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HIGH PRECISION SPECTROSCOPY OF PIONIC AND MUONIC X-RAYS TO EXTRACT AN UPPER LIMIT FOR THE MUON–NEUTRINO MASS*

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A new experiment for a high precision measurement of the pion mass is presented. It combines the cyclotron trap to produce pionic atoms in a small volume, with a doubly focussing crystal spectrometer to measure pionic and muonic X-ray transitions with high accuracy. The muonic X-rays will serve as new high precision standards. The first test experiments demonstrate the feasibility of the project. It yielded a preliminary value for the pion mass of (139570.71 ± 0.53) keV/c^2. In combination with a recent muon momentum result a new value for the muon neutrino was obtained: $M^2_{\nu\mu} = (0.02898 \pm 0.03267)\text{MeV}^2/c^4$. With some improvements which are being prepared, the next measurement can be expected to yield an accuracy of better than 1ppm for the pion mass and hence a limit smaller than 70 keV/c^2 for the neutrino mass.

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1. Introduction

One of the most challenging goals of modern physics research concerns the mass of the neutrinos [1]. For cosmology the massive neutrino is considered a welcome means to solve the problem of dark matter [2]. For elementary particle physics the value of the neutrino mass provides a crucial check of the basic understanding [3–5]. While classic standard theory excludes a neutrino mass, a large variety of extensions have been suggested, where the concept of unstable neutrinos allows a wide band of mass values [6]. For the electron neutrino there exists, meanwhile, a large number of high precision results [1], but the situation is much less favorable for the muon neutrino. Only a few precision experiments on the muon neutrino mass have been reported during the past 20 years [7]. This encouraged us to start an investigation to determine the muon neutrino mass at high level of precision. Preliminary results of a first test measurement will be presented here.

2. General ideas

We consider the decay of a free positively charged pion at rest:

$$\pi^+ \to \mu^+ + \nu_\mu$$

With the help of the conservation laws of energy and momentum and using the CPT theorem:

$$M_{\pi^+} = M_{\pi^-}$$

we obtain for the mass of the muon neutrino:

$$M_{\nu_\mu}^2 = M_{\pi^-}^2 + M_{\mu^+}^2 - 2M_{\pi^-}\sqrt{M_{\mu^+}^2 + p_{\mu^+}^2}\,. \tag{1}$$

As the mass of the muon is known to high precision (.3ppm) [8] and a new value of its momentum has been reported recently [9], the largest uncertainty is presently introduced by the pion mass M_{π^-} [10]. The situation is illustrated in Fig. 1. The uncertainty of M_ν^2 is given as a function of the uncertainty of the pion mass ΔM_π for several values of the uncertainty of the muon momentum p_μ. The actual value is given by the solid line x——x ($\Delta p_\mu = 3.7$ppm), where the open circle ○ denotes the present value of the uncertainty of the pion mass ΔM_π [10].

If we combine current theoretical models, exploiting unstable neutrinos, with the cosmological bounds [6, 11, 12] a mass region between 70 keV/c^2 and 250 keV/c^2 may exist. For comparison, the lower limit 70 keV/c^2 of the corresponding ΔM_ν^2 is included in the figure as a horizontal line.

To perform this sensitive check with the actual values of Δp_μ and ΔM_μ it is necessary to decrease the present uncertainty of the pion mass by roughly a factor of 5. This is the goal of the present experiment.

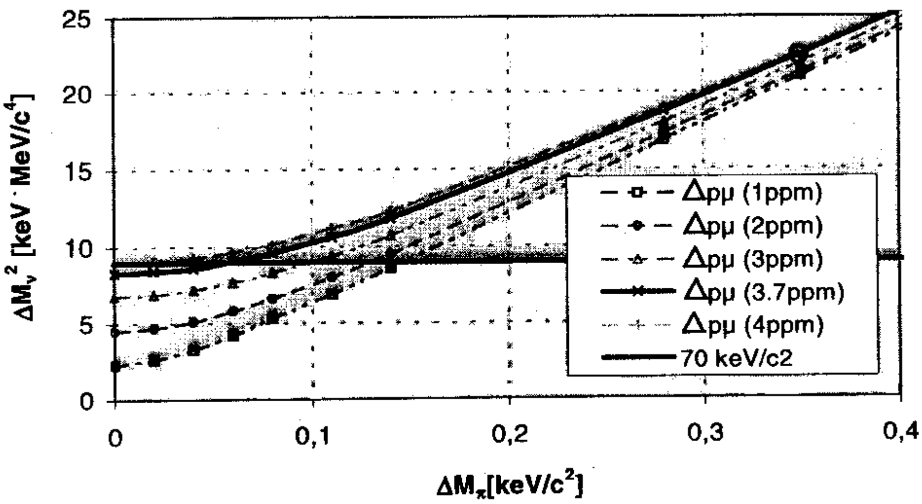

Fig. 1. The uncertainty of the squared muon neutrino mass. For details see the text.

3. Method

As the π^- can form bound atomic systems the most precise determination of its mass can be achieved by the spectroscopy of suitable atomic transitions.

The QED binding energy of a boson in a hydrogen–like system, which connects the pion mass to the energy, is given by the Klein–Gordon equation, to the first order:

$$E_{n,\underline{\ell}} = -\mu \frac{Z^2\alpha^2}{2n^2}\left[1 + \left(\frac{Z\alpha}{n}\right)^2 \left(\frac{n}{\underline{\ell} + \frac{1}{2}} - \frac{3}{4}\right) + \ldots\right], \tag{2}$$

where α is a fine structure constant ($\approx 1/137$), μ — reduced atomic mass, Z — nuclear charge, n — principal quantum number, ℓ — orbital angular momentum, j — total angular momentum, $j = \mid \ell \pm \frac{1}{2} \mid$.

Before applying this relation some precautions have to be considered. In addition to the given electromagnetic interaction the pion states are influenced by the hadronic interaction with the nucleus, depending on the n and ℓ quantum numbers. To avoid the corresponding implications, no innershell transitions should be used.

During the lifetime of a pionic atom the system usually looses most of the electrons. The remaining electrons, however, cause a certain screening of the nuclear charge which can stipulate a complicated satellite structure in the corresponding spectra. This effect is further enhanced if the pionic atom is incorporated in a solid, as electronic refilling from the neighbouring atoms obscures the spectra even more, and prevents an unambiguous interpretation [10, 13]. To circumvent these problems, gaseous targets have to be used measuring transitions low enough in the cascade so that the system is more or less naked [14]. However, the crucial condition for a higher precision measurement requires that eventual satellites must be resolved, which means that such an experiment can only be performed with a high resolution crystal spectrometer [15].

So far, a significant contribution to the uncertainty of the pion mass originates from the calibration standards. In the low energy region generally characteristic X-rays from ionized atoms are used. An inherent disadvantage clearly is the large natural line width. In addition, for a precision measurement the satellite structure has to be taken into account which depends sensitively on the excitation mechanism. Actually, very few X-ray lines have been investigated in sufficient detail so that they can serve for precision calibration.

These problems can be avoided by a completely new approach: The use of muonic X-rays [15]. Due to the lifetime of the pion of 26 ns there always are present muons during the pion mass measurement. When these muons are captured into bound atomic states the energies of hydrogen like states can be described by the Dirac equation to the first order:

$$E_{n,\underline{j}} = -\mu \frac{Z^2\alpha^2}{2n^2}\left[1 + \left(\frac{Z\alpha}{n}\right)^2 \left(\frac{n}{\underline{j}+\frac{1}{2}} - \frac{3}{4}\right) + \ldots\right] . \quad (3)$$

For meaning of symbols see above.

As the natural line width of these transitions is very narrow, it is possible to select transitions, where the eventually occurring satellite lines are weak and well separated. Therefore, by a proper choice of atomic systems and quantum numbers, it is possible to compare transition energies and hence the reduced masses of the pionic and the muonic systems directly, largely avoiding systematic uncertainties. If, in addition, the transitions are chosen so that the corresponding Bragg angles are very similar and the detector is large enough to cover the angular distance, the lines can be measured for one instrumental setting eliminating systematic uncertainties due to spectrometer movements. This is the strategy envisaged in the present experiment.

4. The experiment

The experimental setup consist of three main components: the cyclotron trap [16], the crystal spectrometer and the CCD detector system which are shown schematically in Fig. 2. The setup was installed in the πE5 area of the PSI experimental hall online at the pion beam line.

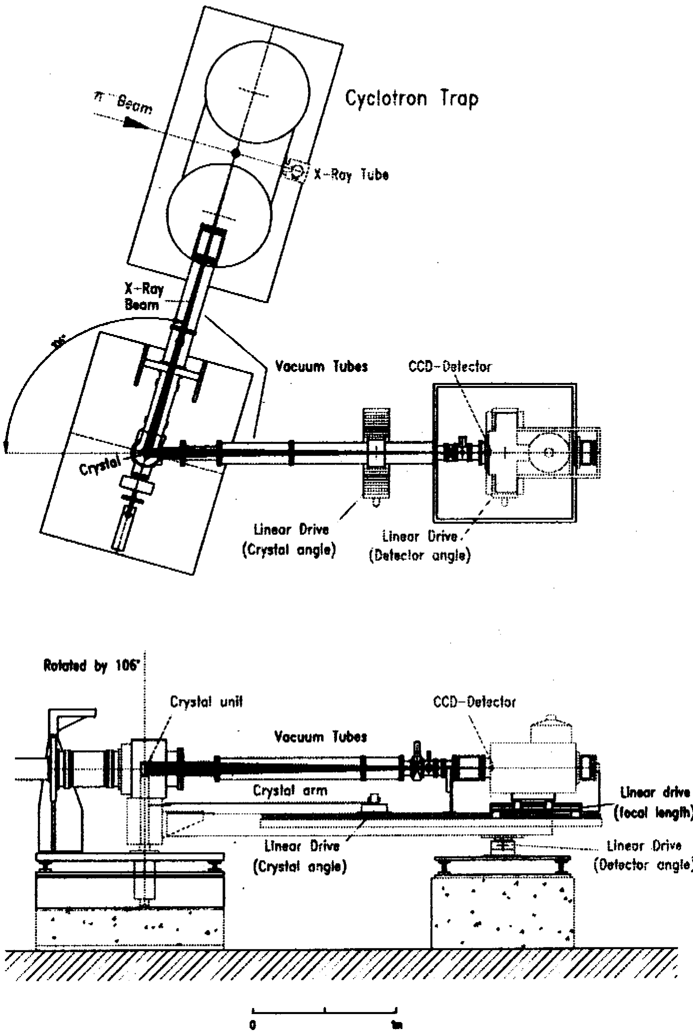

Fig. 2. The experimental setup.

The pion beam is injected into the new cyclotron trap [17], a superconducting split coil magnet. As the trap chamber is filled with the target gas to be investigated, the pions lose energy due to collision with the gas molecules and are thus forced by the magnet field to spiral down to the center of the trap. By a suitable choice of magnet field and pressure, they reach the center with no kinetic energy left and are captured with high probability into excited bound atomic states. During the deexcitation the exotic atom looses its electrons and the pion cascades down via characteristic electromagnetic transitions. These X-rays pass through vacuum tubes and reach the spherically shaped crystal of the Bragg spectrometer. A novel technique has been developed to produce such large area doubly focussing Bragg crystals with high precision [18]. It could be shown that the resolution, even with diameters up to 10 cm, is close to the theoretical limit. For the experiment, the crystal spectrometer was equipped with a 10 cm diameter Si(220) crystal with a radius of curvature of 2985.4 mm. The X-rays are reflected according to Bragg's law and focussed in horizontal and vertical direction. In this way, at the focus a small image of the source is produced which allows to use a CCD detector for registration.

The CCD detector offers three advantages: Due to the very small pixel size ($22.5 \times 22.5\,\mu\mathrm{m}^2$) it exhibits an intrinsic high spatial resolution. As it is two dimensional position sensitive it allows to correct for the curvature of the X-ray images thus maintaining the resolution of the crystal. Finally, as the real X-ray events mainly occur as single pixel hits, a hit cluster analysis of the CCD pixels allows a drastic reduction of the background. The excellent energy resolution of the CCD allows a further reduction by applying narrow pulse height windows. This is a very essential feature as the associated intense neutron flux creates a high background, which cannot be eliminated even by a 1m thick concrete shield around the detector.

The detector arm and the crystal arm are moved to the preselected angular position by linear tables. In addition, the detector is positioned at the corresponding focal point by another linear drive. The actual positions are measured by angular encoders with an accuracy of 0.12 arcsec and linear potentiometers with an accuracy of 0.1 mm, respectively, stabilized by piezoceramic units and controlled by a PC.

For calibration purposes, it is possible to introduce into the center of the trap a solid target that can be excited to photo-fluorescence by means of an X-ray tube.

During the test measurement a proton beam of maximum 1.5 mA was available that yielded a pion beam of $5 \times 10^7 \pi^-/\mathrm{s}$. About 3% of the pions were stopped in the cyclotron trap. We measured the $5 \rightarrow 4$ transitions in pionic N_2 and muonic O_2 with energies around 4.05 keV at a Bragg angle of about 52°. To check the instrumental resolution we also measured in second order the 5g$\rightarrow$ 4f transition in pionic Ne and muonic ^{3}He. As there was only a CCD with 17 mm width at disposal [19], we had to move the instrument between the pion measurements and the others. In the main reflections of N_2 and O_2 we obtained a count rate of 200/h for pions and 10/h for muons. In view of the limited beam time, the intense fluorescence X-rays (up to 1000/h) from Cu, Sc and Xe were measured as secondary energy calibration. In the table below we give a complete list of the measured transitions, their energies, and Bragg angles. The experiment was performed by a several times cyclic alternation of measurements of pionic N_2, muonic O_2, electronic

Cu K$\alpha_{1,2}$, Sc K$\alpha_{1,2}$ and Xe Lα_1. The measuring time was chosen so that the combined statistical errors became minimum with exception of muonic O_2.

Element	Transition	Energy, in eV[1]	θ_B in degree
μ^{-16}O	$5g_{9/2} \to 4f_{7/2}$	4023,757	53.3559
	$5g_{\frac{7}{2}} \to 4f_{5/2}$	4024,308	53.3486
π^{-14}N	$5g \to 4f$	4055, 376[2]	52.7595
	$5f \to 4d$	4057,669	52.7297
μ^{-3}He	$2p_{1/2} \to 1s$	8149,25043	52.4027
	$2p_{3/2} \to s$	8149,39508	52.4036
π^{-20}Ne	$5g \to 4f$	8306,438	51.0184
Sc	Kα_2	4085.96 ± 0.04	52.1735
	Kα_1	4090.75 ± 0.03	52.1125
Xe	Lα_2	4096.38 ± 0.03[3]	52.0114
	Lα_1	4110.09 ± 0.02	51.7674
Cu	Kα_2	8027.993 ± 0.005[4]	53.5436
	Kα_1	8047.837 ± 0.002[5]	53.3528

[1] The energies of the exotic atoms translations have been calculated by S. Boucard and P. Indelicato
[2] Pion mass according to solution B of [10], $m_\pi = 139.56995 \text{MeV}/c^2$
[3] Mooney *et al.*, *Phys. Rev.* **A45**, 1531 (1992)
[4] Deutsch *et al.*, *Phys. Rev.* **A51**, 283 (1995), Table II, Single crystal
[5] Deutsch *et al.*, *Phys. Rev.* **A51**, 283 (1995), Table II

5. Results and discussion

As the analysis is on its way the results should be considered preliminary. A typical spectrum of the $5 \to 4$ transition in pionic N is shown in Fig. 3. On the left hand side the 5g→4f circular transition and the 5f→4d parallel transition are clearly visible with an intensity ratio of $(6.7 \pm 0.2)\%$. More details can be seen on the right hand side which is the identical spectrum at an expanded vertical scale. It shows the fit model as a superposition of a narrow (solid) and a broad (dashed) Gaussian. Further can be observed 5d→4p transition which is shifted and broadened due to the hadronic interaction and the 5g→4f transitions in the isotope ^{15}N. With the help of cascade calculations it was estimated that the intensity of a satellite with remaining K-electron is less than 2%. It could not be identified with the present statistics. The peak to background ratio of 500:1 for the main line underlines the high quality of the data. As we could not collect sufficient statistics in the muonic O_2 transitions we use for the absolute energy calibration the Cu Kα_1 line, because there exists a precise recent parametrization [20].

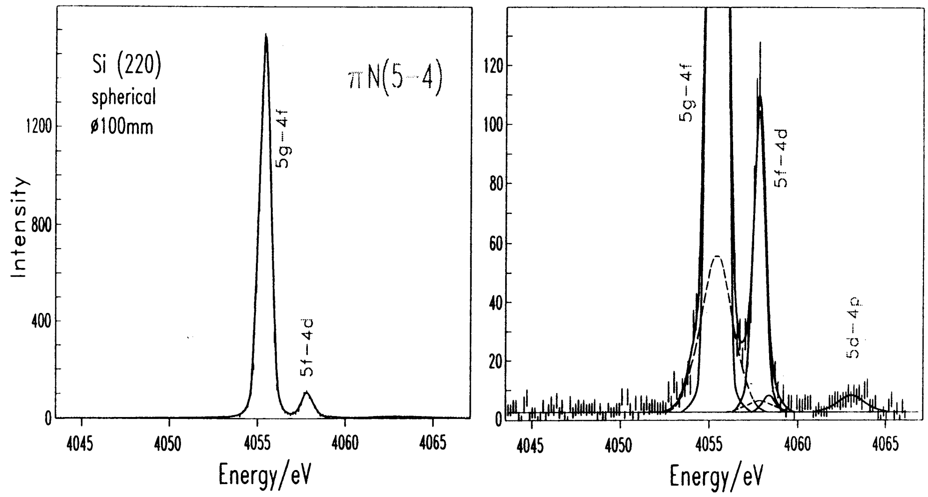

Fig. 3. The spectrum of the $5 \to 4$ transition in pionic N. The left-hand side shows the total view of the collected data. The right-hand side is the same spectrum at expanded vertical scale, revealing details about the weaker components.

When we include the QED corrections, correct for the refraction index shift, using the N mass from [21], we find a pion mass value of (139570.71 ± 0.53) keV/c^2. The uncertainty is obtained by a quadratic summation of the statistical uncertainties (1.1 ppm) and the systematic uncertainties (3.6 ppm) as stability, geometry, alignment, defocussing and fit, which have been partly estimated by MC simulations [22]. When we use the most precise published values for p_μ [9] and M_μ [8] we obtain by means of Eq. (1) for $M^2_{\nu_\mu} = (0.02898 \pm 0.03267)\text{MeV}^2/c^4$. This result is compared with previous published values in Fig. 4. Here $M^2_{\nu_\mu}$ is displayed as a function of the pion mass M_π. The results of Assamagan [9] for the muon momentum p_μ shows up as an almost diagonal band denoted by $\pi^+ \to \mu^+\nu_\mu$. Solution A and B of Jeckelmann *et al.* [13,10] with their uncertainty bands shadowed are given and the combined final uncertainty is indicated as ellipse. Our preliminary result together with its uncertainty band shadowed is denoted as this experiment. It is compatible with zero neutrino mass and with Jeckelmann B [10]. If we assume $M_{\nu_\mu} = 0$ the Assamagan result [9], indicated as Assamagan 96 ($M_{\nu_\mu} = 0$), yields an improved value for the pion mass which is also included in Fig. 4.

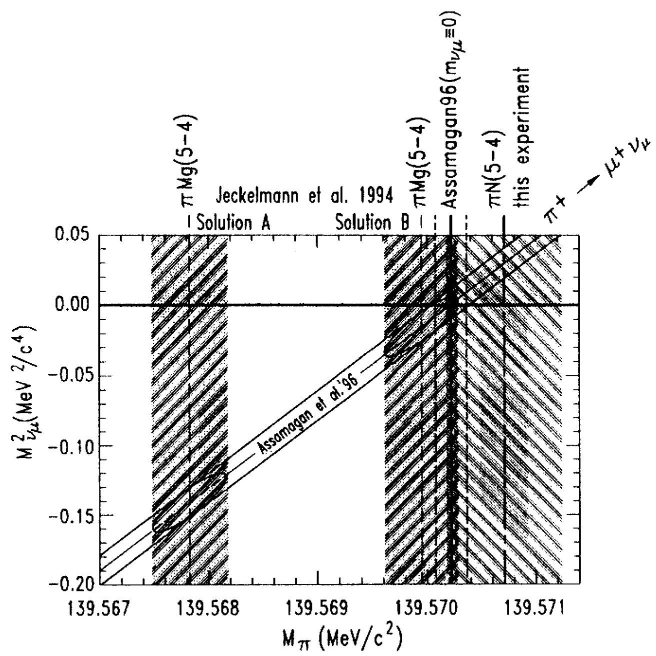

Fig. 4. The squared neutrino mass as a function of the pion mass. The slanted band denotes the muon momentum p_μ. The vertical bands indicate recent pion mass measurements. The overlap regions of the p_μ band with the individual pion mass bands denote the corresponding $M^2_{\nu_\mu}$ values.

6. Conclusion

A critical inspection of the uncertainties of the experiment shows that with the envisaged improvements: the cyclotron trap optimized for high intensity and a large CCD with a size of $60 \times 60\text{mm}^2$ using a stable proton beam of 1.5 mA a final uncertainty of the pion mass of less than 1 ppm is feasible. This will allow us to reduce the uncertainty of the muon neutrino mass below the crucial value of 65 keV/c^2.

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REFERENCES

[1] A comprehensive review of the actual state can be found in Proc. Int. Conf. Neutrino and Astrophysics, Capri 1996, *Nucl. Phys.* **B**, (1997).

[2] F. Klinkhamer in Proc. 6^{th} Moriond Workshop, Editions Frontieres Gif-sur-Yvette, M48, 1986, p.33; G. Steigman, Proc. 6^{th} Moriond Workshop, Editions Frontieres Gif-sur-Yvette, M48, 1986, p. 51; D. Spergel, Proc. 6^{th} Moriond Workshop, Editions Frontieres Gif-sur-Yvette, M48, 1986, p. 113.

[3] P. Langacker, *Nucl. Phys.* **B38**, 152 (1995) and references therein.

[4] G. Ross, *Nucl. Phys.* **B38**, 164 (1995) and references therein.

[5] C. Heusch, *Nucl. Phys.* **B38**, 313 (1995) and references therein.

[6] D. Sciama, *Nucl. Phys.* **B38**, 320 (1995) and references therein.

[7] Particle Data Group, *Phys. Rev.* **D54**, 1 (1996).

[8] Particle Data Group, *Phys. Rev.* **D50**, 1173 (1994).

[9] K. Assamagan *et al.*, *Phys. Rev.* **D53**, 6065 (1996).

[10] B. Jeckelmann, P.F.A. Goudsmit, H.J. Leisi, *Phys. Lett.* **B335**, 326 (1994).

[11] H. Harari, Y. Nir, *Nucl. Phys.* **B292**, 251 (1987).

[12] S.L. Glashow, *Phys. Lett.* **187B**, 367 (1987).

[13] B. Jeckelmann *et al.*, *Nucl. Phys.* **A457**, 709 (1986).

[14] R. Bacher *et al.*, *Phys. Rev.* **A39**, 1610 (1989).

[15] D. Anagnostopoulos *et al.*, PSI Proposals R-94.01 and R-97.02.

[16] L.M. Simons, *Phys. Scr.* **T22**, 90 (1988).

[17] L.M. Simons, *Hyperfine Interactions*, North Holland Pub. Com., Amsterdam, **81**, 253 (1993).

[18] The technique has been developped in collaboration with the optical company Carl Zeiss, Oberkochen.

[19] D. Varidel *et al.*, *Nucl. Instrum. Methods* **A292**, 147 (1990).

[20] M. Deutsch *et al.*, *Phys. Rev.* **A51**, 283 (1995).

[21] F. DiFilippo *et al.*, *Phys. Rev. Lett.* **73**, 1481 (1994).

[22] A more detailed discussion can be found in a forthcoming paper S. Lenz *et al.* in *Phys. Lett.* (1997).