PRECISION MEASUREMENT OF NUCLEAR MUON CAPTURE BY ^{3}He

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Nuclear muon capture was discovered more than forty years ago, but we still lack a precise experimental verification of our understanding of this process. The accuracy requirements are rather high. In particular, the muon capture rate in hydrogen in the reaction

$$\mu^- + p \rightarrow n + \nu_\mu \tag{1}$$

must be measured with the accuracy of 1%. It requires either an absolute calibration of the neutron detector on a level of <1% or the muon lifetime measurements (*via* the $\mu \rightarrow e$ decay) with the accuracy not worse than 10^{-5}. Experimentalists have not yet reached the required accuracy. Moreover, the interpretation of the data on the muon capture rate in hydrogen is hampered by existing uncertainties in the data on the mesomolecular processes in hydrogen (the rate of the $pp\mu$-molecules formation and, especially, the transition rate of the $pp\mu$ orto-molecule into the $pp\mu$ para-molecule), because the muon capture rate essentially depends on whether muon is in a μp atom, in an orto-molecule, or in a para-molecule. On the other hand, study of muon capture on nuclei of medium mass suffers from the unreliability of the theoretical interpretation due to the necessity of involving nuclear models.

Among all these reactions, the muon capture in ^{3}He gives a unique opportunity to improve both the accuracy of measurements and the theoretical interpretation of obtained results. This concerns the nuclear muon capture reaction leading to formation of ^{3}H:

$$\mu^- +^3 \mathrm{He} \rightarrow^3 \mathrm{H} + \nu_\mu. \tag{2}$$

In this case the initial state of the μ^3He system is well defined: it may be statistically populated either singlet or triplet state of the μ^3He atom. Moreover, the muon capture rates in these states do not differ much thus enhancing the reliability of the measurement. For the data interpretation it is important that ^{3}He and ^{3}H nuclei are members of an isospin doublet. Thus, the muon capture reaction (2) is especially well suited for a reliable application of the so-called "elementary particle model" pioneered by C.Kim and H.Primakoff in 1965. In this approach, the data on the muon capture are analyzed together with the data on the β-decay of ^{3}H and the electron scattering on ^{3}He nucleus thus enabling the simple reconstruction of the form factor for the pseudoscalar interaction of the muon with the nucleus. Finally, it is important that the $A = 3$ system is studied in details theoretically. The wave function of this system is well defined. It opens the possibility for "microscopic description" of the muon capture reaction and, in particular, for revealing the "meson currents" role in the nucleus.

Prior to this experiment there were only three measurements of the absolute rate of the reaction (2), all performed more than 30 years ago. For the first time the muon capture on ^{3}He was observed in 1963 by the B.Pontecorvo's group at JINR (Dubna) in the experiment with a ^{3}He-filled diffusion cloud chamber. They identified about 200 events and determined the muon capture rate as $\lambda_c = 1410 \pm 140$ s^{-1}.

The next result reported by D.Clay et al. in 1965 was obtained in the experiment where the muons were stopped inside a gas scintillation counter filled with a ^{3}He/Xe mixture. They found $\lambda_c = 1465 \pm 67$ s^{-1}. A similar technique was used in the experiment of L.Auerbach et al. (Berkeley, 1965, gas scintillation counter, pure ^{3}He). Their result: $\lambda_c = 1505 \pm 46$ s^{-1}.

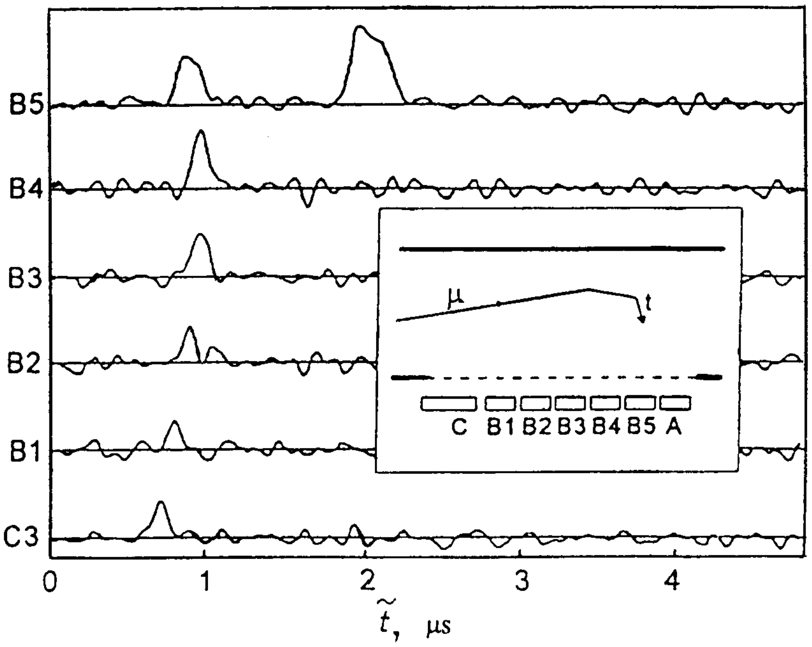

Fig. 1. A μ-capture event in ^{3}He registered in the Ionization Chamber with the FADCs. The sequence of the muon signals at the C, B_1–B_5 anodes and the ^{3}H signal at the B_5 anode are displayed. Inserted is a cross-view of the Ionization Chamber.

In 1993 the PNPI group in collaboration with physicists from Switzerland, Germany, Austria, Belgium, and USA accomplished a new measurement of the muon capture rate on ^{3}He [1]. The experiment was carried out in the muon beam of the Swiss meson factory. The experimental method was developed at PNPI. The muons were stopped in a high pressure gridded ionization chamber (IC) filled with 120 atm of isotopically ultra-pure ^{3}He gas (Fig. 1). The sensitive volume was 15 cm^3 with 1.5 cm vertical drift distance (cathode to grid) and 10 cm^2 area of the anodes B1–B5. The anodes C defined the incoming muon direction, the anodes A served as an anticoincidence ring. The IC operated at -40 kV on the cathode and -5 kV on the grid. The anode plane was at zero potential. The IC allowed to detect both the stopped muons and the charged reaction products, i.e. tritons from the reaction (2) and protons and deuterons from the breakup reactions

$$\mu^- +^3\mathrm{He} \rightarrow p + 2n + \nu_\mu, \quad \mu^- +^3\mathrm{He} \rightarrow d + n + \nu_\mu. \tag{3}$$

Each anode had a separate read-out, the signals being digitized with fast 8-bit flash ADCs during 10 μs. The amplitude E, the arrival time T, and the duration of each signal were measured.

The strategy of measurements was to select a very "clean" sample of muon stops, N_μ, in the zone of the B-anodes well isolated from the cathode and the grid. This procedure should guarantee the 100% efficiency in detection of the tritons without any corrections for wall effects. Then the measured ratio N_t/N_μ was a direct measure of the muon capture rate in the reaction (2). During 4 weeks of data taking 374,028,500 muon stops not accompanied by muon capture had been accumulated that satisfied the above requirements. At the same time 1,141,263 muon stops followed by triton signals with the energy of 1.9 MeV from the reaction (2) had been detected. The majority (78.3%) of the triton signals proved to be separated in time from μ-signals with the total energy loss located in the zone of one of the B_i anodes. The amplitude spectrum of such signals is shown in Fig. 2. The energy resolution was 30 keV (σ). The background was easily subtracted contributing to the total error on the level of 0.08%.

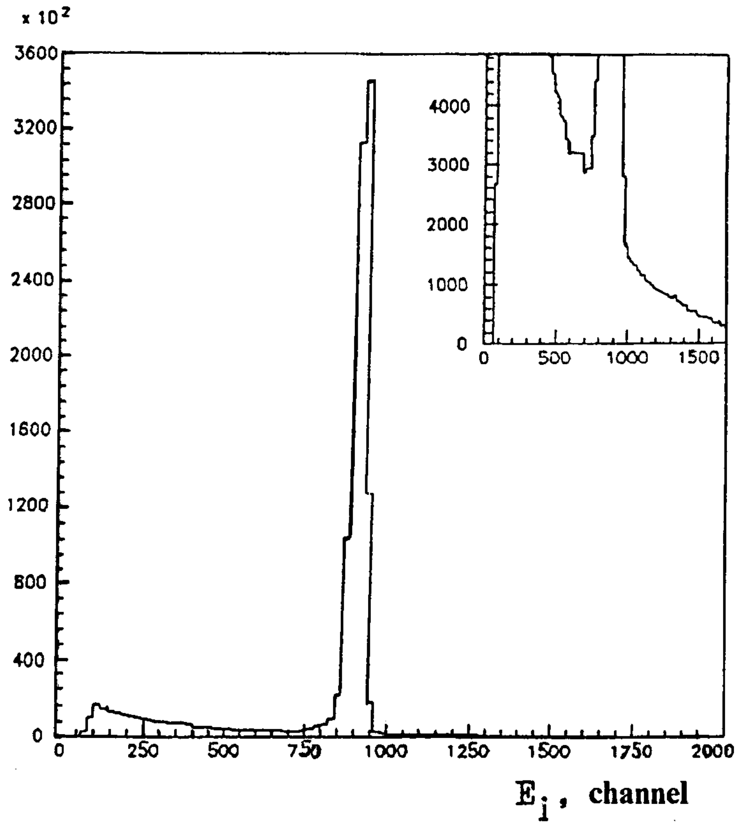

Fig. 2. Amplitude spectrum of triton signals separated in time from muon signals.

In about 7% of the events the triton energy was divided between two neighbouring anodes. In those cases the triton energy was determined by the sum of amplitudes from the anodes. Some of the triton signals (14.7%) piled up with the muon signals. Such events formed a peak in the $(E_i + 2E_{i-1})$ plot (Fig. 3).

The main correction (6.45%) to the measured number N_t was a trivial one taking into account the analyzed time interval of 6 μs. Other corrections took into account some possible small losses of the triton events. The total value of those corrections was 0.73%. Finally we obtained

$$\lambda_c = 1496 \pm 3(\text{stat}) \pm 3(\text{syst})\ \text{s}^{-1}.$$

The indicated systematic error was defined by the error in the correction factor to the number of tritons ($\pm 0.2\%$) and by the error in the linear extrapolation of the background caused by the breakup reactions (3) under the triton peak ($\pm 0.2\%$).

The measured value of λ_c corresponds to statistical population of the singlet and triplet states of the μ^3He atom.

The rate of the $s \to t$ transition is generally expected to be low, so the relative population of the states should not be changed within the observation time. Fortunately, we can control this process by measuring the exponential decay constant from the time distribution of the triton

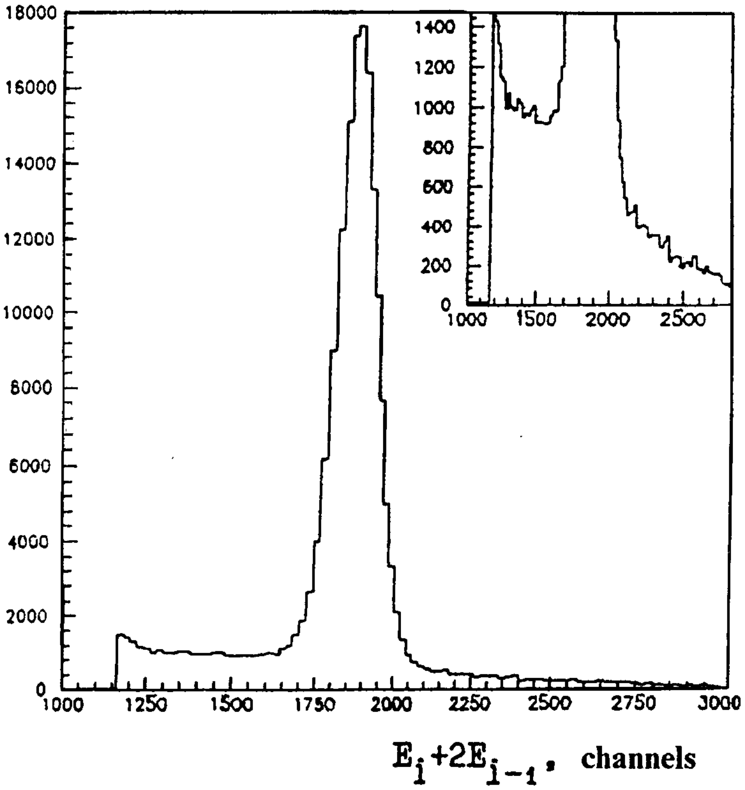

Fig. 3. Distribution of the first signals in the IC as a function of the sum of the amplitudes from two neighbouring anodes, B_i and B_{i-1} (1 channel = 1.6 keV). The peak corresponds to ^{3}He-signals that pile up with μ-signals.

events (Fig. 4). This decay constant proved to be exactly equal to the sum $\lambda_o + \lambda_{c(tot)}$. Here λ_o is the free muon decay rate, $\lambda_{c(tot)}$ is the total muon capture rate in the channels (1), (2), and (3). As a result, we eliminate the $s \rightarrow t$ transition on a level

$$\lambda_{st} < 0.01\,\mu\text{s}^{-1}.$$

This corresponds to the possible influence of the $s \rightarrow t$ transition on the observed muon capture rate on a level of <0.17%.

Another uncertainty might arise if the transition from the metastable $2S$-state proved to be large and comparable with the muon lifetime. However, according to the present understanding such transition should occur in much shorter time and not influence our result. But again, we can control this effect with our own data by comparing the area extrapolated to $T_t - T_\mu = 0$ (the number of events not included into the time distribution, Fig. 4.) with the observed number of piled-up events. These values proved to be practically equal, so we found the limitation

$$\tau_{2S} \leq 50\,\text{ns}.$$

Such a short-term muon stay in the $2S$-state may influence the result of our measurement of the muon capture rate only by $\leq 0.15\%$.

The obtained result can be analyzed in the frame of the EPM ("Elementary Particle Model"). In this model the weak current of the ^{3}He$\rightarrow^3$H transition is parametrized by four form

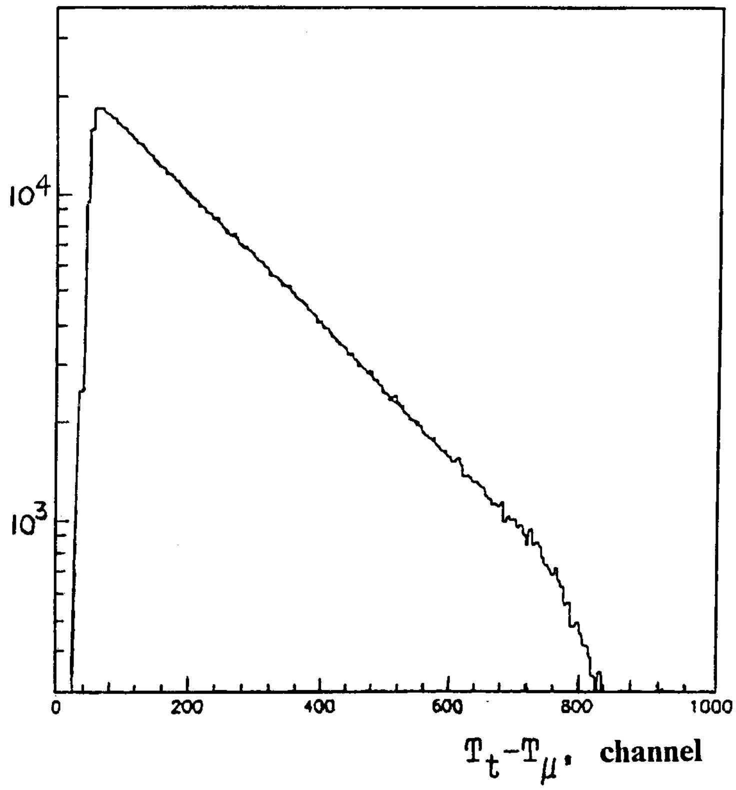

Fig. 4. Delay time spectrum of the triton signals (1 channel = 10 ns). The gap in the distribution at $T < 200$ ns is caused by overlapping of triton and muon signals.

factors $F_{V,M,A,P}$ evaluated at the relevant value of the four-momentum transfer $q^2 = -0.954m_\mu^2$. Two of these parameters, F_V and F_M, are derived from the isotriplet vector current hypothesis (CVC) and from the results of elastic electron scattering by ^{3}He and ^{3}H. Following the recent work by S.Congleton and W.Fearing (1993),

$$F_V(-0.954m_\mu^2) = 0.834 \pm 0.01 \text{ (vector form factor)},$$
$$F_M(-0.944m_p^2) = 13.969 \pm 0.052 \text{ (magnetic form factor)}.$$

Taking these data as an input, our measurement of λ_c determines the correlation between possible values of F_A and F_P, as shown in Fig. 5. The indicated width of the allowed region is determined now mostly by the error in F_V, not in λ_c.

The next step can be done if we use $F_A(-0.954m_\mu^2) = 1.52 \pm 0.011$ extrapolated from $F_A(0) = 1.212 \pm 0.004$ as measured by the ^{3}H β-decay (vertical lines in Fig.5, J.Congleton and W.Fearing, 1993). This allows to determine

$$F_P = 21 \pm 3.$$

A disadvantage of this method is involving of some theoretical considerations based on the impulse approximation in the extrapolation from $q^2 = 0$ to $q^2 = -0.954m_\mu^2$ that resulted in an increase of the error in $F_A(q^2)$. In principle, one could avoid involving the tritium β-decay data if the asymmetry A_ν in the muon capture by polarized ^{3}He nuclei were measured. Such an experiment is now going on in Canada at the TRIUMF accelerator, but the required accuracy (5%) is not reached yet. Fig.5 displays also the relation between F_P and F_A based on the

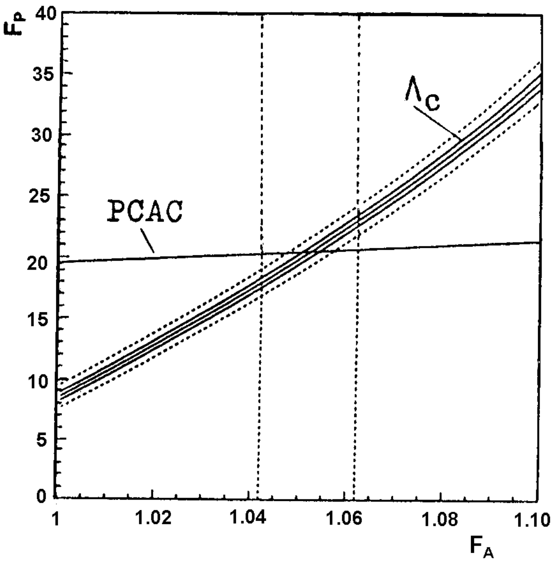

Fig. 5. Constraints on the axial F_A and pseudoscalar F_P form factors. Solid lines are from λ_c with its errors only. Dashed lines are from λ_c with errors in F_V and F_M added. Vertical dashed lines are from F_A extrapolated from ^{3}H beta decay. Horizontal solid line is the PCAC relation.

Partially Conserved Axial Current (PCAC) hypothesis:

$$F_P(q^2) = \frac{2m_\mu M_3}{m_\pi^2 - q^2} \times F_A(q^2). \tag{4}$$

One can see that the central values of F_A and F_P obtained in our analysis are in a surprisingly good agreement with the PCAC relation having in mind the approximate character of this relation.

It is well known that the form factor F_P of induced pseudoscalar interaction describes the capture of the muon by a virtual pion in the nucleus, therefore the muon capture constitutes a sensitive probe of the pionic degrees of freedom in nuclei and their possible modification by nuclear matter. That is why it is important to compare the experimental data on the muon capture with the nuclear microscopic theory. As we have already mentioned, the muon capture in ^{3}He is especially convenient for such comparison due to progress in the microscopic nuclear theory achieved now for nuclei with $A = 3$. Such a work is going on, and the first results were published recently by J.Congleton. It was noted that the calculation in the impulse approximation gave $\lambda_c = 1304$ s^{-1} which differed strongly from the experimental value. It means that the meson currents should be correctly incorporated into the calculations. The last work by J.Congleton and Trulik (1995) demonstrates that including the meson currents really brings calculations to a good agreement with our experiment. These calculations give $\lambda_c = 1502 \pm 32$ s^{-1}.

Other results obtained in this experiment are also of considerable interest. For example, our chamber registered protons and deuterons from the breakup reactions (3). So we determined the rate of these reactions [2]:

$$\lambda_{c(breakup)} = 720 \pm 70 \ \text{s}^{-1},$$

as well as the total muon capture rate in ^{3}He:

$$\lambda_{c(tot)} = 2216 \pm 70 \ \text{s}^{-1}.$$

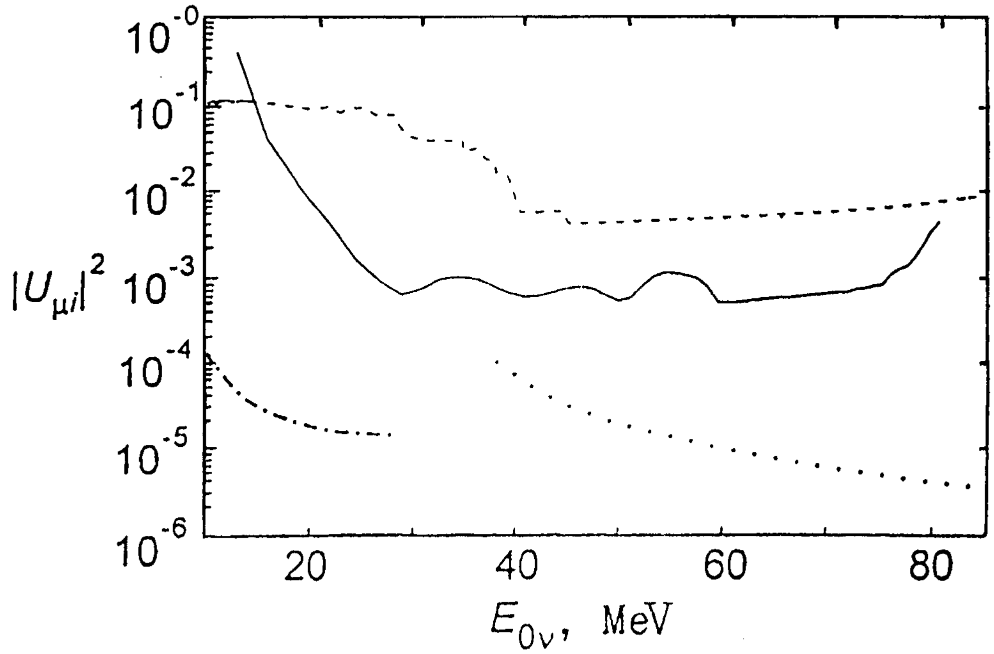

Fig.6. Probability of the heavy neutrino admixture vs its mass. Solid line – result of this work, dashed line – result of the PSI experiment (1991), dotted-dashed line – data from the experiments of Abel et al. (1981) and Daum et al. (1987), dotted line – data of Yamazaki et al. (1984).

Besides, with ^{4}He-filling of the chamber we have measured the muon capture rate in ^{4}He for the nuclear breakup channels [2]:

$$\lambda_{c(breakup)^4He} = 415 \pm 40 \ \ s^{-1}.$$

And finally, by analyzing the amplitude spectrum shown in Fig. 2 it was possible to estimate an upper limit for the muon capture rate on ^{3}He followed by emission of the hypothetical "heavy" neutrino with the mass m_ν = 25–75 MeV [3]:

$$\mu^- +^3 \text{He} \longrightarrow^3 \text{H} + \nu_h. \tag{5}$$

Such reaction would reveal itself in appearing of a ^{3}H-peak with the energy less than 1.9 MeV. Fig. 6 illustrates the results of such estimate.

In conclusion, we may say that the new experimental method developed at PNPI in combination with the unique muon beam of the Swiss meson factory enabled to carry out measurements of muon capture on ^{3}He on the qualitatively new level: the precision in the muon capture rate measurements was improved up to 0.3% that is more than an order of magnitude better than in earlier experiments. As a result, the induced pseudoscalar form factor in this process was reliably determined. The obtained result already stimulated development of the muon capture microscopic theory which takes into consideration the meson currents in ^{3}He nucleus.

μ^3He–collaboration:

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