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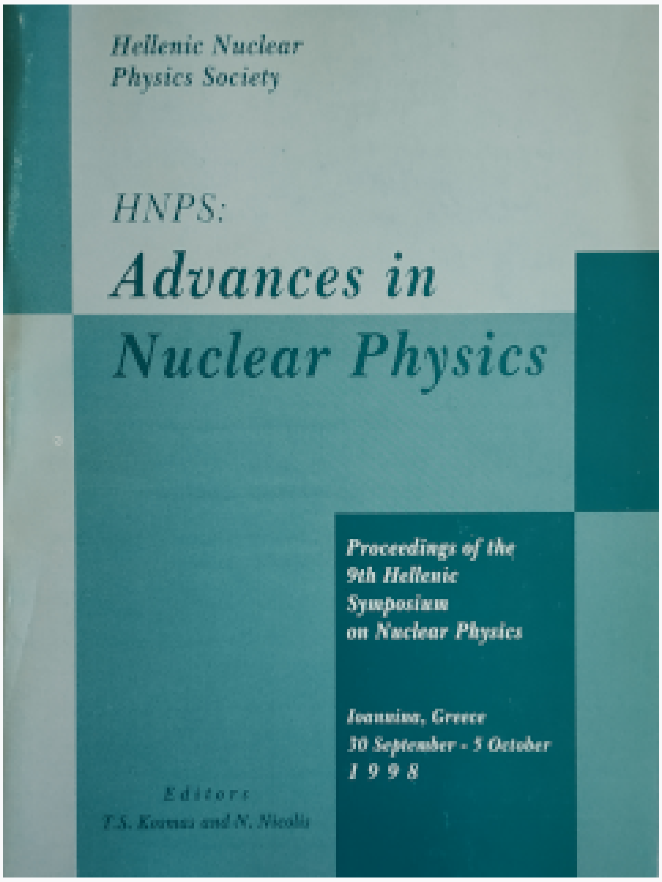

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Mass determination of the charged pion, using high precision X-ray spectroscopy

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Abstract

X-ray transitions in pionic nitrogen were measured using a curved crystal spectrometer. From the transition energy, calibrated with the help of the copper $K\alpha_{1,2}$ electronic transition, a value for the charged pion mass of (139.57071± 0.00053) MeV/c^2 was deduced. In order to reduce the uncertainty of the charged pion mass in the level of 1 ppm, we propose the determination of pionic transition energy based on the more precisely known energies and line shapes of muonic transitions.

1 Introduction

The precise determination of the charged pion mass come either from measurement of the muon momentum in pion decay (assuming knowledge of the muon-neutrino mass) or from measurement of X-ray energies in pionic atoms (assuming knowledge of the relation between transition energy and pion mass) [1–8] (Fig. 1). Based on X-ray spectroscopy, the most precise value for the negatively charged pion up to now was obtained from an experiment at Paul

Scherrer Institute measuring the energy of the 4f→3d transition in pionic magnesium with a solid state target [5]. The measured transition line shape, using a DuMond crystal spectrometer, revealed a FWHM by 20% broader than the expected value. This was attributed to the fact that the 4→3 pionic transition takes place in the presence of either two or one or none K electrons, respectively, which cannot be resolved experimentally (only the influence of the K electrons is significant). The uncertainty of the electron population, and the associated electron shielding of the nuclear charge, causes ambiguity for the pionic transition energy. In the original analysis it was assumed that the strongest component corresponds to the one K electron configuration ($m_{\pi^-}(A)$=139.56782±0.00037 MeV/c^2). In view of more recent cascade studies, a re-analysis leads to a second possible solution, where the strongest component originates from the presence of two electrons in the K shell ($m_{\pi^-}(B)$= 139.56995±0.00035 MeV/c^2) [7].

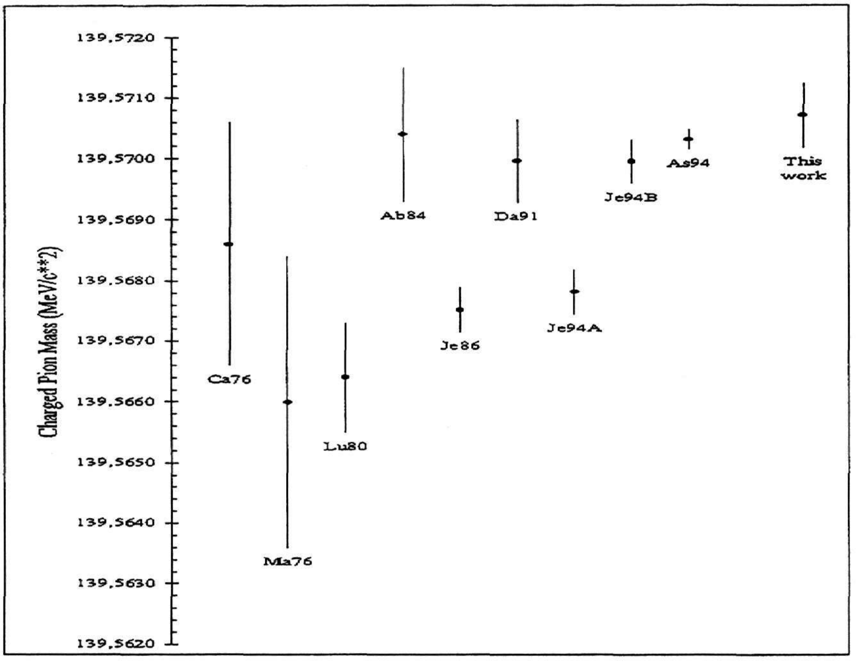

Fig. 1. Previous charged pion mass measurements [1-8, 9] compared to the present study.

These results have a severe impact on the determination of the muon neutrino mass from a precision measurement of the muon momentum in pion decay at rest [8,9]. Corresponding to the two solutions, A and B, two different values for the square of the neutrino mass are obtained. Solution A leads to a negative value by six standard deviations, and thus is regarded to be unphysical. Using solution B, an upper limit of 170 keV/c^2 was determined for the neutrino rest mass.

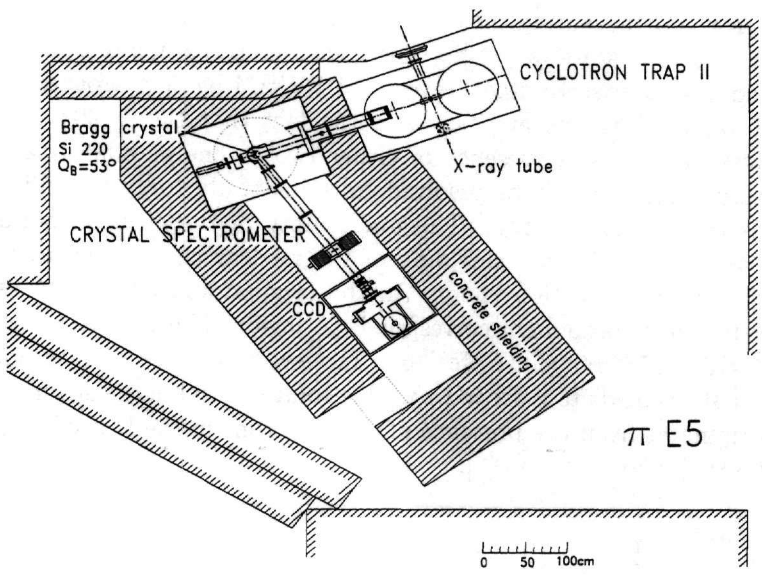

Fig. 1. Set-up of the cyclotron trap and the crystal spectrometer in the πE5 area at PSI.

2 Study of X-ray transitions in pionic nitrogen

The mentioned experiment of X-ray spectroscopy in pionic Mg illustrates the limitations set by the use of dense targets. Since the electron screening cannot be avoided in solid states targets, we performed measurements of pionic X-rays emitted from gas targets, where almost complete ionization can be achieved. The 5g→4f transition of pionic nitrogen, with an energy of about 4.055 keV and natural line width of 8 meV, was selected as optimal choice as:

• It is ideally suited for reflection type crystal spectrometers, equipped with high reflectivity perfect crystals (silicon or quartz), allowing to reach an energy resolution in the order of 10^{-4},

• The photon energy is high enough to avoid attenuation of the X-rays in the target windows and low enough to be detectable in high resolution, position sensitive, silicon detectors, • Predictions from cascade calculations predict that for nitrogen, at a pressure of one bar, there should be a probability of less than 3% for one remaining K-electron when the exotic atom is in the 5g state [10]. The energy separation between the pionic nitrogen 5g→4f transition in the presence of one spectator K-electron and the transition without the presence of K electron is about 0.5 eV. With an experimental energy resolution of less than 1 eV, the contributions from the various electron shell configurations can be determined in the experiment and ambiguities in the determination of the pion mass due to line shifts avoided.

• Parallel transitions and isotope effects causing an energy difference of more than 2 eV are easily disentangled.

The experiment was installed in the πE5 area at the Paul Scherrer Institute (Fig. 2) [11]. The beam line was tuned to a momentum of 85 MeV/c. The intensity was about 4×10^7 π^-/s at a proton current of 1 mA. Inside the target chamber of the cyclotron trap, a cylindrical target container with a diameter of 60 mm and thin walls (50 μm Kapton) was mounted. When this container was filled with nitrogen gas at one bar pressure, about 1.2×10^6 π^-/s were stopped. The X-rays were reflected, in first reflection order, by a spherically bent Si 220 crystal, of 10 cm diameter and a radius of curvature of 2985 mm. The Bragg angle for 4.05 keV photons is about 53°. A CCD detector with a total area of about 17 $\times$ 60 mm^2 (width$\times$height) was used for the X-ray detection. The pixel size was 22.5 $\mu m\times$22.5 μm and the depletion depth about 30 μm.

In Fig. 3a is shown the measured position spectra of the π^{-14}N(5$\rightarrow$4) transitions. The detection rate of pionic nitrogen transitions was about 120/h. The main line corresponds to the pionic 5g$\rightarrow$4f transition, the weaker one to the 5f$\rightarrow$4d parallel transition. The observed line width of about 700 meV (FWHM) is by factor 2 larger than the expected resolution of the spectrometer. This broadening was revealed in the case that diatomic molecules were used as gas target, but was disappeared in the case of monoatomic gases, like Ne. The broadening has been attributed to Doppler broadening, originating from the Coulomb explosion of the molecule [12].

The energy determination of the π^{-14}N(5g$\rightarrow$4f) X-ray transition was completed using the Cu Kα_1 fluorescence X-ray line for calibration. The Cu Kα transitions are among the best studied electronic X-ray lines [13]. For the energy calibration the pionic nitrogen X-ray measurements alternated with measurements of Cu fluorescence X-rays, originating from a copper target irradiated with an X-ray tube. The fluorescence target was placed in the center of the cyclotron trap, at the position of the nitrogen target, without breaking the vacuum and thus avoiding mechanical misalignments. The reflection from the Si (220) crystal planes, in the second reflection order, yields an image close to that of the pionic line and with a small rotation, the Cu reflection could be placed on the detector. The Cu Kα X-ray spectrum is shown in Figure 3b. The obtained, from the calibration procedure, energy of the π^{-14}N(5g$\rightarrow$4f) transition is (4055.398$\pm$0.015) eV.

A calculation including all quantum electrodynamical contributions connects the pion mass, in (MeV/c^2), to the (5g$\rightarrow$4f) transition energy, in (eV), according to the following relation [14,15]:

$$m_{\pi^-} = 0.03475592362 \times (Transition\,Energy) - 1.378395493 \qquad (1)$$

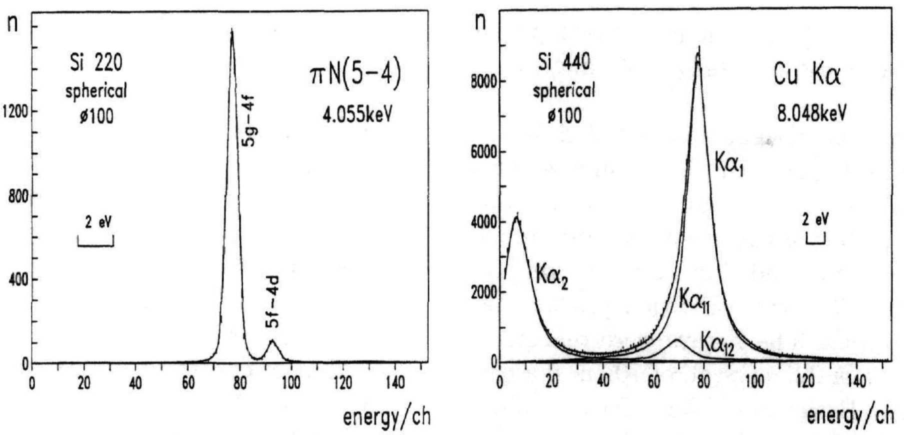

Fig. 2. a) Spectrum of the 5→4 transitions in pionic nitrogen. Ten channels correspond to 1.46 eV b) $K\alpha_{1,2}$ fluorescence spectrum of Cu. The energy of the diagram line $K\alpha_{11}$ is 8047.837(2) eV [13]. correspond to 2.81 eV.

From the measured transition energy and the above mentioned relation, we obtained a pion mass value of (139.57071±0.00053) MeV/c^2. This value is (5.5±3.8) ppm higher than m_{π^-}(B) and more than 15 ppm higher than m_{π^-}(A) (see Fig. 1). Thus our measurement independently corroborates solution B.

3 Towards 1 ppm accuracy on the pion mass determination

An important result of the previous study is the resolution of the ambiguity of [7] in favor of solution B. Nevertheless we should emphasize that more than 50% of the error of our measurement is due to systematic uncertainties of the Cu Kα transition line shape. In order to provide a more precise determination of the muon neutrino mass with a sensitivity of about 70 keV/c^2, which is essential to disentangle various theoretical approaches in the framework of Standard Model, an improved measurement of the pion mass by a factor of about 5 is necessary. An accuracy on the pion mass determination of 1 ppm or better from pionic X-ray measurements requires a calibration line at this level of precision. Fluorescence X-rays with their large natural line widths are unsuitable in this respect. We propose to use a muonic transition of almost equal energy as the pionic transition for the energy calibration [16]. We use the fact that the positive muon mass is known to an accuracy of 0.32 ppm [9]. In assuming CPT invariance we take the same mass value and error for the rest mass of the negative muon. By measuring transitions from different nuclei at quantum numbers not affected by finite size and strong interaction effects, the muonic transitions serve as a precise calibration for the pionic ones. Because of instrumental reasons, the muonic transition should have almost the same energy. The additional requirement to use the same transition in terms of quantum numbers and the request to use gaseous targets led to the pair pionic nitrogen - muonic oxygen. On the basis of these considerations, a feasibility study was performed at PSI to optimize pion and muon stop rates, to investigate the background conditions, and to find the optimal transition. The source of X-rays emitted by the exotic atoms was formed by stopping the pion beam in the cyclotron trap in gaseous targets. There the pions were captured into bound atomic states and they decayed predominantly by photon emission providing an intense X-ray source. During their stay in the trap the pions partially decayed to muons, followed by creation of muonic atoms and their decay through muonic X-rays emission. Muonic oxygen was measured and a count rate of 3/h was obtained, for target gases pressure of 1 bar. From the results of the feasibility study we conclude for the proposed measurement to use the (5g→4f) transitions from π^{-14}N and μ^{-16}O. The calculated transition energy is 4055.376 eV for the (5g→4f) π^{-14}N transition (using m_{π^-}(B) as pion mass value) and 4023.747 eV for the ($5g_{9/2}\rightarrow 4f_{7/2}$) μ^{-16}O. A production run, aiming to 1 ppm accuracy, is scheduled for winter of 1999.

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