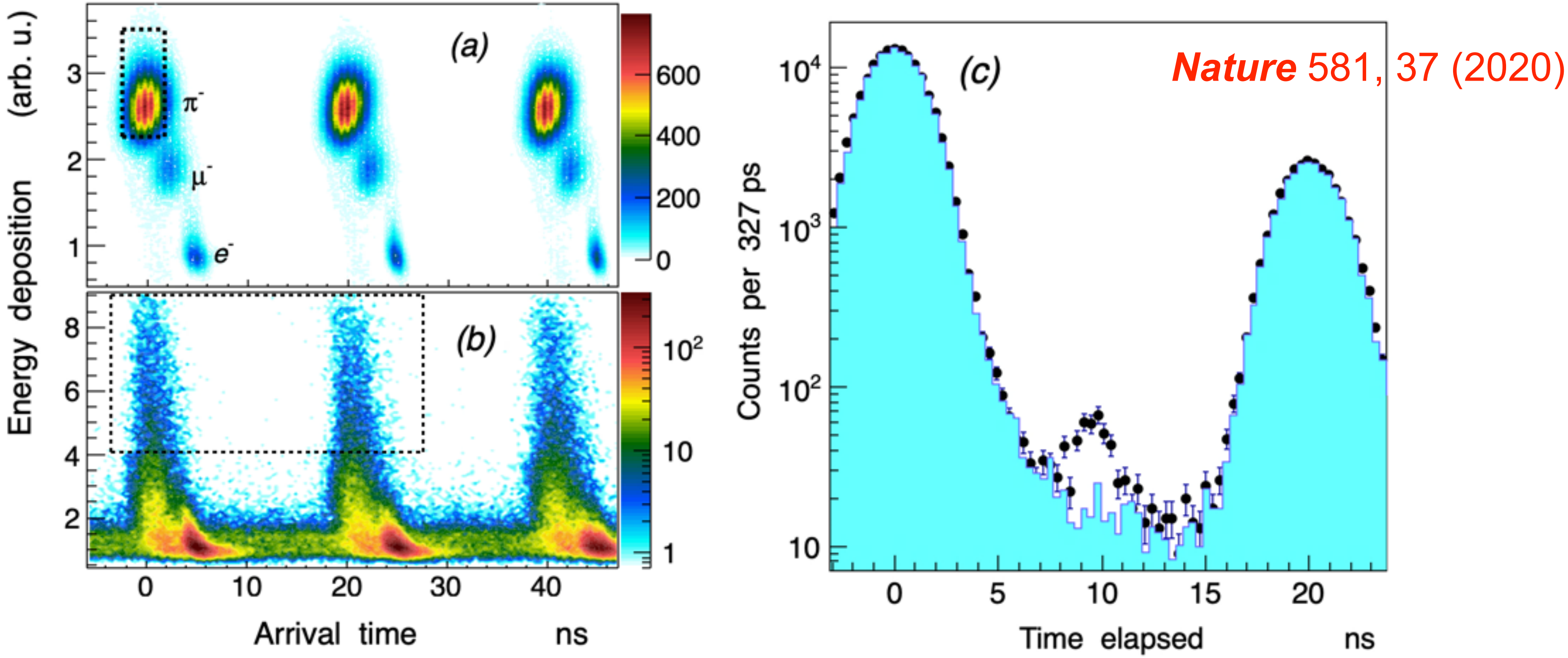
Pions arrive in a cycle of 19.75 ns

Fire laser synchronized to cyclotron RF divided down to 80 Hz.

Neutrons/protons recorded with 1 ns scale timing resolution using waveform digitization and ASIC's

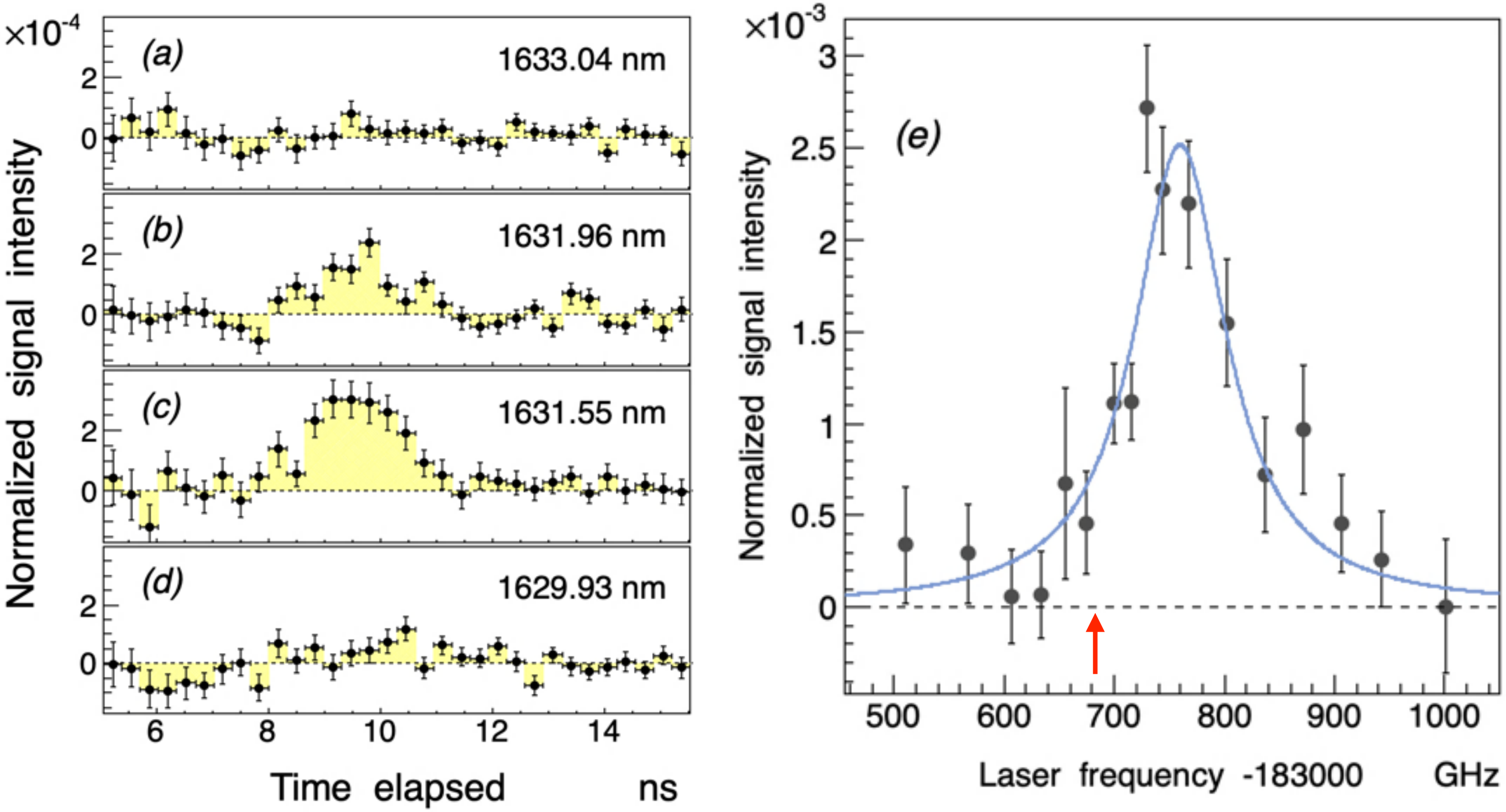


Analysis and signal isolation



- Identify pions based on their arrival time and energy loss of 2.6 MeV in a 4.7 mm thick plastic scintillator placed at the entrance of the experimental target.
- Identify signal nuclear fragments by selecting events with a >20-25 MeV energy deposition in the 140 plastic scintillators. The scintillators were adjusted to a "magic thickness" of around 40 mm so that the background electrons could simply be rejected based on their much smaller 6-8 MeV energy deposition.

Experimental result

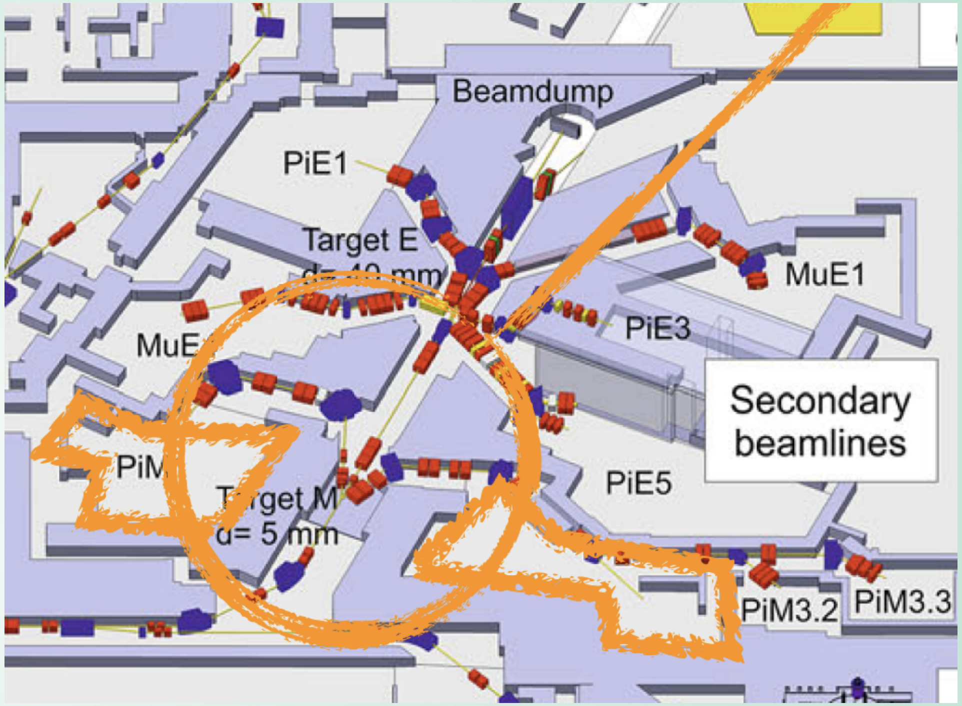


Nature 581, 37 (2020)

- By plotting the relative number of counts under the laser-induced peak as a function of laser frequency, we obtained the Lorentzian profile shown.
- Resonance centroid 183760(6)$_{\mathrm{STA}}$(6)$_{\mathrm{SYS}}$ GHz. The 6 GHz statistical uncertainty is due to the small number of detected atoms, the systematic uncertainty due to the selection of the Lorentzian fit function and the frequency modulation due to OPG and OPA processes. Atomic collisions shifted the resonance by 78 GHz.

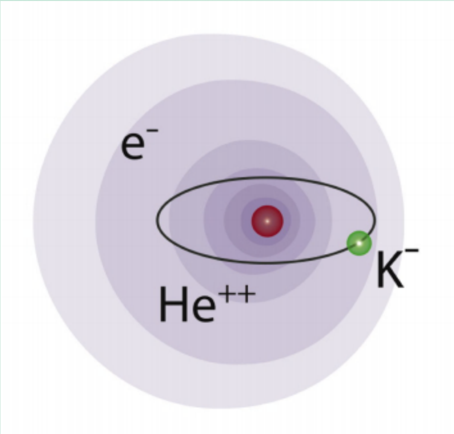
Future of pionic helium at PSI

- UV transition (n,l)=(17,16)→(16,15) is expected to be factor 100x narrower than observed transition. Even narrower visible transitions at n=18 are predicted.
- Utilize High intensity Muon Beam (HiMB) upgrade of PSI facility to obtain more experimental beamtime.
- Lower-momentum beam and spectroscopy in gas targets.
- High-power, high repetition rate Innoslab lasers are probably needed.
- Improve experimental precision by factor 100x, and determine charged pion mass with much higher precision.

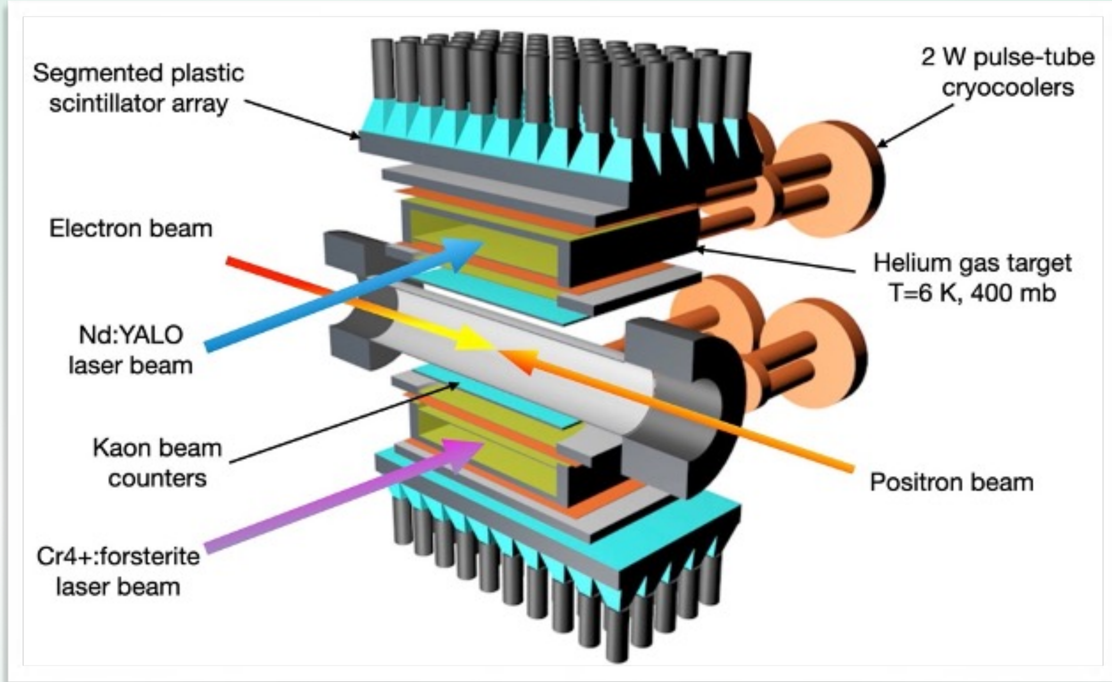


A. Papa (2019)

Laser spectroscopy at the DAFNE collider



KHe$^+$: kaonic helium
$n=l-1=29$,
Lifetime $\tau \approx 10$ ns.
Wavelength orange.
DAFNE collider.



- Evaluating the possibility to carry out the experiment at the DAΦNE facility of the Frascati laboratory
- Injection-seeded pulsed Nd:$YAlO_3$ or chromium forsterite lasers must be synchronized to the bunches in the synchrotron.
- First laser spectroscopy experiment in a collider, and of an atom containing a strange quark.
- Energy resolution of laser spectroscopy is typically few hundred nano-eV to a few micro-eV.
- Determine the charged kaon mass to a precision of $<10^{-7}$ (hundred times better than before).

Summary

- During the previous AD program we carried out sub-Doppler two-photon laser spectroscopy of antiprotonic helium atoms. so that the transition frequencies were measured with a fractional precision of 2.3-5 parts in 10^9.
- Comparisons with QED calculations yielded an antiproton-to-electron mass ratio $M_{\bar{p}}/m_e = 1836.1526734(15)$, which agrees with the proton-to-electron experimental value within 8×10^{-10}. ELENA facility will provide electron-beam cooled antiproton beams to achieve higher precision experiments.
- Laser spectroscopy of the transition $(n, \ell) = (17,16) \rightarrow (17,15)$ of metastable pionic helium was detected at PSI. This verified that the atom exists and constitutes the first excitation of an atom that includes a meson. Quantum optics techniques can now be used to study **mesons** and the method can probably be utilized for other mesons such as kaons that include the strange quark.
- By measuring such narrow resonances at various densities of a helium gas target, we may determine the transition frequency to much higher precision. This would lead to an improved charged pion mass "by up to 2 to 3 orders of magnitude".
- We hope to transplant the experiment to DAFNE to carry out laser spectroscopy of kaonic helium and improve the charged kaon mass by more than factor 100.