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KAIUM at DAΦNE?

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Abstract The possibility of producing and detecting at DAΦNE a new hydrogen *isotope* formed by a (K^+e^-) bound system (*Kaium*) is addressed, considering a dedicated, and relatively simple experiment of short duration. If Kaium will be detected, it could in perspective pave the way for a series of highly sophisticated experiments focused on the precision measurement of several observables, as the $K^+ - K^-$ mass difference, strictly related to CPT invariance.

Keywords Exotic atoms · Positive kaons · CPT test

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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 [2–5]. 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

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welcome tagging and calibration signal [6] or an unwelcome background [3]. 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.

The electron capture (also known 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 [8]: 1) slowing down by excitation and ionization according to the well established Bethe-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; 2) when $v_{X^+} \approx \alpha$c, a cycle of CE reactions starts, 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 CE reactions proceed, together with further slowing down, and can reach even the number of hundreds; 3) after several CE cycles, the particle can emerge as positive, with a velocity so low that it cannot any more catch an e^-, and then thermalizes as a positive ion; or the particle emerges bound to an e^- with too much low velocity to undergo an ionization collision, and then thermalizes as a neutral atom. In any phase of the process, the particle, if unstable, can decay. 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 [8]: several ns for step 1); $\approx$ 1 ns for step 2). Hence, the 12.4 ns lifetime of K^+ should not prevent the possibility of Kaium 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

Kaium 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. Since the mass of a K^+ is $\approx \frac{1}{2}$ that of a p, the reduced masses of Kaium and hydrogen differ for less than 0.05%. Kaium properties will then be very similar to those of hydrogen, apart the absence of hyperfine interactions due to the different spin. In particular the binding energy of H and Kaium will be very similar, as well as the scheme of the levels. The Kaium radiative transitions from excited levels to lower levels will reproduce the well know pattern of hydrogen: the Lyman series, the Balmer series, the Paschen series; and so on. These facts suggest that a simple way to detect the formation of Kaium is to try to detect one of the characteristic lines of its radiative de-excitation. In this respect the most appealing

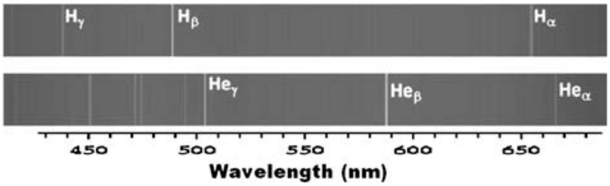

Fig. 1 H and He Balmer emission spectral lines, showing, in particular, the position of the H_α, H_β and H_γ lines respect to the He_α, He_β, and He_γ lines

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. As a first step, the relevant quantities have not to be calculated *ab initio*, but may be taken from experiments which used slow proton beams for the same purpose. A very slow proton, in fact, behaves, in loosing energy and undergoing CE processes, almost exactly as a very slow K^+: the only thing to consider (lifetime apart), for a meaningful comparison, is that it must be done at the same velocity. Taking the data from the literature [9], the capture cross sections turn out to be very huge, of the order of up to ≈ 0.2–3 Mb in He gas for the levels with n = 3. The ionization cross section is even bigger, of ≈ 80 Mb in He [9]. It is also possible to find in the literature the cross section for Balmer H_α emission of slow protons in several gases. For instance, in case of He, it has a maximum of ≈ 3.5 Mb at ≈ 45 keV p kinetic energy [10], corresponding to ≈ 23 keV K^+ kinetic energy.

2.2 Formation and detection

The choice to report results for He gas is not only as an example, but a precise choice. In fact, He is a noble gas, and its own Balmer lines are rather well separated from the Balmer lines of H, as shown in Fig. 1. 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. The conditions at which to use the He gas can be inferred by past experiments using very slow proton beams to look for H formation in He through Balmer H_α emission: He is in the gas state, at a pressure of the order of $\approx 1 - 10 \times 10^{-3}$ mbar; the gas cell is few tenth of cm long. In case of very slow K^+, in order to detect Kaium formation with the same technique, similar experimental conditions should hold. The maximum of H_α emission in He is ≈ 3.5 Mb [10] at ≈ 23 keV K^+ kinetic energy, corresponding to a velocity of ≈ 0.4 cm ns^{-1}. The corresponding ionization cross section is ≈ 60 Mb [9] and, at a He gas pressure of 9×10^{-3} mbar, the *collision length* turns out to be ≈ 72 cm. At the same pressure the H_α *interaction length* is ≈ 1000 cm, meaning that in a cell length of ≈ 5 cm (crossed in ≈ 10 ns) such a K^+ has a probability of ≈ 0.5% to produce H_α photons. For an integrated luminosity at DAΦNE of ≈ 20 pb^{-1} per day, there will be a production of 3.1×10^7 K^+/day. With a *tagging* acceptance of ≈ 20%, the number of K^+ /day would be $\approx 6.2 \times 10^6$. This translates, with an efficiency of ≈ 0.5% to slow down the K^+ to the optimal range of velocities inside the He cell, to a number of useful K^+ /day of $\approx 3.1 \times 10^4$. This flux in its turn would produce in the He cell $\approx 1.6 \times 10^2$ Balmer H_α photons/day. This means $\approx 5 \times 10^3$ H_α photons are 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), if the efficiencies of the spectroscopy set up to analyze the emitted light do not drastically reduce them. This implies that the performance of the spectroscopy set up should have an efficiency not worse than, let say, $\approx 40\%$.

2.3 Background

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. 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 their 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. 1). 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 decay particles. In this respect, there is a fact to be considered: the Doppler Effect. When Kaium deexcites radiatively, 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 ($\approx$ some tens of meV equivalent energy), and will generate H_α photons with negligible Doppler broadening. All the above suggests that the main method that can prove that Kaium is really formed is the presence of H_α Doppler broadened photons for K^+ but not for K^-.

3 A possible (and just more than gedanken) experiment to find Kaium at DAΦNE

We outline an idea for a reliable and simple experimental set up for a *yes/not* answer to the question of Kaium formation at DAΦNE. Its characteristics should be the following:

1. A simple device consisting of two thin scintillators to select the K^+-K^- pairs, similar to the one already employed successfully [11] and the one working on DAΦNE [12].
2. A further scintillator thick enough to stop the K^+/K^-. This, as detailed below, will discriminate, with high efficiency, K^+ from K^-, without the need of magnetic fields and tracking detectors.
3. Following one of the thin scintillators, a set of sheets of appropriate material (*Brakes*) to decrease the velocity of the charged kaons to the desired range of values.
4. After the Brakes, a suitably shaped cell (of height ≈ 10 cm or more, and bottom base of $\approx 80\ cm^2$), able to contain pure He at $\approx 1 - 10 \times 10^{-3}$ 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 at the He cell and will employ optical filters coupled to fast PMs (or Si-PMs [13]), able of single photon detection. The optical

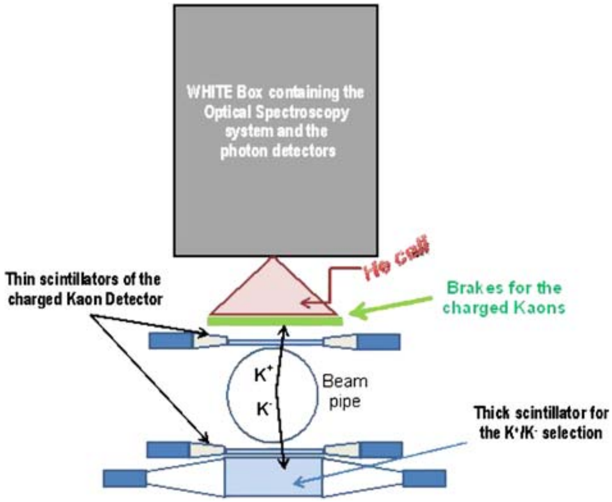

Fig. 2 Sketch of a possible set up (not on scale)—The overall dimensions should not exceed ≈ 50 cm, mainly in the vertical direction

set up should have an overall efficiency not lower than 40% around the (656 ± 30) nm wave region, with a resolution of ≈ 2 nm.

The logic of the experiment is very simple: the DAΦNE RF signal, gated by the coincidence of the pair of the two thin scintillators, will trigger the DAQ, already selecting, at a ≈ 80% level or better, the back-to-back correlated, charged kaon pairs [11]. 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, two signals will appear: 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^-. A stopping K^+, instead, cannot have a destructive strong interaction, and will 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 or Flash TDC for the PMs of the thick scintillator, the delayed or prompt events can be off-line identified, and this will provide an efficient tool to disentangle K^+ over K^-. Examining this basic set-up, a sketch of which is depicted in Fig. 2, one can conclude that the delicate point could be the optical spectrometer. This part of the set-up could be however fully tested in advance at a low energy proton machine, like the one at the LABEC laboratory of Florence [14].

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. 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_α 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 whose most critical component can be tested in advance on a low energy proton machine, seems fully feasible on the present DAΦNE configuration.

A further and 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.

The successful detection of Kaium at DAΦNE would not only be the first ever, but could pave the way for direct, high precision measurements, using sophisticated techniques as the Doppler-Free two photon pulsed laser spectroscopy [15], magnetic traps for electrons and positrons [16] (eventually coupled to a compact Anticyclotron [17]), of the $(K^+ - K^-)$ mass difference, and hence to precision tests of CPT invariance in the charged kaon sector. In is worth to note, in this respect, that the charged kaon mass difference quoted in PDG is based on an *indirect* measurement performed in 1972 [18].

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