Laser spectroscopy of pionic helium atoms

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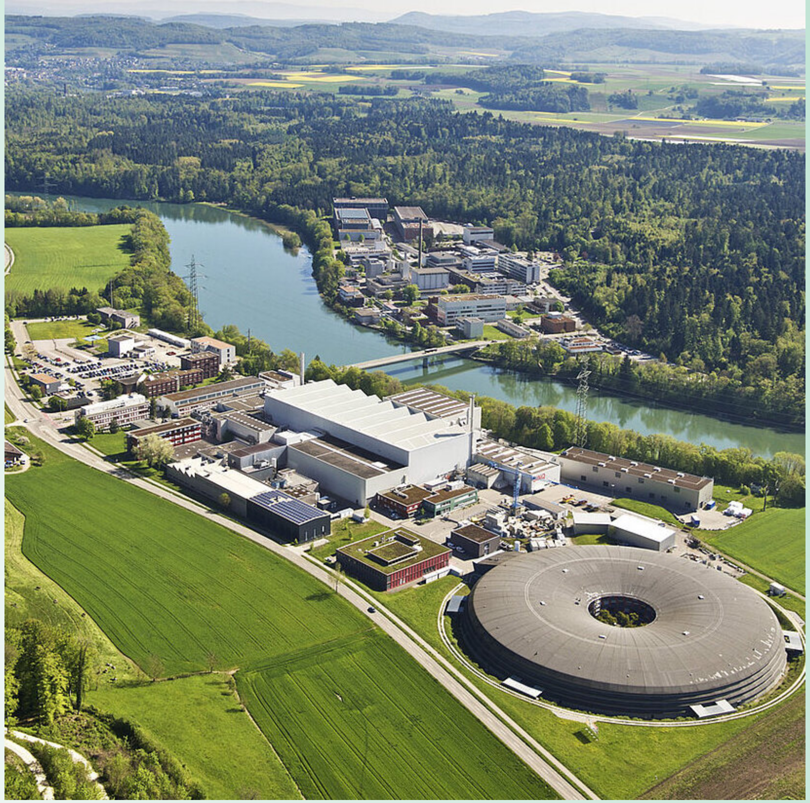
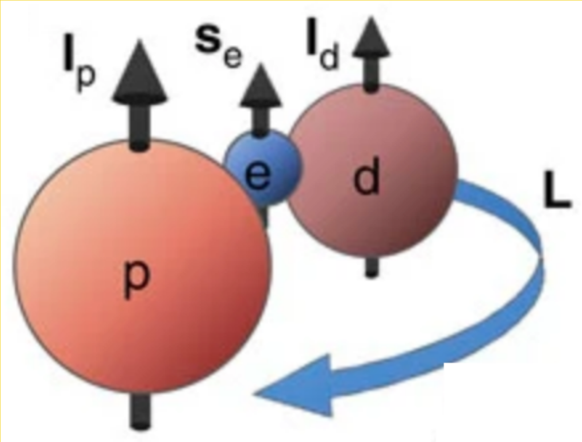
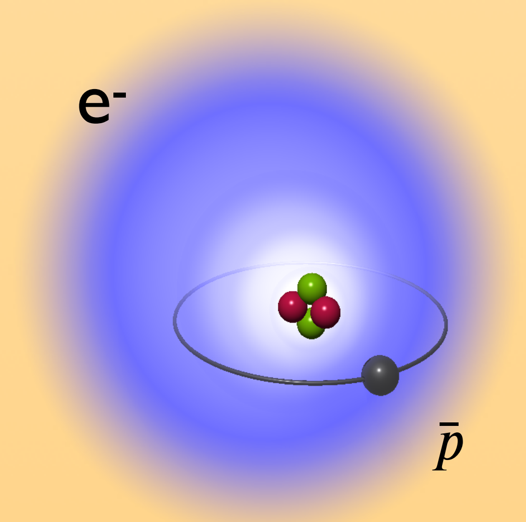


Fundamental three-body atoms containing two heavy particles

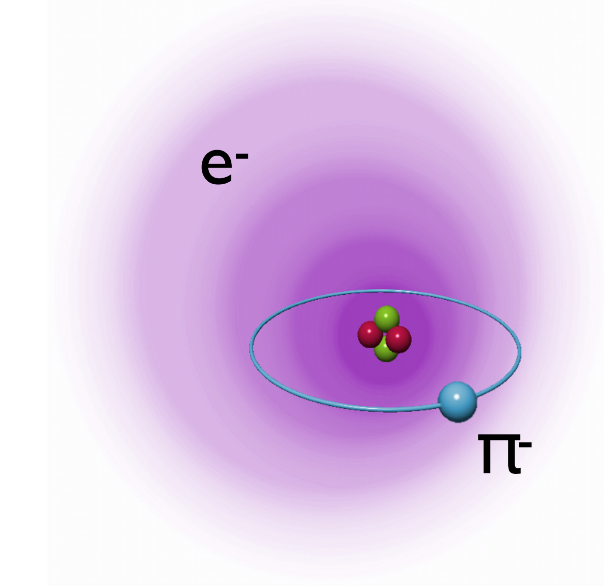


Nature Comm. 7, 10385(2016)

HD⁺: Hydrogen deuteride molecular ion, first molecule studied by quantum mechanics in 1927. Still most well-understood molecule in QED.



$\bar{p}He^+$: antiprotonic helium atom. Antiproton in a 100 pm diam circular orbital n=l-1=38 Average lifetime $\tau \approx 4\ \mu s$ 1s electron protects $\bar{p}$ against external collisions.



πHe^+: metastable pionic helium atom, negative pion in n=l-1=17 orbital, lifetime $\tau \approx 7$ ns.

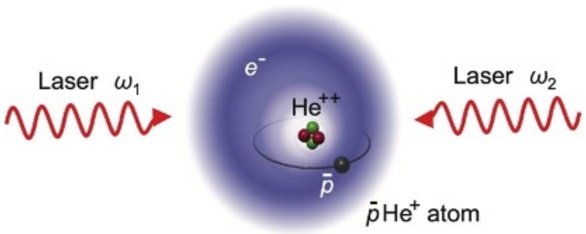
- Non-relativistic QED calculations have begun to determine the transition frequencies of HD^+ and $\bar{p}He^+$ with 10^{-11} scale precision by including $m\alpha^7$ scale QED corrections.
- Same level of theoretical precision as two-body atoms, often less sensitive to nuclear effects.
- Experiment-theory comparison allows determination of fundamental constants, consistency test of CPT symmetry, upper limits on beyond-Standard Model interactions.

Laser spectroscopy of $\bar{p}He^+$ atoms by ASACUSA@CERN

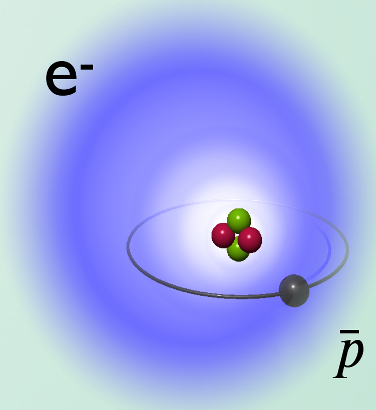
- Sub-Doppler two-photon and single-photon transitions of antiprotonic helium $\bar{p}He^+$ atoms in the UV to IR range were measured with fractional precision of 2.3-5 parts in 10^9
- Comparisons with ab-initio NRQED calculations yields

  Antiproton-to-electron mass ratio 1836.1526734 (15) *Science 354, 610 (2016)*
- Consistency test of CPT invariance in a hadron-antihadron system.
- Combined with the cyclotron frequency Q/M of antiprotons in a Penning trap by TRAP and BASE collaborations, constrains any possible difference between antiproton and proton masses and charges to a fractional difference of 5×10^{-10}

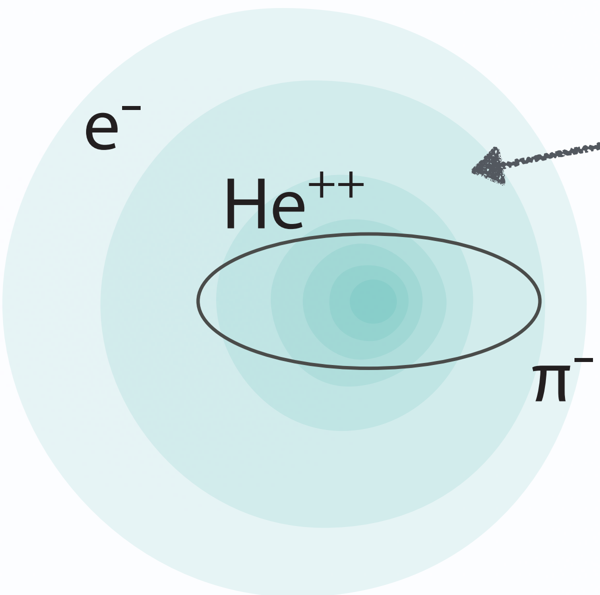
Non-relativistic energy	$(n,l)=(36,34)\rightarrow(34,32)$	1 522 150 208.13 MHz
$m\alpha^4$ order corrections		-50320.64
$m\alpha^5$ order corrections		7070.28
$m\alpha^6$ order corrections		113.11
$m\alpha^7$ order corrections		-10.46(20)
$m\alpha^8$ order corrections		-0.12(12)
Transition frequency		1 522 107 060.3(2)
Uncertainty from alpha charge radius		+/-0.007
Uncertainty from antiproton charge radius		< 0.0007



Korobov, Hilico, Karr, *PRL* 112, 103003 (2014), PRA 89, 032511 (2014).



Using the knowledge gained with antiprotons and modern laser techniques, we can now attempt spectroscopy of metastable pionic helium

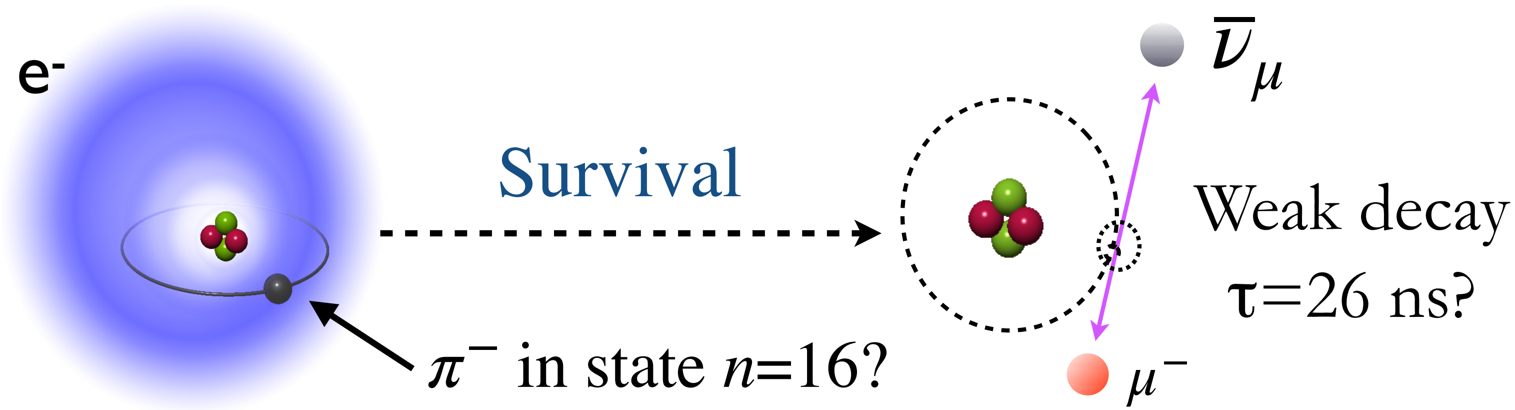


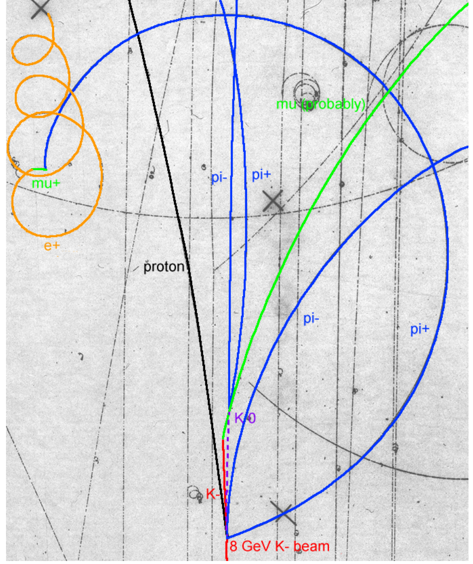
Electron in 1s orbital. Strongly attached to the nucleus with 25-eV ionization potential.
Auger emission is suppressed.

Negative pion in a 'circular' Rydberg orbital n=17, l=n-1 with diameter of 100 pm.

- Localized away from the nucleus.
- The electron protects the antiproton during collisions with ordinary helium atoms.

$\tau \sim 7$ ns !



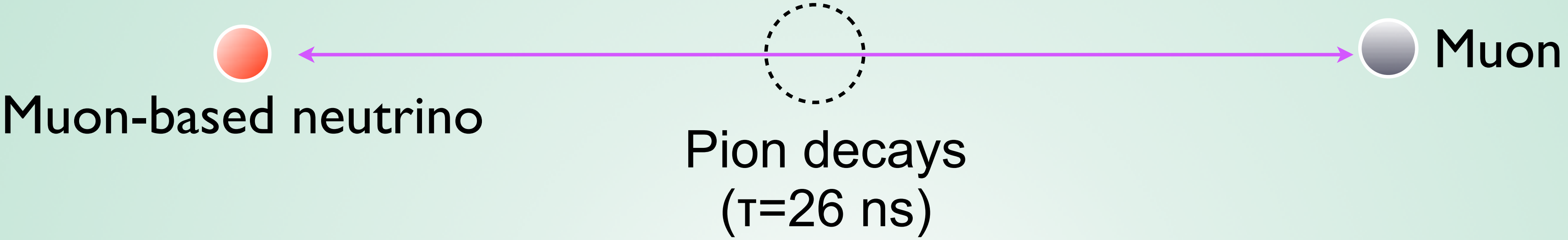


- **1963-67:** (Chicago + Pittsburg) Bubble chamber experiments reveal a small fraction of π^- stopped in liquid He undergoes the reaction, $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$. This appears impossible as π^- should be rapidly absorbed into the nuclei. A lifetime τ=0.3-0.4 ns is inferred. USSR experiment infers a similar lifetime.
- **1964:** George Condo (Tennessee) qualitatively proposes that metastable $\pi^{4}\mathrm{He}^+$ populating a state of n=16 is being created that prevents the π^- from being absorbed by the nucleus.
- **1969-1970:** J.E. Russell (Cincinnati) calculations suggest that antiprotonic helium $\overline{p}^{4}\mathrm{He}^+$ is long-lived due to the large mass of the antiproton, but $\pi^{4}\mathrm{He}^+$ is too unstable to explain the bubble chamber experiments: "The rate for the $\alpha\pi^- e^-$ atom with n=16 would make a direct experimental detection of pions trapped in these circular orbits exceedingly difficult".
- **1992:** TRIUMF counter experiment indicates a lifetime τ=7 ns. "(Condo-Russell scenario) cannot quantitatively account for the time distribution, shape, lifetime, or trapping fraction."

Physics motivation for πHe^+ laser spectroscopy

- Definitive evidence for the existence of three-body metastable πHe^+ It would be the first laser excitation and spectroscopy of an atom containing a meson.
- As the ^4He nucleus and pion are spin-0 bosons, there is no spin-spin hyperfine structure. The atomic energy levels obey the Klein-Gordon equation $\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m^2\phi^2 +$ etc. as opposed to the hydrogen atom etc. which behaves according to the Dirac equation $\mathscr{L}_{QED} = \overline{\psi}\left(i\gamma^\mu \partial_\mu - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - q\overline{\psi}\gamma^\mu \psi A_\mu$
- Precise determination of the π^- mass would be possible. The theoretical natural widths of some lines indicate that a determination at a level of ≦10^{-8} precision is in principle possible, though practically it may be difficult.
- Improvement on the direct laboratory limit of the muon antineutrino ν_μ mass.
- May allow us to set upper limits on exotic forces coupling to mesons as in antiproton case.

Pion mass determines (muon-type) neutrino mass



Determine this!

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

105.6583668(38) MeV

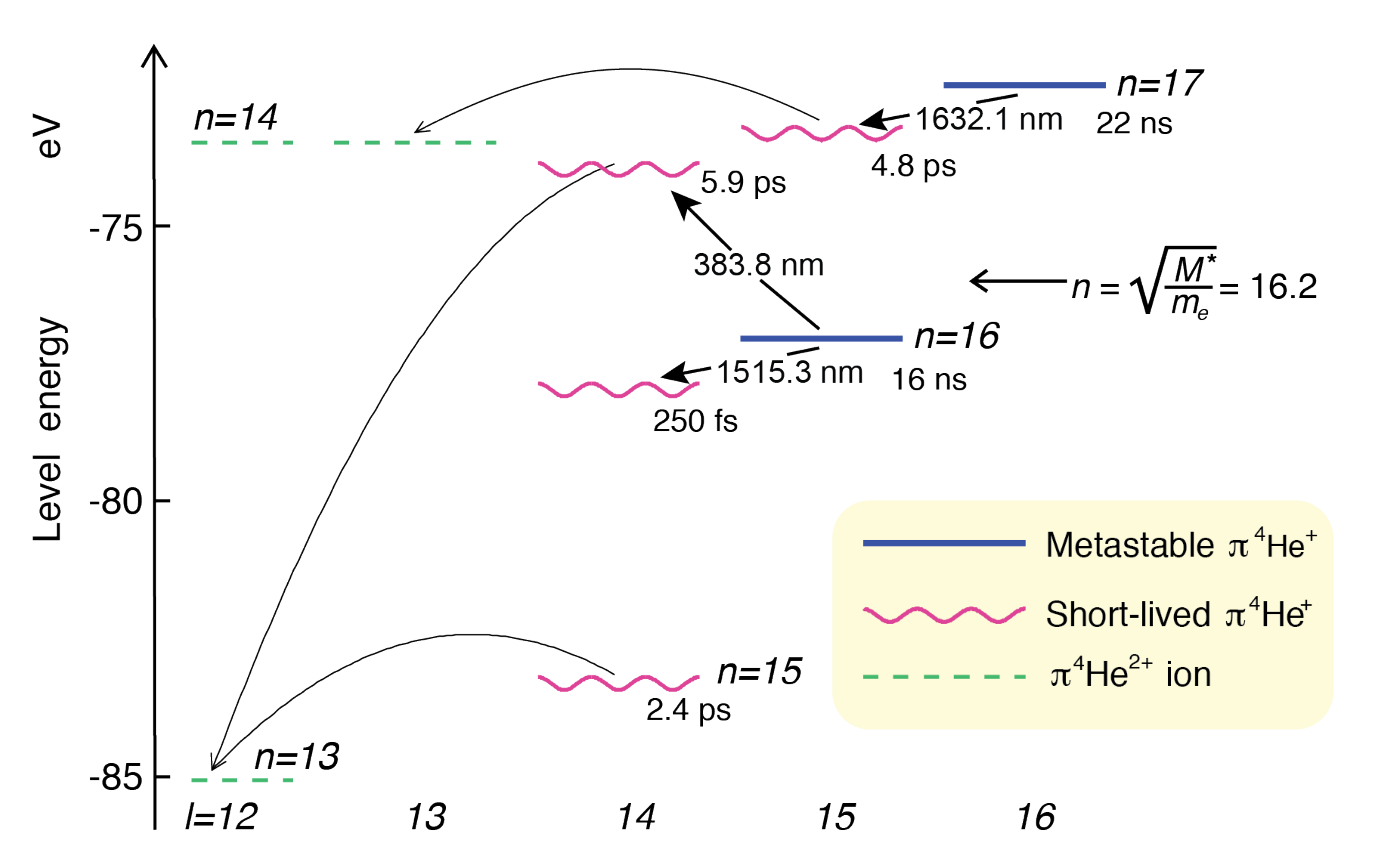
Measure this.

29.79200(11) MeV/c

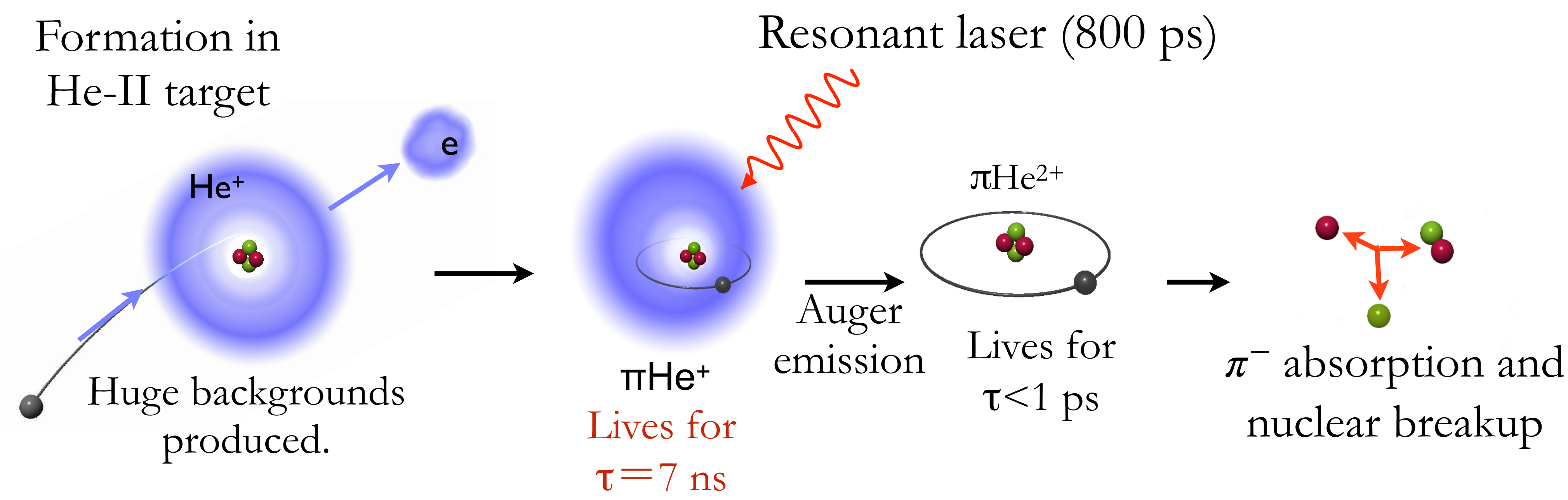
K. Assamagan et al., *PRD 53, 6065 (1996).*

Best value <1 eV obtained from neutrino oscillation experiments

Energy levels of pionic helium



Proposed principle of laser spectroscopy

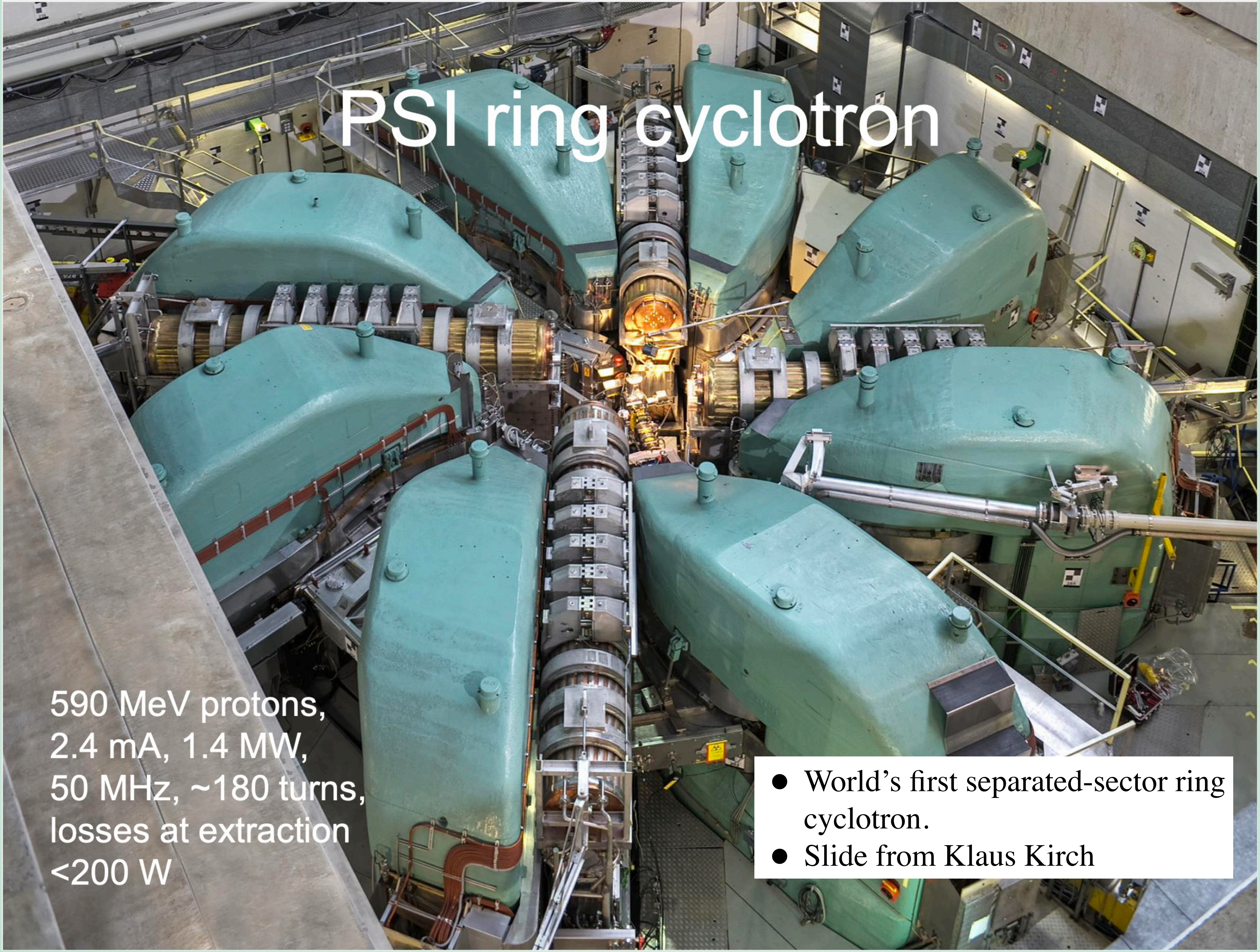


- When the laser is in resonance with the atom, the nucleus absorbs the pion and non-radiatively breaks up (fission).

$$\pi\mathrm{He}^{+} + \text{laser} \rightarrow p + n + n + n, \quad d + n + n, \quad \text{or} \quad t + n$$

- Detect nuclear fragments (MeV neutrons, protons, deuterons) in synchronization with laser pulse.
- Very high backgrounds (relative yield $>10^3$) from decay electrons, nuclear fission, and contamination in the particle beam itself.
- Ultra low-rate experiment: 2-3 events per hour. Must accumulate data for months.

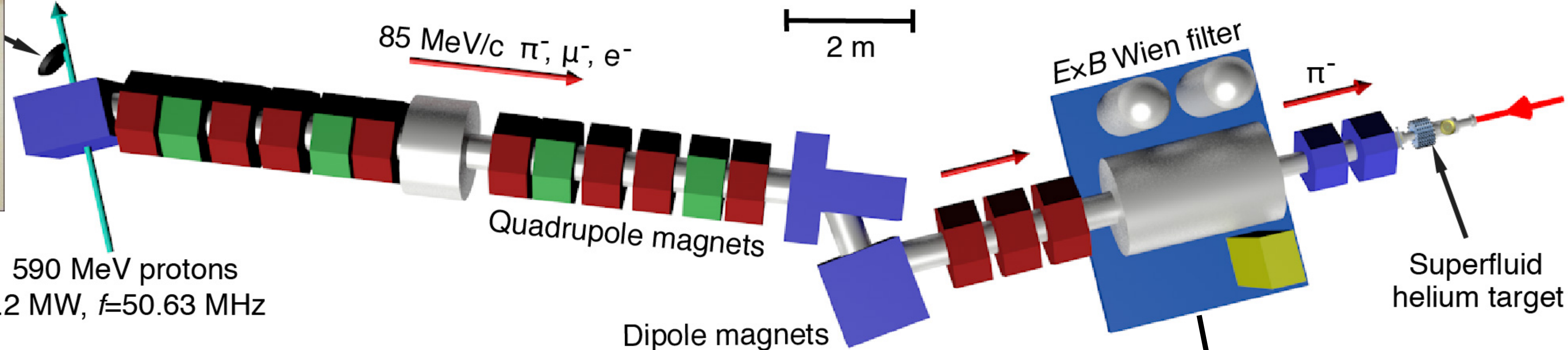
PSI ring cyclotron

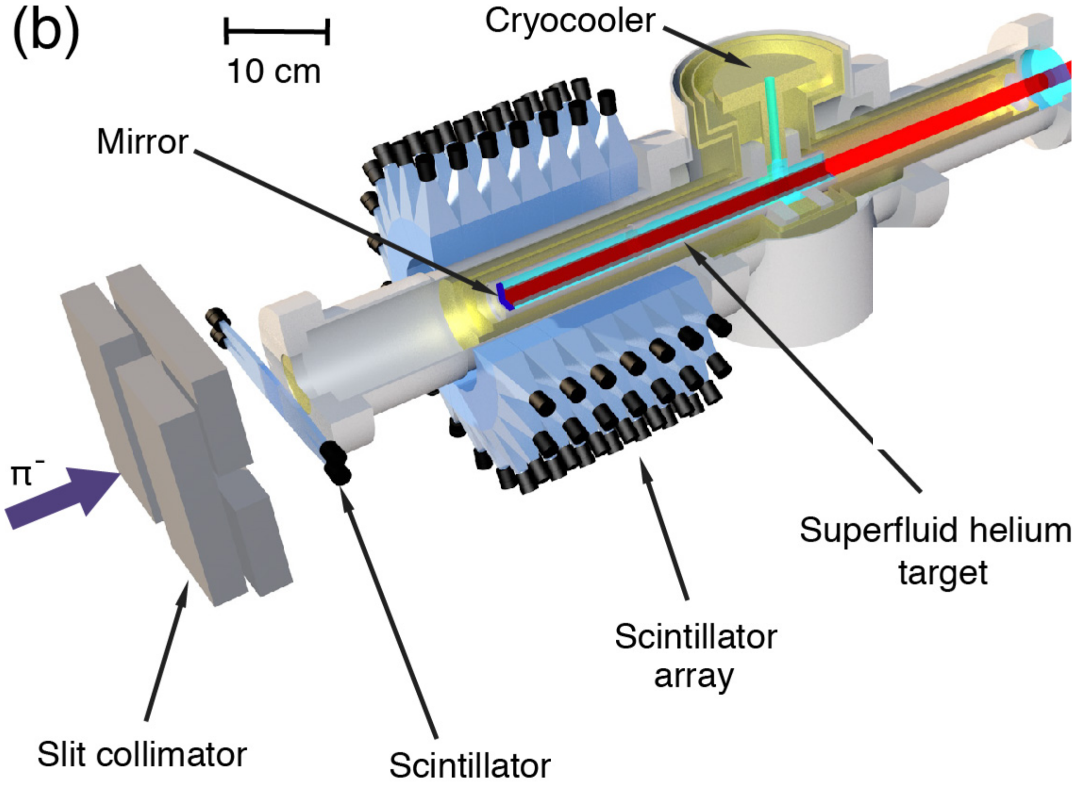


590 MeV protons,
2.4 mA, 1.4 MW,
50 MHz, ~180 turns,
losses at extraction
<200 W

- World's first separated-sector ring cyclotron.
- Slide from Klaus Kirch

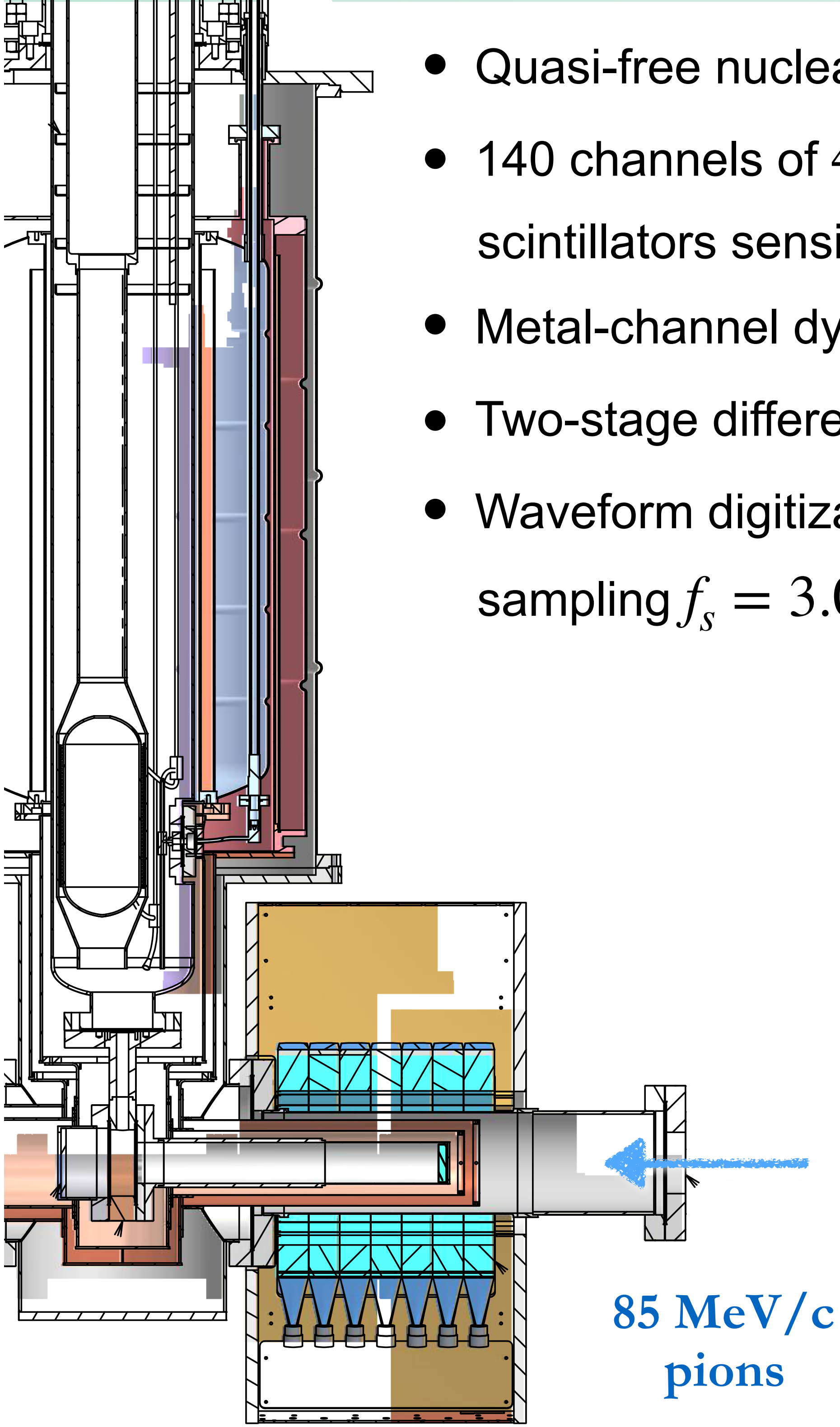
Experimental setup

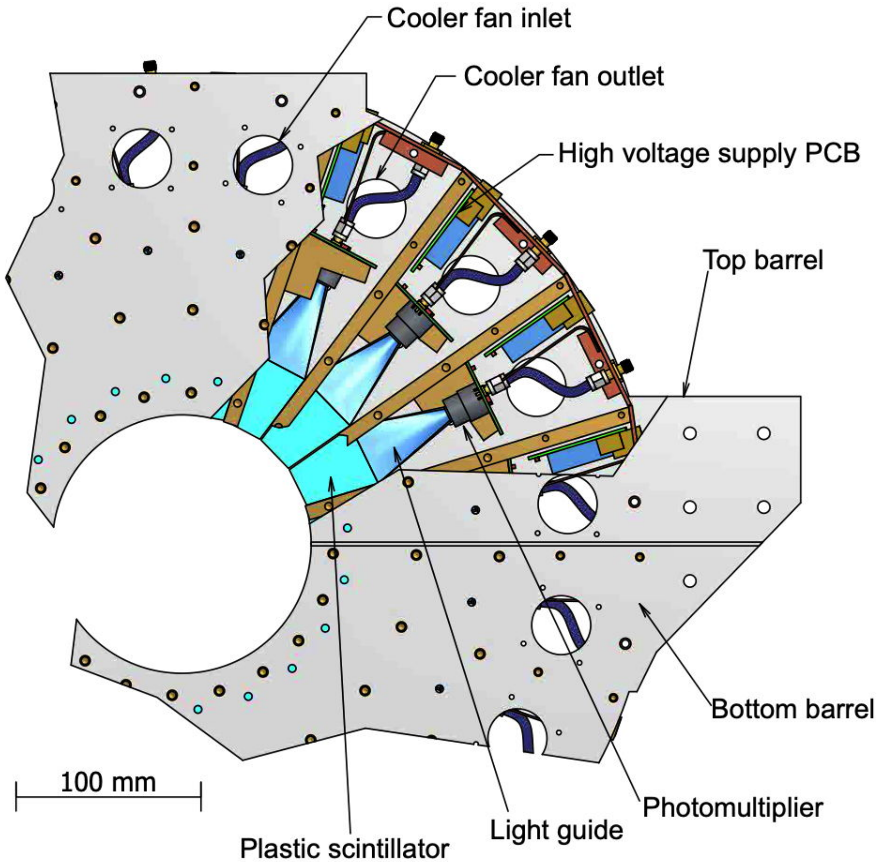




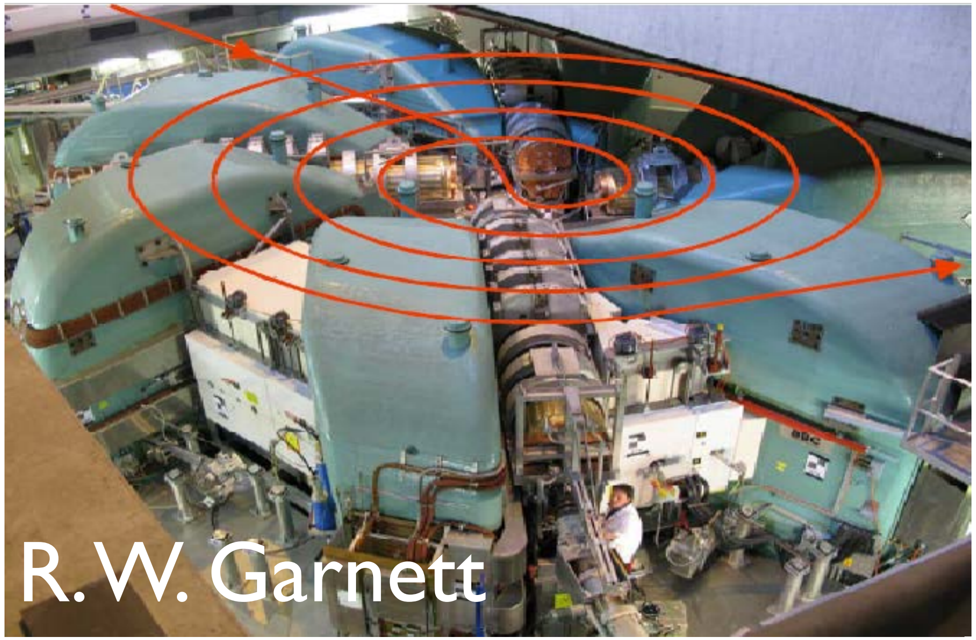
Constructed by PSI accelerator group
1.7 m long electrodes of 150 mm gap
voltage ΔV=550 kV

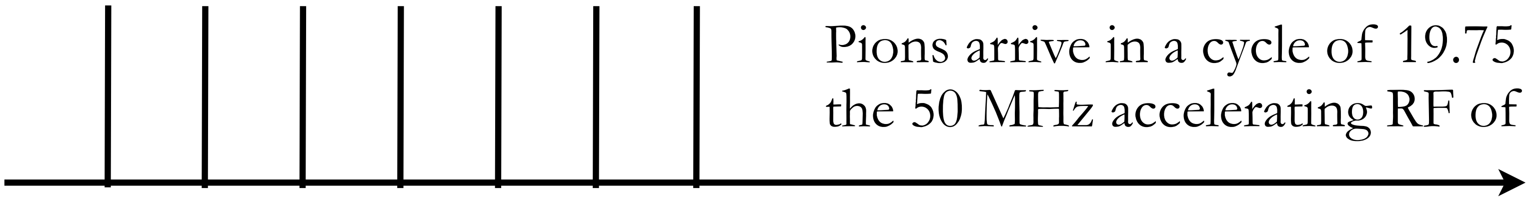
- Quasi-free nuclear absorption of π
- 140 channels of $40 \times 30 \times 34$ mm³ Elijen EJ-200 plastic scintillators sensitive to neutrons, protons, and deuterons.
- Metal-channel dynode photomultipliers HPK R9880U-110.
- Two-stage differential preamplifier bandwidth $f_b = 400$ MHz
- Waveform digitization using Domino Ring Sampler DRS4 ASIC of sampling $f_s = 3.06$ Gs s^{-1}. Average transfer rate 13-15 GB h^{-1}





How to coincide the laser pulses and pionic helium



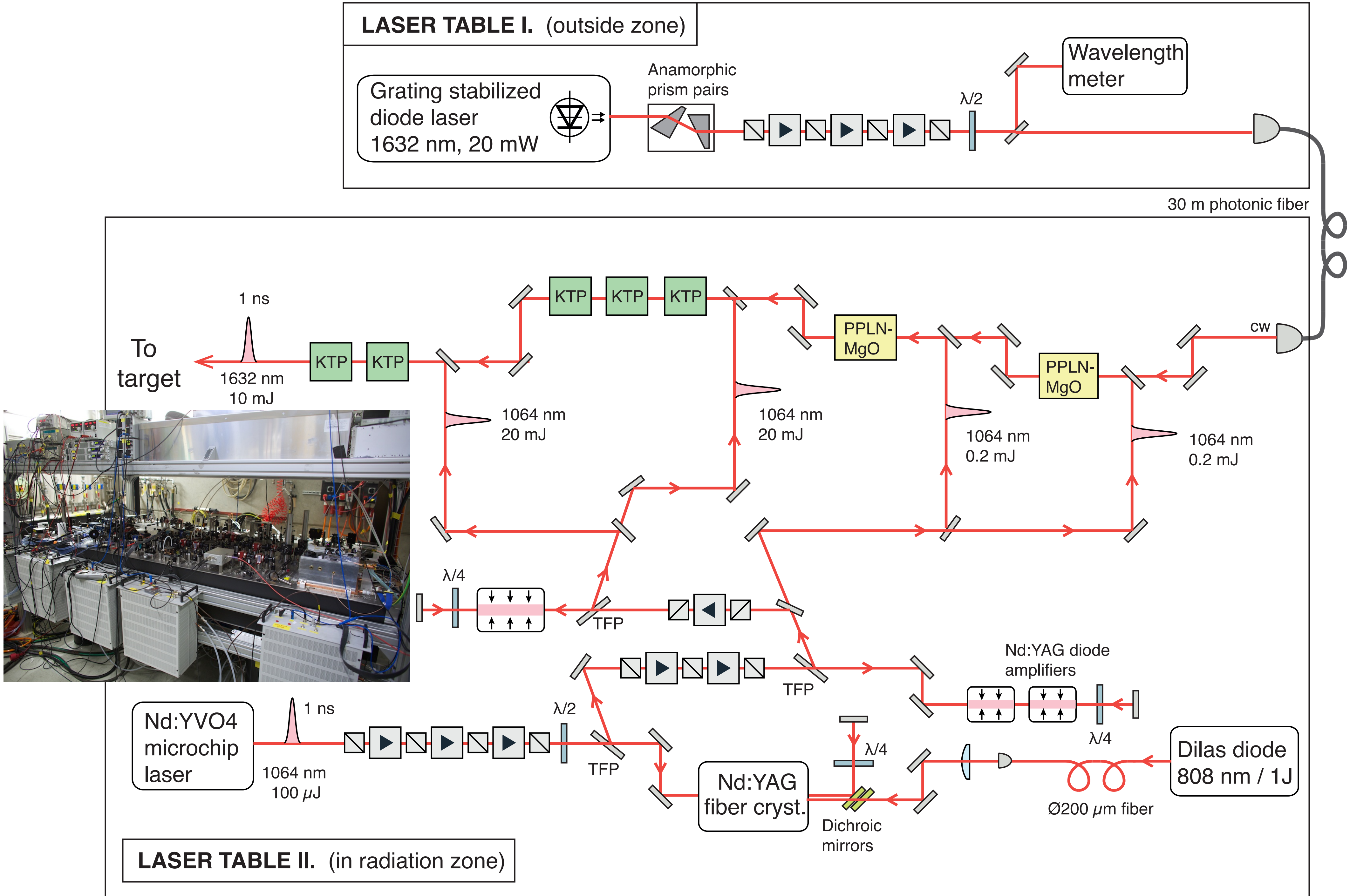


Pions arrive in a cycle of 19.75 ns which arises from the 50 MHz accelerating RF of the PSI cyclotron.

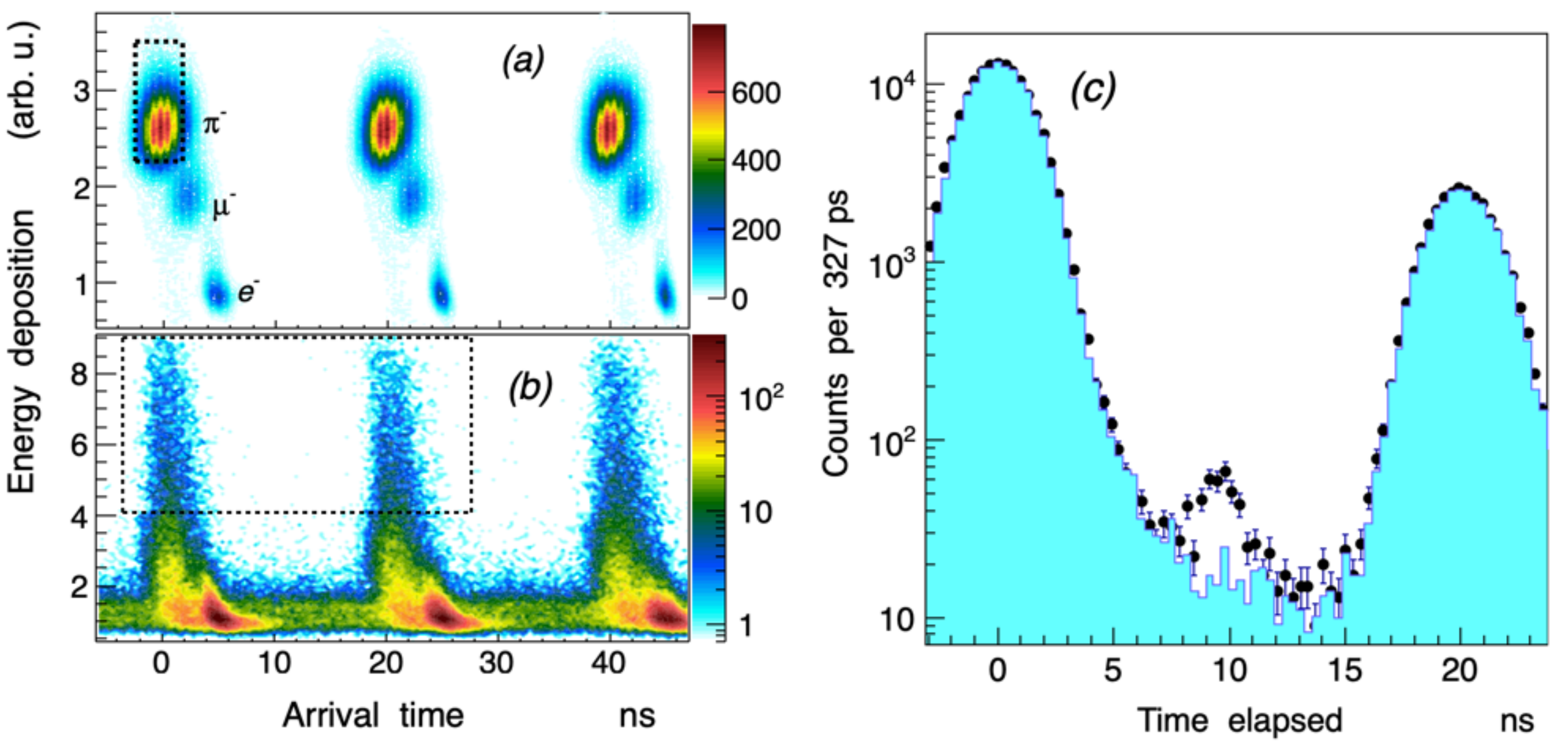
Fire laser synchronized to cyclotron RF divided down to 80 Hz

Neutrons/protons detected by 140 plastic scintillators with 1 ns scale timing resolution and waveform digitization based on ASIC technology.

1515-1633 nm / 800 ps / 10 mJ tunable optical parametric generator + amplifier with a firing timing jitter of <1 ns.

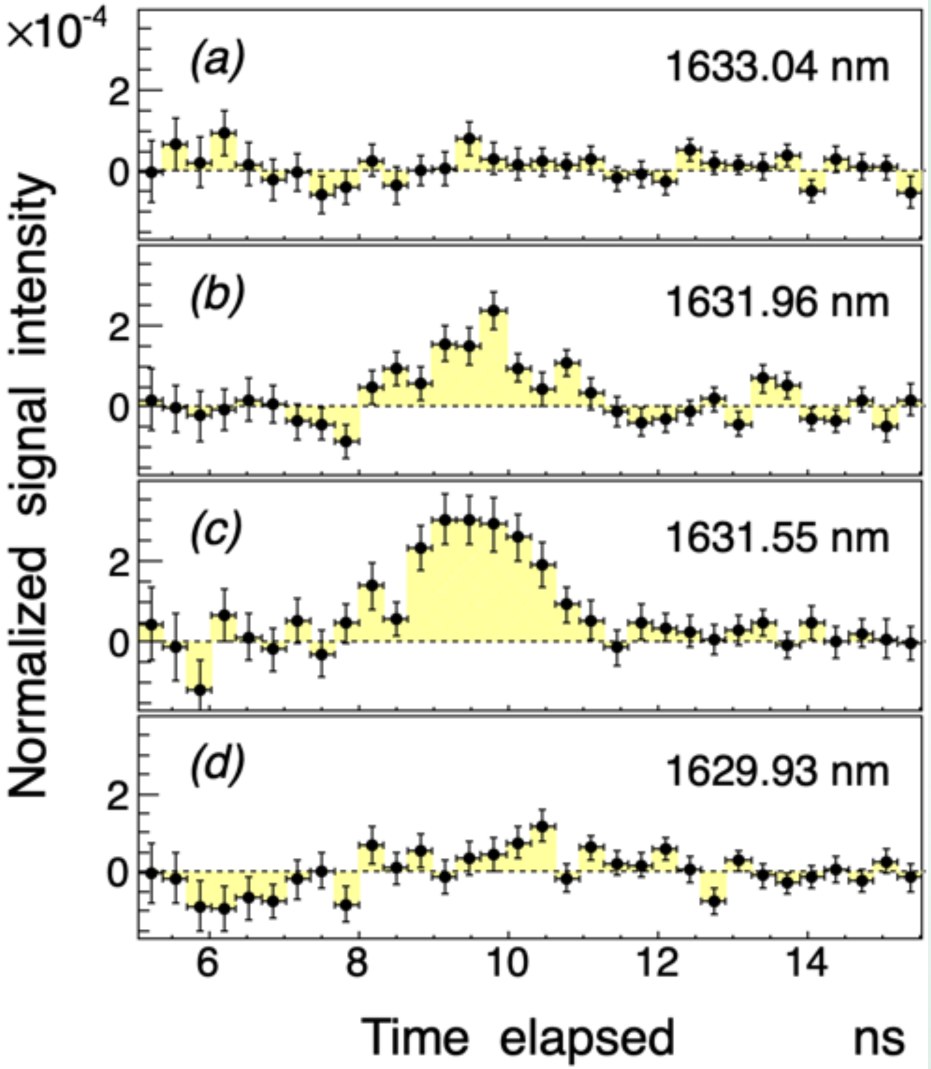


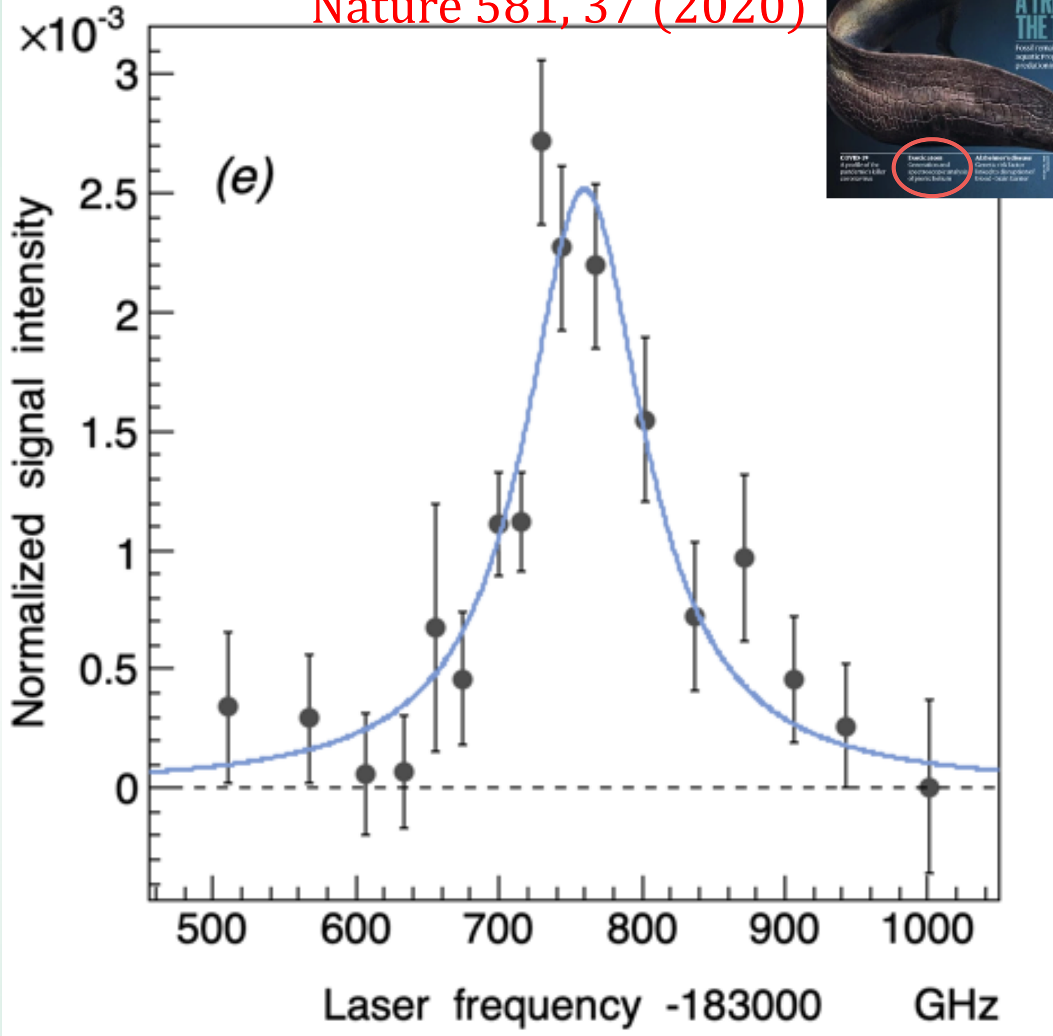
Analysis and signal isolation



- 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 scintillator thicknesses were adjusted to 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 $183760(6)_{STA}(6)_{SYS}$ 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.

Experimental result and summary

- Laser spectroscopy of the transition $(n, \ell) = (17,16) \rightarrow (17,15)$ of metastable pionic helium was detected. 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.
- The experimental frequency $183760(6)_{\mathrm{STA}}(6)_{\mathrm{SYS}}$ GHz was larger than the theoretical value 183681.8(0.5) GHz by $\Delta\nu = 78(6)$ GHz. As in the antiprotonic helium case, this is believed to be due to the very high rate of atomic collisions that are encountered in the superfluid helium target.
- The resonance width of 100 GHz is primarily due to the large Auger width 33 GHz of the resonance daughter state (17,15) and power broadening effects. We selected this transition due to the ease in detecting the resonance.
- Some UV transitions in πHe^+ are predicted to have natural widths of <100 MHz. 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.