EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

PRECISE MEASUREMENT OF THE $2S_{1/2}$-$2P_{3/2}$ SPLITTING IN THE $(\mu^{-4}He)^+$ MUONIC ION

G. Carboni*), G. Gorini*), L. Palffy**), F. Palmonari***),
G. Torelli*) and E. Zavattini***)

CERN-Pisa University Collaboration

ABSTRACT

The results of a new measurement of the $2S_{1/2}$-$2P_{3/2}$ splitting S^1 in the muonic ion $(\mu^{-4}He)^+$ are presented. We found $S^1_{exp} = 1527.5 \pm 0.3$ meV. Using the new, recently determined, value of the r.m.s. charge radius for the ^{4}He we obtain for the difference D, between S^1_{exp} and the corresponding theoretical prediction, the value $D = 0.2 \pm 4.2$ meV: this value directly confirms, assuming μ-e universality, the QED vacuum polarization prediction to 0.25%.

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*) Istituto di Fisica dell'Università and INFN, Pisa, Italy.

**) CERN, Geneva, Switzerland and IISN, Belgium: Present address: Université Catholique de Louvain, Louvain la Neuve, Belgium.

***) CERN, Geneva, Switzerland.

In this letter we report the results of a new, more precise, measurement of the $2S_{1/2}-2P_{3/2}$ splitting S^1_{exp} in the muonic ion $(\mu^{-4}He)^+$. The principle of the experiment is the same as for that described in Refs. [1-3]; however several improvements have been introduced in order to obtain a better long-term stability of the apparatus and an improved signal-to-background ratio.

The measurement was performed stopping negative muons from the CERN Synchrocyclotron in a target filled with ^{4}He at 40 atm (T = 293 K). About 4% of the muons actually stopped in gas form the metastable $(\mu^{-4}He)^+_{2S}$ system (lifetime ∿ 1.6 μsec) [4]. A short time (∿ 0.5 μsec) after the stop an energetic pulse of laser light is sent into the target to excite the $2S_{1/2} \rightarrow 2P_{3/2}$ transition. The laser is tuned across the resonance line and the eventual transition is identified by detecting, with NaI crystals, in coincidence with the laser pulse, the 8.2 keV X-ray emitted in the $2P_{3/2} \rightarrow 1S_{1/2}$ decay (2P level lifetime $\tau_{2p} = 5 \times 10^{-13}$ sec).

The schematic arrangement of the apparatus is shown in Fig. 1: a telescope of plastic scintillation counters defines the incoming muon beam, which is slowed down by suitable CH_2 moderators. The last telescope counter is a thin plastic scintillator mounted inside the target vessel. Eight NaI(Tl) counters (A_1 ... A_8) were used to anticoincide the muon beam and to detect the 8.2 keV muonic X-rays. In order to avoid spurious signals from the laser light, the A_i counters photomultipliers were coupled to the light guides through Corning CS 4.97 blue filters (attenuation factor > 4×10^4 for the laser light to be used).

A useful cylindrical stopping region V (14 cm long and 4 cm in diameter) was defined inside the target itself (see Fig. 1) by a 12 μm thick Al foil, internally gold coated (400 Å), in order to ensure maximum reflectivity for the laser light.

The light entered the target vessel through an antireflecting window W: 6 mm diameter holes were provided in the Al foil and in the anticoincidence counter 5 closing the region V. To ensure the entering of the light in the region V an internally gold coated thin metal conic tube C was driving the laser light through the holes.

The light source was a dye laser pumped by a Q-switched ruby laser*). The dye laser was basically the same as in the experiment described in Ref. 3 except that remote controlled tuning was provided, the diffracting grating DG being driven by a stepping motor SM (see Fig. 1). Each motor step corresponded to 2.2 Å change of the laser wavelength. The motor was linked to a HP 2100 computer via a CAMAC interface. The calibration of the stepping motor was performed using a digitized spectrometer (2 Å steps) the scale of which was fixed using as a reference the two lines of an Ar lamp λ_1 = 8115.3 Å and λ_2 = 8103.7 Å. The stability of the spectrometer was found to be better than 1 Å over the data-taking period.

Per each dye laser pulse a small fraction of the infrared light was sent to the spectrometer, in order to monitor continuously the region spanned by the stepping motor: furthermore, the energy associated with each pulse was monitored by means of the fast photodiode D2 (see Fig. 1). The diode D2 was frequently calibrated against a pyroelectric detector**).

The mean energy $\bar{E}$ associated with the infrared laser pulses was 0.27 J and the time width 20 nsec.

The synchro-cyclotron operation was synchronized with the laser one, supplying a bunched muon beam at the same repetition frequency as the ruby laser flashing (0.25 Hz) [2,3].

A MUSTOP signal = $1\bar{2}34\bar{5}\ \overline{\Sigma A_i}$ (see Fig. 1) identified the stopping muon; this signal generated:

i) A prompt 2 μsec wide gate signal G; during this gate time the first pulse P_i given by each of the 8 A_i counters was signalled (if present).

ii) A 0.5 μsec delayed trigger pulse to the ruby laser Q switch.

iii) A properly delayed signal which, at the end of the event, triggered the data acquisition process.

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*) Apollo model 22.

**) Laser Precision RK-3230.

Among others the following relevant data were recorded for each event on magnetic tape via the HP 2100 computer:

i) The integrated amplitudes and the times of all signalled pulses P_i.

ii) The stepping motor position SMP, the reading of the spectrometer, and the energy E and time t_1 of the laser pulse.

All times were measured with respect to the MUSTOP signal.

After completion of the data acquisition period, the dye laser wavelength was changed by 2.2 Å via the stepping motor.

An interval of about 38 Å, centred at about 8117 Å, was continuously spanned backwards and forwards, the entire range being swept in about three minutes. We remind here that in the first measurement of the $2S_{1/2}$-$2P_{3/2}$ splitting the value [1] 1527.4 ± 0.9 meV was obtained, which in wavelength reads $\lambda_0' = 8117 \pm 5$ Å.

A typical run had a duration of $\sim$ 8 h, corresponding to about 3000 muons actually stopped in gas; on-line analysis provided continuous monitoring of the apparatus performance during the data-taking runs. A total number of $\sim$ 70,000 stops in gas was recorded.

The main result is presented in Fig. 2. On the ordinate is given the number of events detected in a time interval of 250 nsec from the laser time t_1, by the 8 A_i counters as a function of the stepping motor positions SMP spanned during the experiment. The wavelength scale shown on the abscissa is obtained from the calibration.

The selection (done off line) of the events presented in Fig. 2 went through the following steps:

i) Of all signals P_i registered, only those which were most likely due to a scintillation in the NaI crystal were selected; this was done by means of a simplified pulse-shape analysis.

ii) Subsequently only those signals were retained corresponding to X-rays which left in the NaI crystal an energy between 2 and 20 keV.

iii) Finally only those events for which the corresponding energy of the infrared light pulse E was more than 0.2 J were accepted as good events.

Figure 2 shows a prominence near the centre of the interval of wavelength explored: we attribute this peak to the fact that the infrared light pulse, in the region of the peak, excites the transition $2S_{1/2} \rightarrow 2P_{3/2}$ in the muonic ion $(\mu^{-4}\mathrm{He})^{+}_{2S}$ present in the target.

The full-line curve drawn through the data points represents the best fit ($\chi^2 = 11$) with a Lorentzian line plus a constant background contribution; in the fit, the width Γ (FWHM) of the Lorentzian curve was fixed at the value $\Gamma = 8$ Å which represent the theoretical width for S^1. The wavelength value λ_0 of the centre of the Lorentzian line, according to the best fit, is

$$\lambda_0 = 8116.8 \pm 1.5 \text{ Å} \tag{1}$$

which expressed in meV is

$$S^1_{\mathrm{exp}} = 1527.5 \pm 0.3 \text{ meV} \quad . \tag{2}$$

The error quoted includes the statistical error as well as the uncertainty in the spectrometer calibration. The number of events in the peak given by the best fit is 233 ± 45 and the signal-to-background ratio at the peak is 1.04. A fit with only a straight line (no effect) gives $\chi^2 = 38$. The number of events found is in agreement with the expected one.

We have also made a fit leaving the parameter Γ as a free parameter; in this case we have obtained $\Gamma_{\mathrm{exp}} = 7.2 \pm 2.8$ Å and the same value (1) for λ_0. Our value (1) is in agreement with that obtained by Bertin et al. [1], who found $\lambda_0' = 8117 \pm 5$ Å.

The latest theoretical prediction [5] for the $2S_{1/2}-2P_{3/2}$ splitting in the muonic ion $(\mu^{-4}\mathrm{He})^{+}$ made by Rinker gives:

$$S^1_{\mathrm{th}} = (1813.1 - 102.0 \langle r^2 \rangle) \pm 1 \text{ meV} \tag{3}$$

where $\langle r^2 \rangle^{\frac{1}{2}}$ is the r.m.s. charge radius of the ^{4}He nucleus.

Recently Sick et al. [6], with new data on electron scattering from ^{4}He, have obtained for the ^{4}He r.m.s. charge radius the value

$$\langle r^2 \rangle_e^{\frac{1}{2}} = (1.674 \pm 0.012)\ \text{fm} \quad . \tag{4}$$

Using Eqs. (3) and (4), one obtains for the difference D between the experimental value (2) and the theoretical prediction the value

$$D = 0.2 \pm 4.2\ \text{meV} \quad . \tag{5}$$

This result shows that the QED vacuum polarization contribution is experimentally verified to ±0.25%. It may be interesting to say that the vacuum polarization terms in α^2 included in (3) contribute for 11.6 meV [5].

On the contrary, using our value (2) and assuming the QED theoretical prediction (3) to be valid, one obtains for the r.m.s. of the ^{4}He charge radius, as seen by the muon, the value

$$\langle r^2 \rangle_\mu^{\frac{1}{2}} = 1.6733 \pm 0.0030\ \text{fm} \quad , \tag{6}$$

from which one obtains

$$\langle r^2 \rangle_e^{\frac{1}{2}} - \langle r^2 \rangle_\mu^{\frac{1}{2}} = 0.0007 \pm 0.012\ \text{fm} \quad ; \tag{7}$$

this difference is interesting since it gives a limit to a possible muon-hadron anomalous interaction [7].

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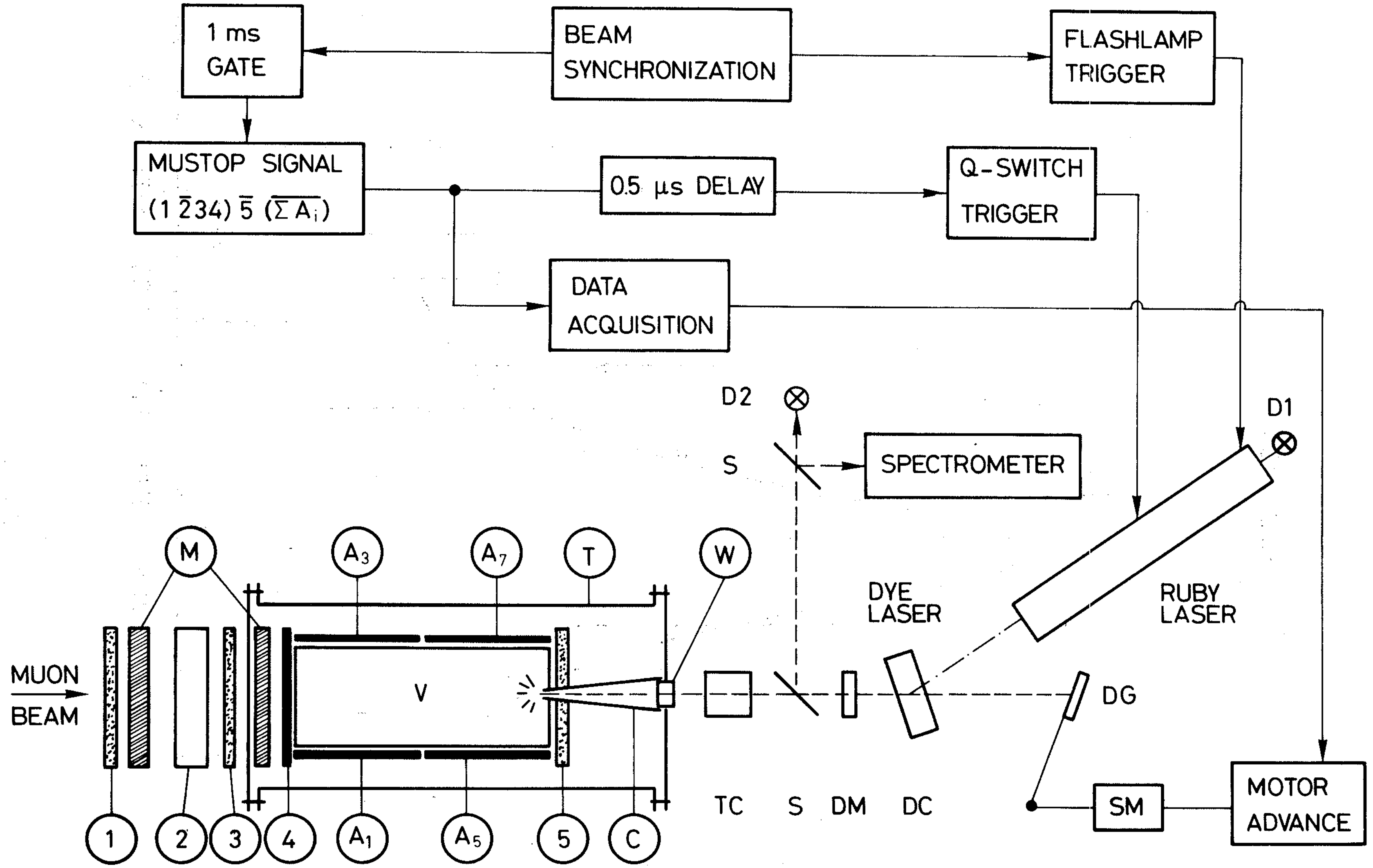
Figure captions

Fig. 1 : Schematic view of the apparatus: M = CH_2 moderators, 1, 3, 4, 5 = plastic scintillators, 2 = anticoincidence Čerenkov counter (lucite), T = Invar steel vessel, V = useful muon-stopping volume, A_1 ... A_8 = NaI(Tl) counters, DC = dye cell, DM = dielectric mirror (R = 30%), DG = diffraction grating (1200 lines/mm), SM = stepping motor driving DG, D1-D2 = photodiodes, C = internally gold-coated conical light pipe, W = antireflecting window, S = light beam spitters, TC = optical telescope.

Fig. 2 : The $2S_{1/2}$-$2P_{3/2}$ resonance signal. Each datum point represents the number of events, normalized to the same number of stopped muons, per stepping motor position SMP; the scale in wavelength (shown below) is fixed by the calibration procedure (λ_1 and λ_2 are two lines of an Ar lamp, as specified in the text). The full line curve drawn on the data is the result of a best fit analysis ($\chi^2 = 11$) with a Lorentzian line (assuming for Γ the theoretical value $\Gamma = 8$ Å) plus a constant background. For the central wavelength value of the Lorentzian line we have obtained $\lambda_0 = 8116.8 \pm 1.5$ Å. Having Γ as a free parameter the best fit has given $\Gamma_{exp} = 7.2 \pm 2.8$ Å and the same value for λ_0. The theoretical prediction for λ_0 is 8115.6 ± 21.8.


1 ms GATE
BEAM SYNCHRONIZATION
FLASHLAMP TRIGGER
MUSTOP SIGNAL $(1\bar{2}34)\bar{5}(\overline{\Sigma A_i})$
0.5 µs DELAY
Q-SWITCH TRIGGER
DATA ACQUISITION
D2
S
SPECTROMETER
D1
RUBY LASER
DYE LASER
DG
MUON BEAM
M
A3
A7
T
W
V
1
2
3
4
A1
A5
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C
TC
S
DM
DC
SM
MOTOR ADVANCE

Fig. 1

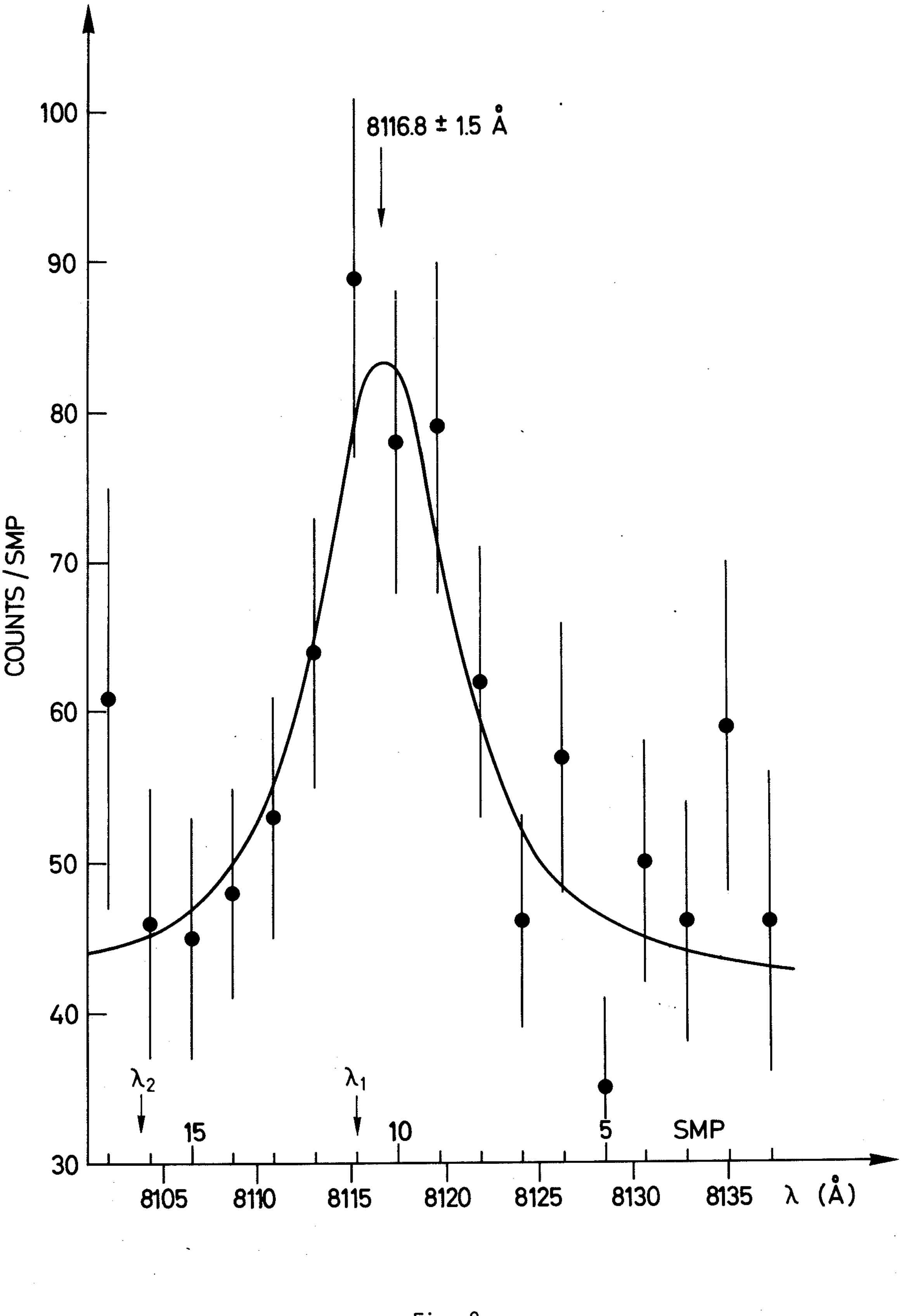
COUNTS / SMP
100
90
80
70
60
50
40
30
8116.8 ± 1.5 Å
λ₂
λ₁
15
10
5
SMP
8105
8110
8115
8120
8125
8130
8135
λ (Å)

Fig. 2