MASS OF THE CHARGED PION*

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(Received June 29, 2000)

A recent precision measurement of m_π is described. The goal of the experiment is to bring the current mass uncertainty $\frac{\Delta m_\pi}{m_\pi}$ of 3 ppm down to 1 ppm.

PACS numbers: 14.40.Aq

1. Motivation

The current value for the mass of the charged pion is $m_\pi = 139.57018 \pm 0.00035\mathrm{MeV}/c^5$ [1]. The motivation for a more precise measurement of m_π arises from several aspects:

- The error in the muon neutrino mass measurement via $\pi^+_{\text{at rest}} \to \mu^+\nu_\mu$ is dominated by Δm_π (3 ppm), since m_μ is known with a precision of 0.3 ppm [2]. Theoretical considerations concerning extensions of the Standard Model predict that m_{ν_μ} is either ≥ 70 keV$/c^5$ for unstable neutrinos or ≤ 65 keV$/c^5$ for stable neutrinos contributing to the matter density of the universe. Our experiment could improve the sensitivity of the m_{ν_μ} measurement from 170 keV$/c^5$ into this mass range.

* Presented at the Meson 2000, Sixth International Workshop on Production, Properties and Interaction of Mesons, Cracow, Poland, May 19–23, 2000.

- A recent highly sensitive search for muonium–antimuonium conversion ($M\bar{M}$) gives a limit of 10^{-3} for $\mathrm{G}_{M\bar{M}}/\mathrm{G}_F$ [3]. In combination with this, a new limit of $\approx$70 keV/c^2 for the muon neutrino mass would exclude a certain type of theories extending the standard model.
- A forthcoming experiment with pionic hydrogen [4] aims for an improvement in accuracy from 0.5% to 0.2% for the hadronic shift of the $1s$ state. The present contribution to this error from Δm_π is 0.13%. With a precision of 1 ppm for m_π, this would reduce to $\approx$ 0.04%.

2. Experimental method

The experimental approach for a mass measurement of the unstable π^- ($\tau_\pi = 2.6 \times 10^{-8}$ sec) is to determine the energies of X-rays emitted by radiative transitions in pionic atoms. A crystal spectrometer is essentially the only way to measure X-ray energies in the range of few keV with sufficient accuracy.

The basic process for the formation and atomic cascade for such an atom is as follows: Negatively charged pions that have been slowed down to a kinetic energy of a few eV are captured in the Coulomb field of atoms into highly excited atomic levels by the emission of electrons. The depletion of the electron cloud proceeds by Auger emission. In case of refilling from neighboring atoms, the ionization state is not well understood. At low pressures, however, refilling is suppressed and the exotic atom will become a hydrogen-like system in which the energy levels can be calculated very precisely by bound-state QED.

The most precise m_π measurement up to now [5] was done with a solid state target (measuring the πMg($5g$–$4f$) line) where the number of K-electrons at the moment of X-ray emission was unclear due to the aforementioned electron refilling. The first interpretation of the experiment assumed that 1 K-electron was present during most emissions, but since the resulting value for m_π implied a negative muon neutrino mass, it was regarded as unphysical. The second interpretation [6] was based on 2 K-electrons at the moment of the measured transition and led to a result for m_π that is consistent with the limits extracted from the measurement of the muon neutrino mass [2].

To avoid this problem of electron refilling, we used a gas target instead of a solid state target, measuring the $5g$–$4f$ transition in pionic nitrogen [7]. The result of a feasibility study with the Cu Kα_1 fluorescence line as the energy calibration [8] confirmed the second interpretation of the experiment described above [6]; the current value of m_π is based on these two experiments [1].

3. Setup

The experimental setup in the πE5 area at PSI is shown in figure 1. The 85 MeV/c pion beam (intensity $5 \times 10^9 \frac{\pi}{s}$) was injected into the cyclotron trap, where it was slowed down by degraders and circulated into the gas target by the weakly focussing $\vec{B}$-field of the cyclotron trap perpendicular to the beam.

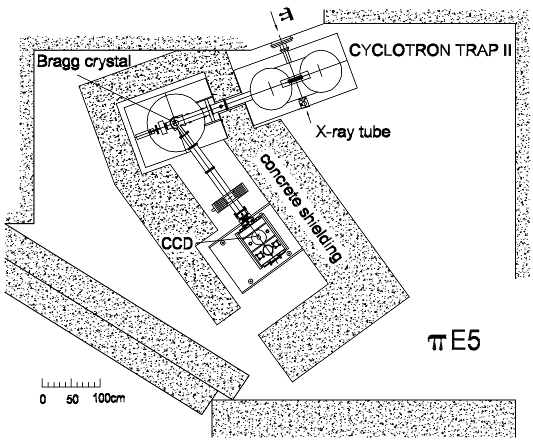

Fig. 1. Setup of the experiment in the πE5 area at PSI.

A crystal spectrometer with Johann geometry was used to reflect X-rays with a certain wavelength (Bragg condition $n\lambda = 2d \sin \Theta_{\mathrm{B}}$) onto a CCD (Charge Coupled device Detector). The crystal is spherically bent ($R \approx 3$ m) to allow for partial vertical focussing. By measuring the horizontal position on the detector, the exact angle of reflection (and thereby the energy) of the emitted X-rays can be calculated with high precision.

4. Calibration

The Cu Kα_1 line used for calibration in the feasibility study sets a limit on the possible precision of the measurement due to its rather complicated line structure. For this reason we calibrated with X-rays from another exotic atom, namely muonic oxygen. The energy of the μO($5g$–$4f$) transition (4023.8 eV) is close to that of the πN($5g$–$4f$) transition (4055.4 eV) and the high accuracy of the muon mass (0.3 ppm) allows a precise energy calculation for this line. To reduce the chance of systematical errors both lines are measured simultaneously. To achieve this, the target container was filled with a mixture of nitrogen and oxygen. The muons are available through pion decay within the cyclotron trap.

The $5g$–$4f$ line is the best choice, since the energy of higher level transitions is so low that X-ray absorption would be a serious problem, whereas lower levels in pionic nitrogen are already influenced by hadronic effects.

5. Background reduction by cluster analysis

An array of 6 CCDs is used for the position measurement, the total detector area amounts to 48 mm width and 72 mm height. Each individual CCD has 600×600 pixels of $(40\mu\mathrm{m})^2$. Due to the good energy and position resolution of these detectors, a very efficient background reduction is possible by keeping only isolated events in the correct energy range. Background events will have much higher energies than the 4 keV of proper events and will therefore deposit charges over a cluster of pixels.

6. Results

During several weeks of data-taking, approximately 9000 events in the πN line and 10000 events in the μ O line were accumulated, which, barring systematical errors, will be enough to reach the envisioned accuracy of 1ppm for m_π. Figure 2 shows sum spectra with $\approx 40\%$ of statistics. Apart from the circular transitions $5g$–$4f$ the parallel transitions $5f$–$4d$ are clearly apparent, for the μ O even with fine structure splitting.

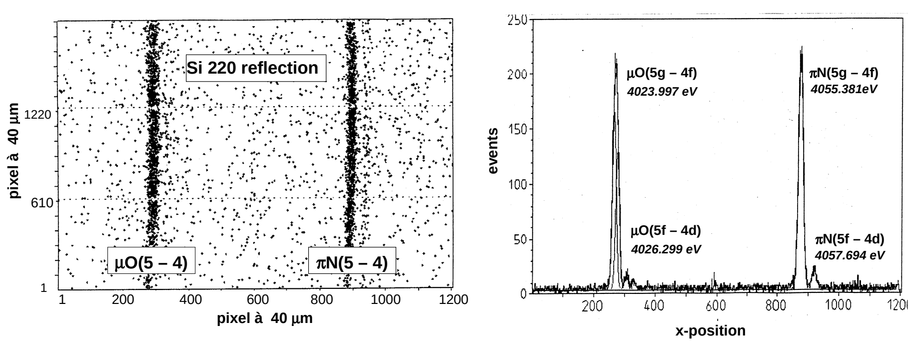

Fig. 2. Sum spectra of the πN and μ O lines with $\approx 40\%$ of all measured events, displayed as a scatterplot (x–y-position) to the left and x-position (after curvature correction) to the right.

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