Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI
SIS – Pubblicazioni

LNF–08/21 (IR)
September 8, 2008

KAIUM at DAΦNE ?

Vincenzo Lucherini[1], Tullio Bressani[2]

[1] INFN-Laboratori Nazionali di Frascati, Via E. Fermi 40, I-00044 Frascati, Italy
[2] Dipartimento di Fisica Sperimentale, Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, I-10100 Torino, Italy

Abstract

The possibility of producing and detecting at DAΦNE, in the present configuration, a new Hydrogen *isotope* formed by a (K^+e^-) bound system (*Kaium*) is addressed, considering the unique opportunity to have the machine tuned at its best on the verge of the KLOE roll-in, with a dedicated, and relatively simple experiment of short duration. If Kaium will be detected at DAΦNE, it could in perspective pave the way for a series of highly sophisticated experiments focused in the precision measurement of several quantities, as the K^+ mass, that, together with K^- mass, are strictly related to CPT invariance.

PACS.: 32.30.Jc, 34.70.+e, 36.10.-k, 36.10.Gv, 07.60.Vg.

1 INTRODUCTION

DAΦNE is an (e^+e^-) collider optimized in Luminosity at the c.m. energy of the $\phi(1020)$ meson 1), whose decays almost at rest produce slow momentum correlated kaon pairs, both neutral and charged, successfully employed in several experiments 2), 3), 4), 5). The experiments employing charged kaons were focused on the study of the interactions with matter of only K^-, leaving for the K^+ the role of producing a welcome tagging and calibration signal 6) or an unwelcome background 3). The experiment mainly focusing on the physics of neutral kaons 2) studied also the charged kaon branch, but only to look for the decays, not for their interaction with matter. Then, it emerges that the potential of the DAΦNE K^+ beam has been left up to now largely idle, with the notable exception of just one measurement 7).

The unique characteristics of the K^+ produced at DAΦNE turn out instead very appealing to perform an experimental search of a system hitherto undiscovered: the (K^+e^-) atom, and to study its properties. The name of such a system is Kaium, according to the established convention for naming atoms: an "*X-onium*" atom is composed by a particle and its antiparticle, X^+X^-, whereas an *electronic* atom formed with an X^+ as its nucleus is called "*X-ium*". Examples are "protonium" (p^+p^-), "protium" (p^+e^-), "positronium" (e^+e^-), the last of which cleverly qualifies under both conventions. In this respect, it should be noted that the (μ^+e^-) atom, discovered in 1960 8), was called not Muium but Muonium, the name appropriate for the $(\mu^+\mu^-)$ atom, since its discovery was well before the official naming convention.

DAΦNE can actually be the best place to try to find Kaium since it provides the basic ingredient to produce such a system: the lowest momentum K^+ today accessible, created in well know conditions and in a clean hadronic environment. These are the same reasons, indeed, why its negative counterpart is fruitfully used to produce Kaonic-Atoms (K^--A)3),9) and Hypernuclei5).

The electron capture (also kown as CE, Charge Exchange) by a slow positive particle in matter is a well known process, and the steps relevant in the slowing down of a few MeV positive and *heavy* (so that radiative energy loss is not at stake) particle X^+ in matter can be summarized as follows 10):

1. Slowing down by excitation and ionization according to the well established Bethe and Block relation for the energy loss of charged particles in matter, until the velocity v_{X^+} of the positive particle reaches a value of the order of $\approx \alpha c$, α being the fine structure constant and c the velocity of light: this is the typical order of magnitude of the velocity of outer electrons orbiting in an atom.
2. Starting , when $v_{X^+} \approx \alpha c$, of a cycle of CE reactions, during which the positive particle can capture one of the electrons of the medium becoming a neutral system, followed by subsequent ionization of the neutral system due to collisions with atoms or molecules of the medium. The particle becomes again positively charged and the previous processes can be repeated. In the meantime, the slowing down will go on according to the Bethe and Block relation for charged (or its generalization to neutral) particles. The CE processes are repeated several times, their number strongly depending on the medium nature and conditions, reaching even the hundreds.
3. After several CE cycles, the outcome can be twofold:
    a. the particle emerges as positive, with a velocity so low that it cannot any more catch an e^-, and then thermalizes as a positive ion;

b. the particle emerges bound to an e^- with too much low velocity to undergo a ionization collision, and then thermalizes as a neutral atom.
In both cases, at a time the particle, if unstable, will decay, if not yet decayed in the previous steps.

The duration of the different steps, in particular 1), depends by the medium nature and conditions. In gases at NTP, the duration is of the order of [10)]: several ns for step 1); ≈ 1 ns for step 2). To fix the order of magnitude of the quantities in the game, a K^+ of velocity $\approx \alpha c$ has a kinetic energy of ≈13 keV and a speed of ≈0.24 $cm \cdot ns^{-1}$.

Has a slowed down K^+ any chance to form Kaium before it decays? The main energy loss process (excitation and ionization) down to the velocity $\approx \alpha c$ is the same for K^+ and K^- (apart the Barkas effect [11)]): then K^+ starts to capture e^- from atoms, while K^- starts being captured by atomic nuclei. This consideration allows to answer yes, at least in principle, to the above question, since it is an experimental fact that K^--A atoms are produced. In this respect, it should be also taken in mind that a slow K^+ cannot have any strong reaction other than elastic scattering with nuclei, in striking difference with a slow K^- with its high strong interaction cross section on nucleons that can cause its disappearance. It can then be anticipated that Kaium should be formed any time a slow K^+ is stopped in matter. Of course, one thing is that it is formed, another thing to be able to detect it. In particular, the ionization of the formed Kaium due to collisions with atoms of the medium (a process not relevant in the case of K^--A atoms since they are much more slower when created and their binding energy are in the keV, not in the eV, energy region) could hamper the efforts to detect it since Kaium can be destroyed after formation.

The scope of this note is to examine the whole matter and to suggest a possible scenario that could allow the successful detection of Kaium, for the first time and at DAΦNE.

2 KAIUM FORMATION AND DETECTION

2.1 Kaium

The (K^+e^-) atom has many similarities with ordinary Hydrogen (or *protium*). Several properties of Hydrogen depend in fact to a great extent just on the value of the reduced mass m_r of the system, that, being the proton much heavier than the electron, turns out to be very close to the e^- mass:

$$m_r = (m_{e^-} \times m_p) / (m_{e^-} + m_p) \approx m_{e^-} \qquad (1)$$

Since the mass of a K^+ is ≈1/2 that of a *p*, it is still ≈1000 times bigger than the electron mass and the relation (1) still holds substituting m_{K^+} for m_p. Indeed, the reduced masses of Kaium and Hydrogen differ for less than 0.05%. Kaium properties will then be very similar to those of Hydrogen, a part the absence of hyperfine interactions due to the spin s ($s = 0$ for K^+ while $s = ½$ for p). In particular the binding energy of H and Kaium will be very similar (≈ 13.6 eV) as well as the scheme of the levels. The Kaium radiative transitions from excited levels to lower levels are then expected to reproduce the well know pattern of Hydrogen: the Lyman series, in the UV region, for de-excitation to the ground level, with n=1; the Balmer series for de-excitation to the levels with principal quantum number n=2, in the Visible Region and in the near UV region; the Paschen series for de-excitation to the levels with principal quantum number n=3, the Bracket series to the n=4 and the Pfund series to the n = 5 levels, in the IR region; and so on.

These facts suggest that a simple (at least in principle) way to detect the formation of Kaium is to try to detect one of the characteristic lines of its radiative de-excitation, considering that, when created, it could be formed in an excited state. Moreover, still for the sake of simplicity, it is tempting to select, as lines to detect, those of the Balmer series lying in the Visible Region: visible light is easy to detect, and external background of visible light is easy to shield. Moreover, the (probably) most used and best known device can be employed as detector: i.e. a phototube, in both its traditional manufacture or in the modern appearance of the so called Si-PM [12)], all of them having very fast response and being able of sustain high photon fluxes as well to perform single photon detection. Last but not least, we have not to forget that measurements involving spectroscopy of light are ones of the most reliable and precise that can be performed in physics. In this respect the most appealing line to search for is the Balmer H_α, in the red region of the visible spectrum, at ≈ 656 nm. Just as a reminder, the Balmer series is due to radiative transitions to the n=2 levels from any level above, the H_α one corresponding to the radiative transition from n=3 to n=2 levels. The Balmer H_α is, in fact, due to three transitions: *3s→2p*; *3p→2s*; *3d→2p*. All these emit photons of essentially the same wavelength, and can therefore be detected simultaneously.

There are now the most relevant questions to address. What is the cross section for the formation of excited levels of Kaium with principal quantum number n=3 during the K^+ slowing down in matter? Moreover, the lifetimes of its excited levels with n=3 are also a critical parameter, considering the finite lifetime (12.4 ns) of the K^+ itself. This is not yet the end of the story, since also the transition probabilities of the levels with n=3 to radiatively decay to the n=2 levels, and not to levels with n=1, is important: otherwise the transition will not be a Balmer but a Lyman one. Finally, competition between radiative de-excitation and ionization is also a crucial point.

Luckily, we have not to embark in complex calculations to have a first reasonable answer to the above questions, since we can look to published results of experiments which used slow proton beams for the same purpose: to study Hydrogen formation in the impact of slow protons on several materials through the Balmer H_α emission. A very slow proton, in fact, behaves, in loosing energy and undergoing CE processes, almost exactly as a very slow K^+ (and as any other *heavy* and very slow positive particle): the only thing to consider, for a meaningful comparison, is that it must be done at the same velocity. A K^+ having a velocity αc is then equivalent to a slow p, just scaling their respective kinetic energy (or momentum) in the ratio ≈ 1/2, i.e. the ratio of their masses. In Fig. 1 we report the cross sections for Hydrogen formation in several *n,l* states by impact of slow protons in He gas, as a function of the proton kinetic energy [13)]. The cross sections turn out to be very huge, of the order of up to ≈ 0.2-3 Mb for the levels with n=3, confirming the considerations above done that any positive particle X^+ slowing down in matter should catch an e^- forming a bound (X^+e^-) system, but also confirming the (much) high probability of its ionization (Fig. 1, left).

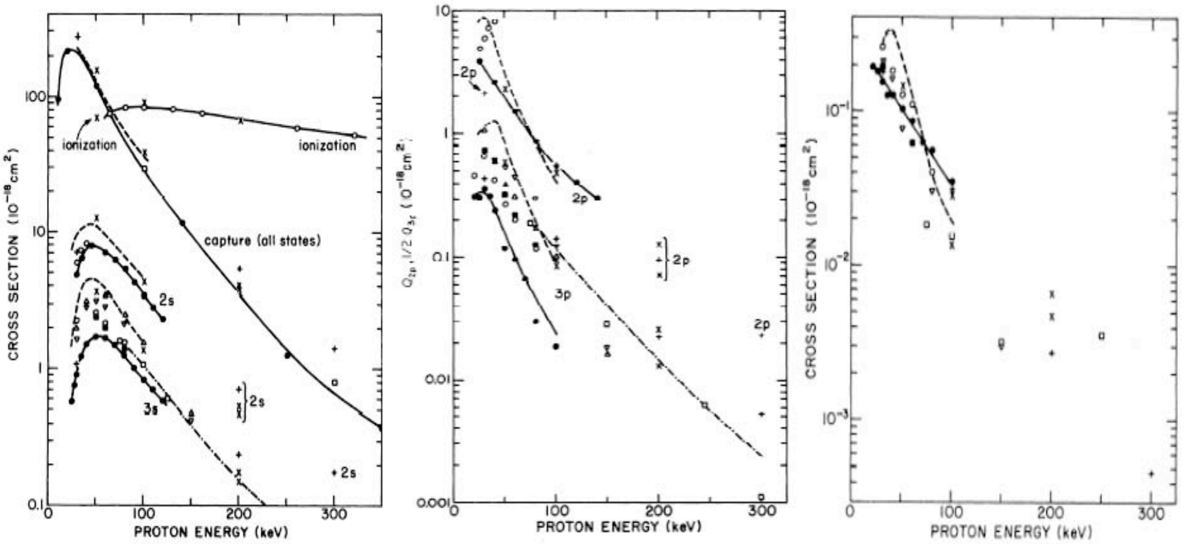

Fig. 1: Experimental results (symbols) and calculations (curves) of the cross section of slow protons in He for: *left)* e^- capture in all states, ionization and e^- capture in s states; *middle)* e^- capture in p states; *right)* e^- capture in 3d state. Note that the 3p capture cross section is divided by 2. From Ref. 13).

Fig. 2 shows the cross section for Balmer H_α emission of slow protons in He [14)]. It has a maximum of ≈ 3.5 Mb at ≈ 45 keV *p* kinetic energy, corresponding to ≈ 23 keV K^+ kinetic energy.

2.2 Formation and Detection

The choice of He in Fig. 1 and Fig. 2 is not only as an example, just to illustrate the order of magnitude of the involved cross sections, but a precise choice in looking for Kaium formation and detection. In fact, He is a noble gas, hence not bound to other elements, it can be easily purified and, most relevant, its own Balmer lines are rather well separate from the Balmer lines of He, as show in Fig. 3. In particular, the He_α (667.82 nm) does not overlap with H_α, (656.28 nm) (but it is close enough to serve as a possible calibration line). Hence, a target filled with He appears a good choice. Other noble gases could be chosen as well, being the relevant cross section even bigger than those for He, paying attention that they do not have emission lines too close to Kaium H_α. In the following, for sake of clarity, all considerations will be referred to He: but they can be easily modified for other noble gases.

At which conditions then the He gas should be used? As seen in Fig. 1), the cross section for ionization in He tops up to ≈80 Mb and is rather flat with energy. Naively, the choice for the He conditions should then be such that the mean free path of Kaium in the gas be long enough to allow a significant probability of a Balmer H_α transition, before a collision with one the He atoms (and before K^+ decay). Again, past experiments using very slow proton beams to look for H formation in He through Balmer H_α emission help to answer the question: the He was used in the gas state, at a pressure of the order of ≈ 1-10 x10^{-3} mbar. Those experiments had several cm as length of the He gas cell.

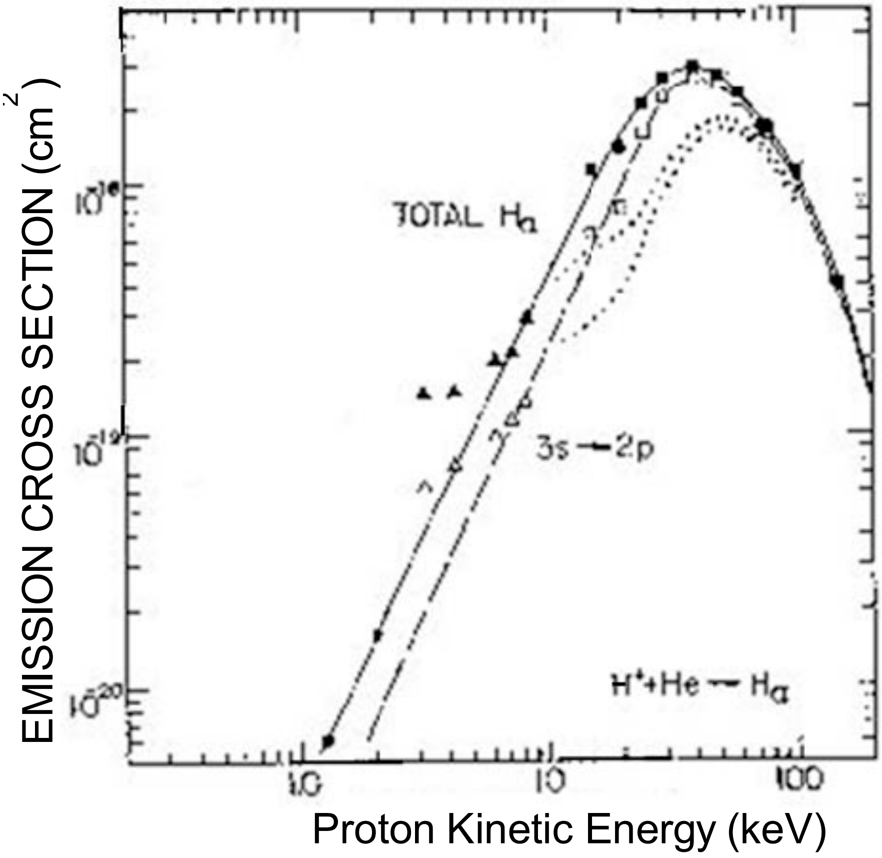

Fig.2: H_α emission cross sections in $p + He$ collisions as a function of proton kinetic energy. The symbols are measurements, the curves calculations (From Ref.14).

In case of very slow K^+, in order to detect Kaium formation with the same technique, similar experimental conditions should hold. In this working hypothesis and using information from Fig. 1 and Fig. 2, one can try to extract the relevant quantities. As it can be seen, the maximum of H_α emission is at $\approx$ 23 keV K^+ kinetic energy, corresponding to a velocity of $\approx$ 0.4 cm·ns^{-1}. The ionization cross section is $\approx$ 60 Mb and at a He gas pressure of 9x10^{-3} mbar, the *collision length* (mean free path between two collisions) turns out to be $\approx$ 72 cm. At the same pressure the H_α *interaction length* is $\approx$1000 cm, meaning that in a cell length of $\approx$5 cm (that it can cross in $\approx$ 10 ns) such a K^+ has a probability of $\approx$0.5% to emit a H_α photon. If DAΦNE could deliver in mid 2009 an integrated luminosity of $\approx$20 pb^{-1} per day, there will be a production of 3.1x10^7 K^+/day. With an acceptance of $\approx$20%, the number of *tagged* K^+ /day would be $\approx$6.2x10^6. This translates, with an efficiency of $\approx$1% to slow down the K^+ to the optimal range of velocities inside the He cell, to a number of useful K^+ /day of $\approx$6.2x10^4. According to what said above, this flux in its turn would produce in the He cell $\approx$3.1x10^2 Balmer H_α photons/day. This means $\approx$10^4 H_α photons produced in one month. These quantities should be enough to fulfill the scope of a first search (a *yes/no experiment* devoted to the discovery of Kaium and assessment of the possibility of DAΦNE to produce it), if the efficiencies of the spectroscopy set up to analyze the emitted light and the photon detection system do not drastically reduce them. Using PMs (or Si-PMs) as photon detectors, an efficiency close to

100% can easily be obtained, also for single photon counting. This implies that the performance of the spectroscopy set up should have an efficiency not worse than, let say, ≈20%.

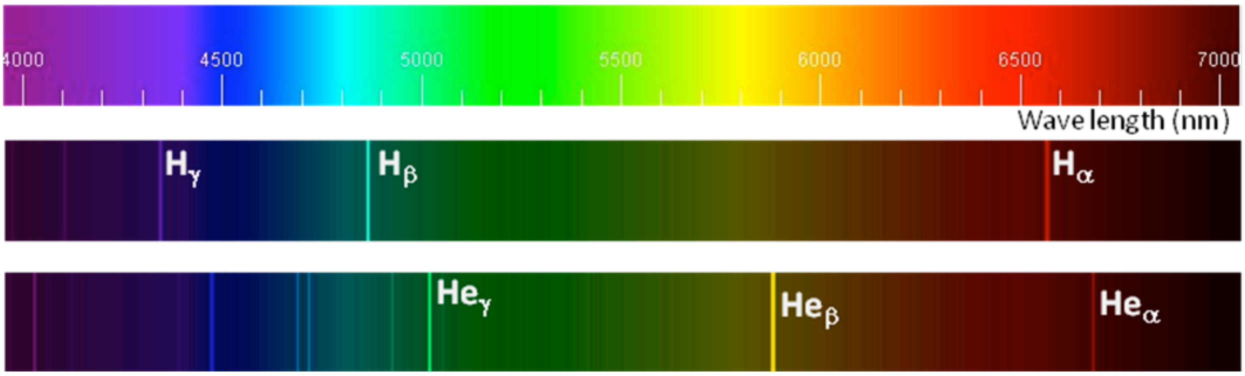

Fig.3: H and He Balmer emission spectral lines, showing, in particular, the position of the H_α, H_β and H_γ lines respect to the He_α, He_β, and He_γ lines.

2.3 Background

Which other physical processes can produce H_α photons in He? The He target cell, put of course in the dark, will be crossed not only by K^+ (and K^-) but also by other ionizing particles and even photons (X or γ rays). Any ionizing particle will create in He a trail of excited atoms, or even electron-ion pairs that during de-excitation or recombination can generate visible light photons. The use of an efficient trigger based on the selection of charged kaons will eliminate to a great extent the background due to any ionizing particle, apart that due to the energy loss process of K^+ or K^- itself (or of they interaction or decay products). Any photon emitted in the visible region due to such processes, however, will have the pattern specific of the He Balmer series, and hence no background can be generated at H_α (Fig. 3). Another possible source of light could be the Cherenkov radiation from fast electrons or positrons resulting form K^+ and K^- decay or interactions: it has however a continuous spectrum that is peaked in the UV region. The only background at H_α can then be due only to Hydrogen itself, i.e. to impurities containing Hydrogen present in the He cell, excited during the slowing down of K^+ or K^- or of their interaction or from their decay particles.

In this respect, there is a fact to be considered that will help to disentangle the H_α background: the Doppler Effect. When Kaium is formed in an excited state with n=3 and is successively decaying into the n=2 states, the emitted H_α photons will experience a huge Doppler shift since the system is fast moving, with an energy of few tens of keV, and emits photons in a random direction respect to the detector. This will produce a sensible Doppler broadening, estimated of the order of ≈7 nm. On the opposite, any Hydrogen impurity is at room temperature (≈ some tens of meV equivalent energy), and will generate H_α photons with negligible Doppler broadening.

The main method, however, that can prove that Kaium is really formed is the presence of H_α Doppler broadened photons for K^+ but not for K^-. Assuming that the acquisition of the emitted light spectrum can be triggered by the selection of charged kaons, background due to other particles will be already greatly reduced. Adding to this the ability to disentangle events due to K^+ or K^- will furnish another, very powerful, tool. At DAΦNE the K^+ and K^- are emitted with identical parameters, almost back-to-back and simultaneously, in the same condition of background. H_α lines due to impurities are equally excited by both, but only K^+ can of course produce Kaium and with its specific Doppler broadening.

With all the above in mind, we can now try to describe a relatively simple experimental set up that could prove the formation of Kaium at DAΦNE.

3 A POSSIBLE (AND A BIT MORE THAN GEDANKEN) EXPERIMENT TO FIND KAIUM AT DAϕNE

We outline an idea for an experimental set up that can be realistically built in a few months, is reliable and simple, and fully compatible with the present DAΦNE configuration. It would be ready to run on DAΦNE as soon as the interaction region will be free just before the KLOE roll-in, and capable to achieve its scope in a few weeks of run, without significantly affecting the already planned schedule.

To achieve this purpose, its characteristics should be the following:

1) Use of the present DAΦNE configuration: the actual beam pipe in the IP1 with the two thin, ellipse shaped, Al windows at the top and bottom. Hence no intervention is required on DAΦNE.
2) A simple device to select the K^+-K^- pairs, consisting of two thin scintillators, facing each other, one at the top and the other at the bottom of the two Al windows, providing the trigger and the selection of the charged kaons. A similar set up was already employed successfully at DAΦNE 15).
3) A further scintillator in the bottom, of a similar shape of the previous ones, but thick enough to stop the K^+/K^-, seen at each end by fast PM of the same type as for the device in 2), immediately mounted below the bottom thin scintillator. This, as detailed below, will discriminate, with high efficiency, K^+ from K^-, without the need of magnetic fields and tracking detectors.
4) In the top side, after the thin scintillator, a set of sheets of appropriate material (*Brakes*) to slow down the velocity of the charged kaons to the desired range of values.
5) Going up, after the Brakes, a suitably shaped cell (of height ≈10 cm or more, and bottom base of ≈80 cm^2, able to contain pure He at ≈1-10x10^{-3} mbar. The walls will assure light tightness and in the inside be reflective, except the top base that would allow light transmission. An appropriate optical set up for the spectroscopy of light will look the He cell and will employ fast PMs, able of single photon detection. The optical set up should have an overall efficiency not lower than 20% around the (656 ± 30) nm wave region, with a resolution of ≈2-3 nm.

The logic of the experiment is very simple: the DAΦNE RF signal, gated by the coincidence at high threshold of the pair of the two thin scintillators, will trigger the DAQ, already selecting, at a ≈80% level or better, the charged, back-to-back correlated, kaon pairs 15). The trigger signal will provide the Common Start to the TDCs (and the gate to the ADCs) of the PMs of the two thin scintillators for the off-line selection of charged kaon (≈100% efficiency) and also to the TDCs (and ADCs) of the PMs of the thick bottom scintillator. In this last, there will be two signals: the signal due to the arrival of the charged kaon itself, and the signal deriving from the fate of the charged kaon stopped in it. The negative kaon will produce a *prompt* signal due to its strong interaction channels with nuclei, i.e. a signal that will overlap in time the signal of the incoming K^-. On the opposite, a stopping K^+ cannot have a destructive strong interaction, and will then simply stop and then decay at rest. The signal due to its decay particles will follow the time distribution dictated by the 12.4 ns long K^+ lifetime, with only a fraction being *prompt*. By using a multiple hit TDC for the PMs of the thick scintillator, the delayed or prompt events can be, off line, easily identified, and this will provide an efficient tool to disentangle K^+ over K^-. The same trigger signal will start of course also the acquisition of the TDCs and ADCs of each of the PMs of the optical spectrometer that collect the photons emitted in the He cell. In the off-line analysis they can be fully correlated to the information of the scintillators of the trigger system and of the thick one. As a refinement, one can even think to implement a coil around the He cell to provide a magnetic field of 40-60 Gauss oriented in the vertical direction, to trap the very slow charged kaons around the vertical axis.

Examining this basic set-up, a sketch of which is depicted in Fig. 4, one can conclude that the realization of the scintillator system poses no problem as their DAQ. This applies also to the set up and DAQ of the PMs of the optical spectrometer. The realization of the He cell is just a problem of mechanics and geometrical optics. The delicate point could be the efficiency of the optical spectrometer. This part of the set-up could be fully tested in advance at a low energy proton machine before mounting it on DAΦNE, to look the H_α line formed from proton impact in He, tuning the conditions to resemble those at DAΦNE. In this respect the LABEC laboratory of Florence has an extracted, triggerable and pulsed (up to a single particle with ps timing) beam of protons of energy up to 6 MeV, that appears nicely suited to the purpose 16).

4 CONCLUSIONS

The Kaium atom, never seen before, could be discovered at DAΦNE which actually provides the lowest momentum K^+ beam at disposal, produced in well known and clean conditions.

On the verge of KLOE roll-in, DAΦNE will be at its best in the present working conditions.

The high cross section of e^- capture by slowing down K^+ implies that a significant number of Kaium atoms is possibly produced at DAΦNE.

Detection of Kaium by measuring its Balmer H_a transition photons appears as the most viable strategy for a first approach to this topic.

An experimental set up, relatively simple, reliable, based on well known techniques and that could be built in a few months, and whose most critical component can be tested in advance on a low energy proton machine as the LABEC of Florence, seems fully feasible on the present DAΦNE configuration and appears compatible with its planned schedule, since the installation, debugging and running period are in the order of few weeks.

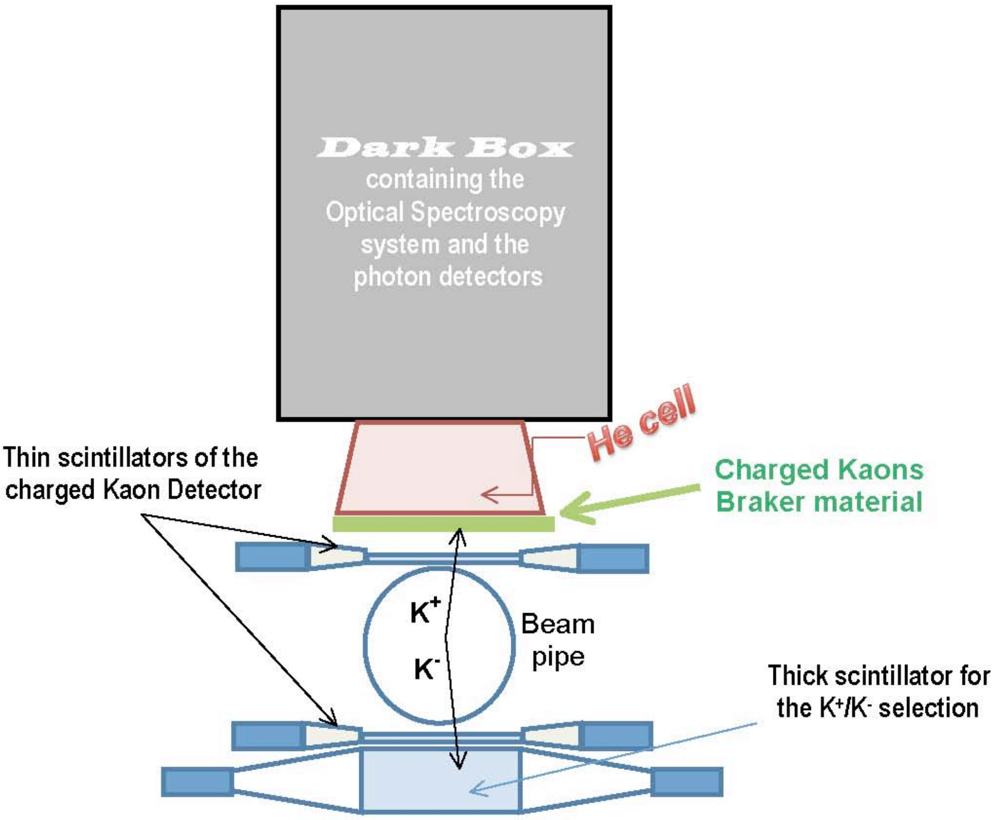

Fig. 4: Sketch of a possible set up (not on scale)- The overall dimensions should not exceed ≈1.0- m, mainly in the vertical.

For the preparation of a Proposal of Experiment a deeper study than the one above exposed would be of course needed, in order to fix the details of the working conditions and provide a more precise estimation of expected counting rates of the signal and the background contamination. To this purpose, however, the usual and well know Monte Carlo simulation techniques appear of straightforward application, since the physical expressions governing all the implied processes are fully known.

The successful detection of Kaium at DAΦNE would not only be the first ever, but could pave the way for future, high precision measurements, using sophisticated techniques as the Doppler-Free two photon pulsed laser spectroscopy 17), magnetic traps for electrons and positrons 18) (eventually coupled to a compact Anticyclotron 19)), of the mass of the K^+ (and of K^-), bringing to direct precision tests of CPT invariance in the charged kaon sector.

5 ACKNOWLEDGEMENTS

We intend to thank Prof. Pier Andrea Mandò for his kindness to illustrate the LABEC Laboratory of Florence and the characteristics of its proton beam lines.

6 REFERENCES

(1) C. Milardi et al., DAΦNE Setup and Performaces, in Proc. of the 2007 Particle Accelerator Conference (PAC2007), Albuquerque, New Mexico, USA, June 25-29, 2007.
(2) The KLOE Coll., Acta Phys. Polon. **B38**, 2731, (2007).
(3) G. Beer et al, Phys. Rev. Lett. **94**, 212302, (2005).
(4) M. Agnello et al., Preliminary results of the FINUDA experiment at DAFNE, in Proc. of the XLII International Winter Meeting on Nuclear Physics, Bormio (Italy) January 25-February 1, 2004.
(5) M. Agnello et al., Phys. Lett. B **622**, 35, (2005).
(6) M. Agnello et al., Phys. Lett. B **640**, 145, (2006).
(7) M. Agnello et al., Phys. Lett. B **649**, 25, (2007).
(8) V. W. Hughes et al., Phys. Rev. Lett. **5**, 63, (1960).
(9) J. Marton, on behalf of the SIDDHARTA Coll., Precision X-ray measurements on kaonic atoms at LNF, in Proc. of the XLV International Winter Meeting on Nuclear Physics, Bormio (Italy) January 14-21, 2007.
(10) M. Senba et al., Phys. Rev. A **74**, 042708, (2006).
(11) W.H. Barkas et al., Phys. Rev. **101**, 778 ,(1956).
(12) F. Risigo et al., The RAPSODI project: SiPM development for applied research in radiation protection, in Proc. of the 10th International Workshop on Radiation Imaging Detectors, Helsinki, Finland, June 29-July 3, 2008.
(13) T. G. Winter, Phys. Rev. **A 44**, 4353, (1991).
(14) B. Van Zyl et al., Phys. Rev. A **33**, 2333, (1985).
(15) V. Lucherini et al., Nucl. Instr. and Meth. in Phys. Res. A **496**, 315, (2003).
(16) N. Taccetti et al., Nucl. Instr. and Meth. in Phys. Res. B **188**, 255, (2002).
(17) B. Cagnac, Hyperfine Interactions **24**, 19, (1985).
(18) D. Wu et al., IEEE Trans. on Appl. Superconductivity 13, 1664, (2003).
(19) P. De Cecco et al., Nucl. Instr. and Meth. in Phys. Res. A **278**, 394, (1997).