NEW UPPER LIMIT FOR $\mu^- \to e^+$ CONVERSION

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An upper limit for $\mu^- \to e^+$ conversion has been established by searching for specific decay properties of the expected final state nucleus. We obtain $R_{coh} = (\mu^- + {}^{127}I \to e^+ {}^{127}Sb^*)/(\mu^- \to \nu_\mu) < 3 \times 10^{-10}$ with 90% c.l.

Recently the interest in studying weak leptonic processes forbidden by separate lepton number conservation [1] has been revived [2,3]. The reason was on the one hand the unification of the electromagnetic and weak interactions suggested by Weinberg and Salam which received additional support by the discovery of neutral currents in the weak interaction, whereas the discovery of the τ lepton and presumably its neutrino brought an additional lepton doublet in the picture. On the other hand, the superior experimental facilities of the meson factories stimulated experiments aiming either at establishing lower upper limits for the so far forbidden processes or at discovering them.

The process $\mu \to e + \gamma$ has been investigated and a new upper limit for the branching ratio $R_\gamma = (\mu \to e + \gamma)/(\mu^- \to \nu_\mu)$ of $< 1.9 \times 10^{-10}$ has been found [4]. A recent experiment at SIN has studied $\mu \to e$ conversion in ${}_{16}S$ where the electron spectra have been observed thus establishing upper limits of [5] $R_{e^-} = 7 \times 10^{-11}$ for the process $\mu^- + Z \to e^- + Z$ and $R_{e^+} = 9 \times 10^{-10}$ for the process

$$\mu^- + A(Z, N) \to e^+ + A(Z-2, N+2)\,, \qquad (1)$$

where it was assumed that in the process $\mu^- + {}^{32}S \to e^+ + {}^{32}Si$ the mean excitation energy of the ${}^{32}Si$ nucleus is 20 MeV. This latter process is of interest in schemes like the one of Konopinski and Mahmoud [6] where μ^-, ν_μ, e^+ and $\bar{\nu}_e$ have the same lepton number. Since, however, the process requires the exchange of two p's into two n's which means a two-step process with reabsorption of the ν_μ,

$$\mu^- + p \to \nu_\mu + n, \quad \nu_\mu + p \to e^+ + n\,,$$

or involving a Δ^{++},

$$\mu^- + \Delta^{++} \to e^+ + n + n\,,$$

it is certainly suppressed by the required nuclear processes. Therefore, if the process of eq. (1) is not seen at a certain level it does not mean necessarily that the KM scheme is not valid; it requires a careful estimate of the rate at which the nuclear process can proceed.

We report here on a new experiment to determine the branching ratio for $\mu^- \to e^+$ conversion, $R_{coh} = (\mu^- \to e^+)/(\mu^- \to \nu_\mu)$, based on a different detection process. Reaction (1) can also be detected if instead of the e^+ the final nucleus $A(Z-2, N+2)$ is observed. We decided to look for this nucleus by combining highly selective and sensitive radiochemical methods with low

level counting techniques. This has several advantages:

(a) no limitation of the useful μ^- beam intensity,

(b) high detection efficiency,

(c) high selectivity for process (1) as compared with competing processes which can also create e^+,

(d) accumulation of events in the beam for several days, measurement off-beam.

The disadvantages to be encountered are:

(a) Only coherent processes where the final state nucleus is not broken up are detectable requiring additional theoretical information to correct for incoherent contributions. $R_{coh} = R_{e^+} \cdot P_{coh}$ where P_{coh} denotes the probability that the final nucleus is produced in a particle stable state.

(b) The competing pionic double charge exchange process leading to the same final state,

$$\pi^- + A(Z,N) \rightarrow \pi^+ + A(Z-2, N+2)\,,$$

must be controlled.

The choice of the isotope should fulfill the following requirements:

– medium or heavy Z in order to have a large capture rate,

– monoisotope in order to comply with radiochemical methods,

– convenient decay scheme,

– good experimental detectability of the final nucleus.

This led us to the process

$$\mu^- + {}^{127}_{53}\mathrm{I} \rightarrow e^+ + {}^{127}_{51}\mathrm{Sb}\,, \qquad (1a)$$

with the decay scheme

$${}^{127}_{51}\mathrm{Sb} \xrightarrow[3.85\,\mathrm{d}]{\beta^-} {}^{127}_{52}\mathrm{Te} \xrightarrow[9.35\,\mathrm{h}]{\beta^-} {}^{127}_{53}\mathrm{I}\,.$$

This particular choice involves a natural pure isotope and leads to a decay chain with two radioactive isotopes with life times facilitating the task of chemical separation of the ^{127}Te formed by this process and emitting β^- with E_{max} = 690 keV. The chemical treatment was aiming at a quantitative separation of only that ^{127}Te which was produced by the decay of ^{127}Sb.

In order to detect small amounts of ^{127}Te a low level counter has been developed particularly suited to detect the β spectrum with its end point at 690 keV. A particular Si surface barrier detector with low natural background was selected. It had a sensitive surface of 200 mm^2 and a depth of 412 μm with a background rate of 420 h^{-1} in the energy region between 200 and 700 keV. This rate could be substantially reduced by shielding the detector closely by 40 g/cm^2 Hg, triply distilled, from all sides (110 h^{-1}), by putting a hat shaped plastic anticounter against cosmic rays on top of it (16 h^{-1}), and mounting 2 cm Pb and Fe on top in order to shower off the γ-component of the cosmic rays. Thus a background rate of 6 h^{-1} could be reached in the energy region of interest.

The experiment proper was performed as follows: A disk of compressed high purity NaI of 8 cm diameter and 1.5 cm (= 5 g/cm^2) thick in compliance with the beam dimensions was bombarded with μ^- for 123 h. The μ^- flux averaged about 8×10^6 s^{-1} and the stop rate about 5.6×10^6 s^{-1} thus totalling 2.8×10^{12} μ^- stops. The rates were determined by standard counter telescope techniques and a small monitor counter and are believed to be correct within 10%. We note that for NaI the fraction of μ stops in I has been measured [7] to be 77% [W(I)/W(Na) = 3.4]. From these 96.4% are captured by the I nucleus [8] yielding 2.1×10^{12} μ^- captures in I or a capture rate $\phi_0 = 1.69 \times 10^{10}$ h^{-1}.

The aim of the chemical separation was to eliminate all primarily formed Te (step 1) in order to assure that all Te extracted afterwards (step 2) has been produced by the β-decay of Sb. To achieve this quantitatively, relatively large quantities of inactive ions of the interesting elements could be added as carriers, so that normal separation techniques could be used. The bombarded NaI-target was dissolved in distilled water and after addition of inactive solutions of Ag^+, Cd^{2+}, Sn^{2+}, TeO_3^{2-} and Sb^{3+} these ions were precipitated as sulfides. The precipitation was filtered off and washed and then heated with an ammoniacal solution of $(NH_4)_2S_x$ and filtered. The insoluble residue contained Ag_2S, CdS and partially SnS, whereas Te, Sb and most of the Sn went into solution. By acidifying this solution with diluted HCl (pH $\approx$ 1) the sulfides of Sb, Sn and Te are reprecipitated. After filtering and thoroughly washing with diluted HCl, the remaining solid was heated with concentrated HCl. Thereby Sb_2S_3 and SnS were dissolved, whilst most of the TeS was reduced to elemental Te which was filtered off. Further purification of the solution from primarily formed ^{127}Te was made by reduction of Te-ions to elemental Te by hydrazine in hot strong HCl. Ions of Sb and Sn have no analogous reaction. For this purpose a further quantity of inactive TeO_3^{2-} and a known activity of ^{125m}Te were added to the HCl solution prior to the reduction with hydrazine.

The precipitate of elemental Te was filtered off. This last step was repeated twice. The resulting HCl solution contained different isotopes of Sb and Sn, but no primarily formed ^{127}Te.

Step 2 was done as follows: From this final solution every 12, respectively 24 h the ^{127}Te formed by decay of ^{127}Sb was isolated by reduction with hydrazine after addition of inactive Te as carrier and ^{125m}Te as a tracer. For further purification of the elemental Te from absorbed Sb and Sn, the precipitate was redissolved by heating with a mixture of H_2O_2 and NH_3. After evaporation of the liquid, the residue was dissolved in strong HCl and the Te once more reduced to the elemental state with hydrazine. After filtering and thoroughly washing and drying, this last precipitate served as the sample to be counted.

As a consequence of the irradiations of ^{127}I with μ^- a great number of radioactive isotopes is produced. Thus, isotopes down to ^{119}Te, ^{118}Sb and ^{117}Sn could be identified by their characteristic γ-radiations measured by a 4π NaI and planar Ge-detectors in the original NaI sample as well as in the various parts of the chemical fractions in the course of the chemical treatment. In this way it was possible to have a close check on losses during the different steps of the chemical separation. In particular the ^{122}Sb isotope with 2.7 d half life was suitable to measure directly the loss of Sb. It amounted to about 15% and was determined for each sample separately and accounted for by the factor f_{Sb} in the counting rate balance.

The ^{125m}Te tracer allowed us to check the chemical extraction efficiency f_{Te} of the whole procedure. ^{125m}Te with $T_{1/2}$ = 58 d shows only a converted γ line at 82 keV which is detectable on the Si surface barrier detector but does not affect the counting rate in the energy region above 150 keV.

8 Te extractions were prepared over a period of 12 days starting 12 h after the end of the μ-irradiation. Each Te sample was counted for 12–24 h in the low level counter where all events between 200 and 700 keV energy have been summed up. The thus obtained rates per hour have been plotted versus time. A typical measurement is shown in fig. 1.

We can now calculate the decay rate per hour, i.e. the activity of the ^{127}Te, A_{Te}, assuming that a fraction R of the μ captures in I lead via the $\mu^- \rightarrow e^+$ conversion process to ^{127}Sb. If we relate this activity to the time $t = 0$ defined as the end of the μ-irradiation

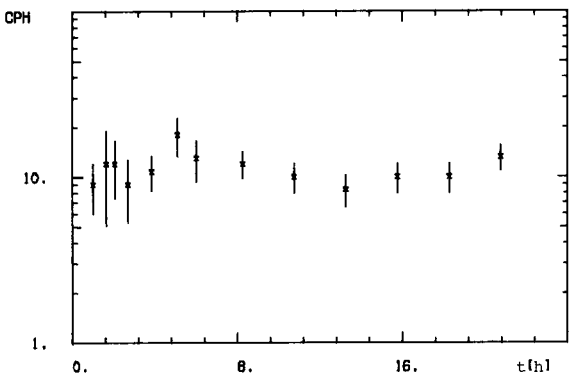

Fig. 1. Time spectrum of the second Te sample.

we obtain

$$A_{Te}(t=0) = A_{Sb}(t_s)\cdot\alpha\frac{\lambda_{Te}}{\lambda_{Te}-\lambda_{Sb}} f_1 f_2 f_{Sb} f_{Te}\cdot\epsilon\,. \quad (2)$$

The Sb activity $A_{Sb}(t)$ is given by

$$A_{Sb}(t) = \phi_0\cdot R_{coh}(1 - e^{-\lambda_{Sb}t})\,. \quad (3)$$

With $\lambda_{Sb} = \ln(2)/3.85\,(d) = 7.5\times10^{-3}\,(h^{-1})$, $\phi_0 = 1.69\times10^{10}\,(h^{-1})$, and the irradiation time t_s = 123 (h), one obtains

$$A_{Sb}(t_s) = 1.02\times10^{10}\cdot R_{coh}\,(h^{-1})\,. \quad (3a)$$

Furthermore we have

$$\lambda_{Te} = \ln(2)/9.35\,(h) = 7.4\times10^{-2}\,(h^{-1})\,.$$

$\alpha = 0.83$ is the branching ratio for the decay of ^{127}Sb in the ^{127}Te 9.35 (h) ground state [9] (not the long living ^{127m}Te). $f_1 = \exp(-\lambda_{Sb}t_1)$ accounts for the decay of the ^{127}Sb where t_1 is the time elapsed between the end of the irradiation $t = 0$ and the beginning of the ^{127}Te production defined by the previous extraction of all Te. $f_2 = \exp(-\lambda_{Sb}t_2) - \exp(-\lambda_{Te}t_2)$ is the fraction of ^{127}Te produced by the ^{127}Sb decay where t_2 is the time elapsed between two successive Te extractions. $\epsilon = 0.20$ is the efficiency of the low level counter to detect a β ray in the energy region between 200 and 700 keV. It was determined experimentally using a ^{127}Te source of known activity.

The product $f^i = f_1^i f_2^i f_{Sb}^i f_{Te}^i$ is different for each ^{127}Te sample extracted. It relates the expected activity for the sample (i) to the time $t = 0$. Each single sample

(i) can be used to determine a value R^i from eqs. (2) and (3a):

$$R^i = A_{\mathrm{Te}}(0)\,\frac{\lambda_{\mathrm{Te}}-\lambda_{\mathrm{Sb}}}{\lambda_{\mathrm{Te}}}\,\frac{1}{1.02\times10^{10}}\,\frac{1}{\alpha\cdot\epsilon}\,\frac{1}{f^i}, \tag{4}$$

$$R^i = 5.44\times10^{-10}\,A_{\mathrm{Te}}(0)/f^i\,. \tag{4a}$$

The time spectrum of a single sample (fig. 1) shows a practically constant behaviour where the activity is somewhat above the empty counter background probably caused by a small contamination of the Te source by long living Sb isotopes.

If we fit a curve of the type

$$A^i_{\mathrm{Te}}(t) = A_{\mathrm{Te}}(0)\,\mathrm{e}^{-\lambda \mathrm{Te} t} + B \tag{5}$$

to the time spectrum one obtains a fit value with its error, $A^i_{\mathrm{Te}}(0) \pm a^i$, for the Te activity. From eq. (4a) R^i values of about 10^{-9} can be deduced in this way.

Now we make use of the fact that we have at our disposal 8 decay curves of single Te samples. In order not to average over possible fluctuations in time we add up each time interval separately where f^i was used as weighting factor. In this way the summed time spectrum as shown in fig. 2 is obtained. This spectrum shows non-statistical fluctuations. Since all single spectra started to be taken at the same time (9 a.m. local time) it was suspected that we observe fluctuations correlated with the day time. Indeed, an earlier background measurement performed over 5 days with a sample without any chemical precipitation on it showed the same variation in time as shown also in fig. 2.

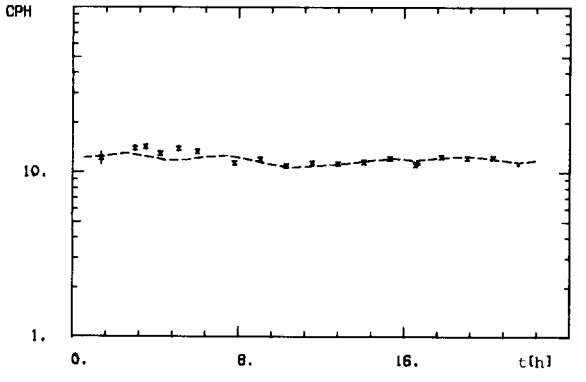

Fig. 2. Time spectrum obtained by a weighted summing up of the time spectra of the eight Te samples X. Background spectrum obtained in 5 days as described in the text – – –.

After subtraction of this background with a suitable normalization a fit procedure analogous to eq. (5) was performed. For the initial ^{127}Te activity at the end of the irradiation a value of

$$A_{\mathrm{Te}}(t=0) = (0.35 \pm 0.22)\,\mathrm{h}^{-1}$$

was obtained. We refrain from interpreting this result as being significantly different from zero. Assuming a gaussian distribution this means that with 90% c.l. at most 0.64 events could be attributed to originate from ^{127}Sb.

With eq. (4a) and $f = 1.46$ we obtain an upper limit for

$$R_{\mathrm{coh}} < 3\times10^{-10}\,.$$

Possible contributions of radiochemical impurities were ruled out in the following way. The entire chemical and counting process was duplicated by an unirradiated sample. No signal was found.

Furthermore, the pionic double charge exchange would lead to the same final state nucleus ^{127}Sb. Though the contamination of π^- in the μ^- beam has been measured to be $<5\times10^{-4}$, a separate experiment is necessary to exclude this process. 1.2×10^{12} π^- have been stopped in an identical NaI target which means that π^- with energies below 30 MeV could have reacted with the target nuclei. The same chemical procedure and low level counting of the ^{127}Te samples has been performed as after the muon irradiation. No sign of a ^{127}Te activity has been found. Therefore, it could be concluded that less than 9×10^{-10} (π^-, π^+) double charge exchange reactions have occurred per π^- stop. With the above quoted pion contamination in the μ beam that means that the charge exchange reaction can play a role only orders of magnitude below our present sensitivity. A similar test was also performed with π^- hitting the target with 220 MeV/c with a very similar result.

In order to interpret the above mentioned ratio R_{coh} in terms of a limit for $R_{\mathrm{e}^+} = (\mu^- \to \mathrm{e}^+)/(\mu^- \to \nu_\mu)$ one has to know P_{coh}, the probability that the conversion process is a coherent process in the sense that the nucleus does not break up but remains in its ground state or in a particle stable excited state.

Since to our knowledge P_{coh} has not been calculated for the process (1a) in any model we prefer to quote our results directly in terms of R_{coh}.

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