PROCEEDINGS OF SCIENCE

Kaonic helium (3 and 4) precision X-ray transitions measurements by SIDDHARTA at DAΦNE

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The strong interaction, described by the QCD in the framework of the Standard Model, is still hiding many mysteries, especially in the low-energy limit, the so called non-perturbative regime. Kaonic atoms, having a K^- replacing an e^- orbiting the nucleus, play a special role in this field due to the strange quark contained in the kaon. Of particular interest are the low Z kaonic atoms, like kaonic helium 3 and 4, protagonist of an intense debate both experimentally and theoretically. Kaonic helium-4 was indeed the subject of a "puzzle" between theoretical predictions and experimental data, whose solution could lead to a deeper understanding of some open questions in the field of the low energy QCD. More profound information can be obtained if precise data on kaonic helium-3 are available too. In this work, the first experimental results coming from the SIDDHARTA experiment at DAΦNE, which performed for the first time precision X-ray measurements on kaonic helium-3 atoms in addition to kaonic helium-4, exctracting also the relative yields to the L_α line for a gaseous target, are presented. These yields information can contribute in a further understanding of the formation and cascade processes involved in kaonic atoms.

XLIX International Winter Meeting on Nuclear Physics, BORMIO2011
January 24-28, 2011
Bormio, Italy

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1. The Kaonic Helium-4 puzzle

For light atoms like helium, a detectable energy shift of the lower n states, with respect to the pure QED value could be expected, as well as an observable broadened ground state level, caused by nuclear absorption (Fig. 1). By measuring these observables (in particular on the 2p state in He case, since transitions to 1s state have an extremely small yield and requires additional dedicated studies), since pure electromangetic values of the energy levels are well known, one can obtain the contribution to the transition energy related only to the strong interaction (see fig. 1).

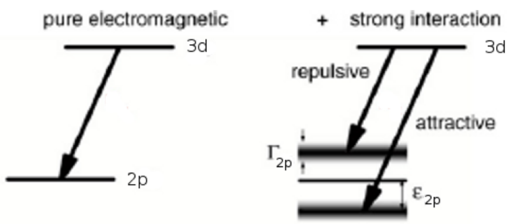

Figure 1: Observables of the strong interaction: shift (ε_{2p}) and width (Γ_{2p}), determined from the measurement of the L_α x-ray transition in comparison to the pure electromagnetic value

For what concerns the kaonic helium-4, the situation till recent years was rather ambiguous; first measurements of the L_α lines have been performed by three experiments [1, 2, 3] more than 20 years ago. Later theoretical predictions [5, 6, 7], based on a complex density dependent optical potential [8, 9], gave, within few σs, results which were more than an order of magnitude lower with respect to the experimental results, giving rise to the so called "Kaonic helium puzzle". Several attempts to reconcile experimental data with theoretical predictions went on, and in these last years a new model, based on a coupled channel approach, was developed [10, 11, 12], allowing higher values for the kaonic helium shift whith respect to the optical potential predictions. Recently, a new experiment [13] performed at KEK in Japan found a value for the shift compatible with zero; even

Quantity	Optical pot. [5, 6, 7]	Coupled ch. [11, 10]	Earliest exp. results [1, 2, 3]	Latest exp. results [13]
$\varepsilon_{2p}(K-^4He)$	$-0.13\pm0.02\,eV$	$<\lvert 11\rvert\,eV$	$-43\pm8\,eV$	$2\pm2(stat)\pm2(syst)\,eV$
$\varepsilon_{2p}(K-^3He)$	$\simeq 0$	$<\lvert 15\rvert\,eV$	not meas.	not meas.

Table 1: Summmary table on kaonic helium 3 and 4 theoretical calculations and experimental results

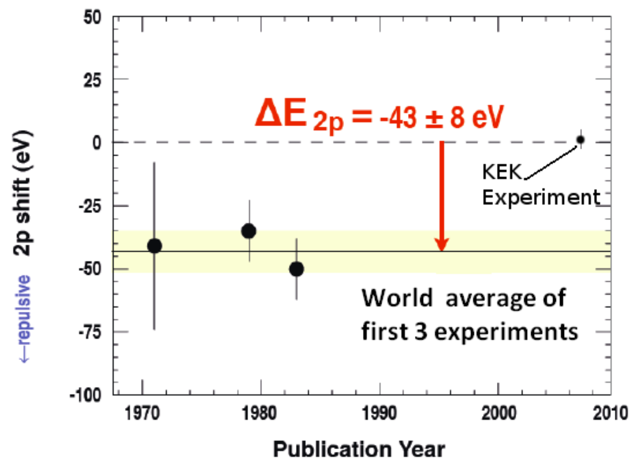

Figure 2: Summary of experimental results on kaonic helium 4

if in better agreement with theoretical predictions, this new result is completely in contraddiction with the previous experiments. The situation is summarized in tab. 1 and fig. 2

From this table, it emerges clearly the necessity to perform a new precise measurement in order to definitively clarify the situation.

2. The SIDDHARTA experimental setup

In the last decade, excellent improvement in detector technology combined with the excellent kaon beam provided by DAΦNE [14, 15, 16, 17] , made a new method for studying low threshold $\bar{K}N$ interaction feasible; the idea is to perform precision measurement of the x-rays photons coming from exotic atoms de-excitation processes. The very low momentum kaons provided by DAΦNE allow to perform experiments with gaseous target, avoiding unwanted effects like Stark Mixing, thus improving the probability for the kaons to reach the lowest n states. SIDDHARTA (SIlicon Drift Detector for Hadronic Atoms Research by Timing Application) [19, 20, 21] is a high precision experiment dedicated to the study of kaonic atoms, which performed in the 2009 the first $K-^3He$ measurement ever, together with the first gaseous $K-^4He$ one, on the DAΦNE collider at Laboratori Nazionali di Frascati of INFN. In fig. 3, a schematic view of the setup is shown.

- Electrons and positrons collide in the interaction region (IR), where a cylindrical beam pipe with a diameter of 6 cm and 350 μm wall thickness is placed (AL6082 [16]). The Φ mesons

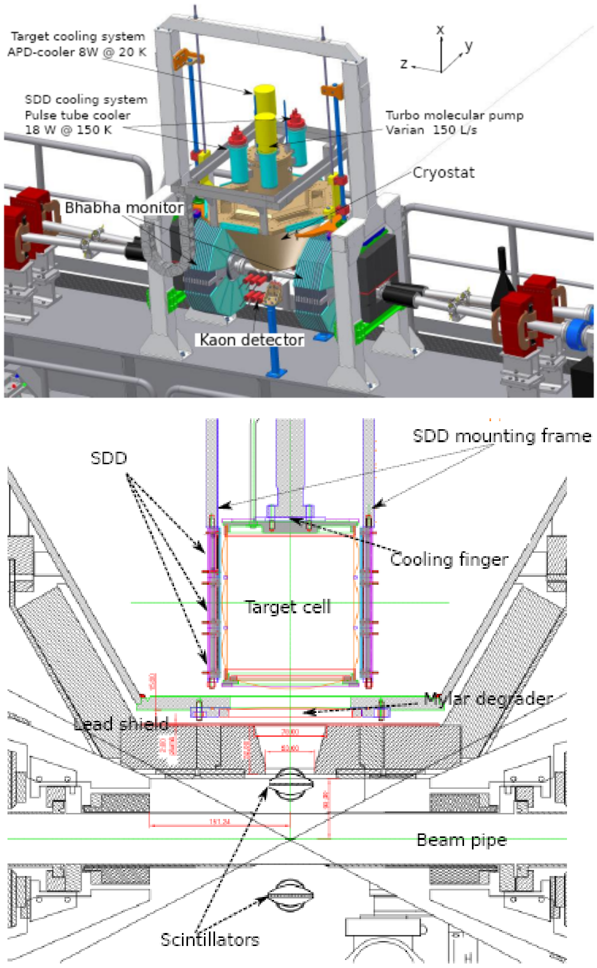

Figure 3: Schematic and cutaway view of the SIDDHARTA setup in the interaction point

which are produced in the IR, decay into back-to-back K^+/K^- pairs with a branching ratio of 49.2%.

- Kaons coming out from the interaction region are detected by two scintillators (BC-420, $152 \times 72\,mm$, $1.5\,mm$ thickness), placed above and below the beam pipe and read out at both sides by Hamamatsu PMTs (Hamamatsu R4998). Coincidence between the two scintillators (4 PMTs) is used as trigger for the data acquisition. This is the SIDDHARTA Kaon Monitor system [22].

- In order to slow down the kaons to a velocity compatible with their capture in the atomic orbits, a mylar degrader, ad hoc shaped taking into account the small boost in the radial direction ($\simeq 50\,MeV$) caused by a small crossing angle between e^+ and e^- beams, is placed just before the entrance window of the target cell. Degrader dimensions are $120 \times 120\,mm$, with an increasing thickness (according to the boost direction) from 100 to 800 μm.

- Kaons enter in the target cell, which is a cylindrical kapton chamber of $16.5\,cm$ height, $7\,cm$ radius and $75\,\mu m$ thickness. The target cell is filled up with gaseous helium at 0.95 bar and

27 K, corresponding to $\simeq 10 \times \rho_{STP}(He)$, and put in a vacuum chamber (10^{-7} mbar).

- X-rays emitted from kaonic helium atoms are then detected by Silicon Drift Detectors [23], placed all around the target cell (according to fig. 4) and cooled down to 170 K. Detectors are read out by an ad hoc built read out electronics [24, 25], and are arranged in arrays of 3 detectors each. SIDDHARTA SDDs are geometrically organized in units of 18 SDD detectors, divided in 3 sub-units, each containing 6 individual SDDs (or two arrays of 3 detectors each). For the SIDDHARTA experiment 8 units of 18 SDDs each were used, for a total of 144 SDDs. Each single SDD has an active area of $1\,cm^2$.

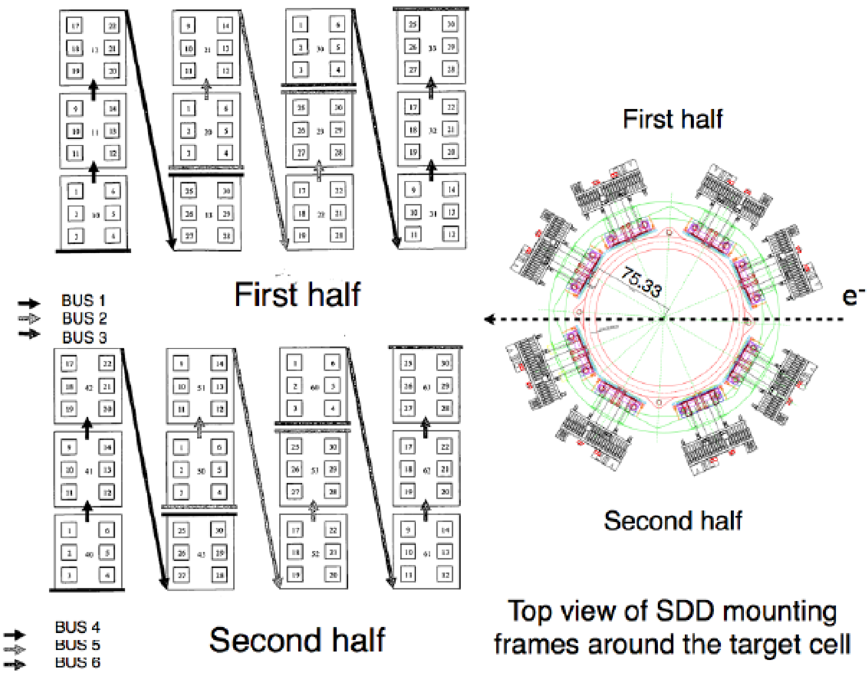

Figure 4: For the readout electronics, the total 144 SDDs are divided into 6 buses, each having 4 chips of 6 SDDs (or 2 arrays). The left diagram shows the sequence of SDDs' arrangement, and the right one illustrates the top view of SDDs and mounting frame surrounding the target cell

3. Data analysis

SIDDHARTA experiment took data during several periods in the 2009, collecting $\simeq 25\,pb^{-1}$ for $K -^4 He$ and $\simeq 20\,pb^{-1}$ for $K -^3 He$.

3.1 Calibration

The Silicon Drift Detectors used by the SIDDHARTA experiment and developed in the framework of the collaboration, were used for the first time on a electromagnetic collider. In order to obtain a precision of 0.1 % on the peak positions a precise calibration of each SDD is needed; each 15 production runs, a calibration run (in the same beam condiction as standard production runs) has been taken. Calibration was performed using an X-ray tube, located below the interaction region and aligned with the entrance window of the target cell, activating Ti and Cu foils placed inside the vacuum chamber. Characteristic X-ray lines of Ti and Cu have been then used for the calibration of the detectors. The σ of each line is fitted according to eq.3.1

$$\sigma = \frac{FWHM}{2.35} = \omega\sqrt{W_N^2 + \frac{F \times E}{\omega}} \tag{3.1}$$

being ω the e-h pair creation energy ($3.7\,eV$), F the Fano factor ($\simeq 0.1$), E the energy of the line and W_N the intrinsic noise of the detector. While ω parameter is constant in our experimental condition, the other two parameters are strictly dependent on temperature and on construction procedure and have to be determined for each detector during the fitting procedure. A typical calibration spectrum is shown, both for Ti and Cu, in fig. 5.

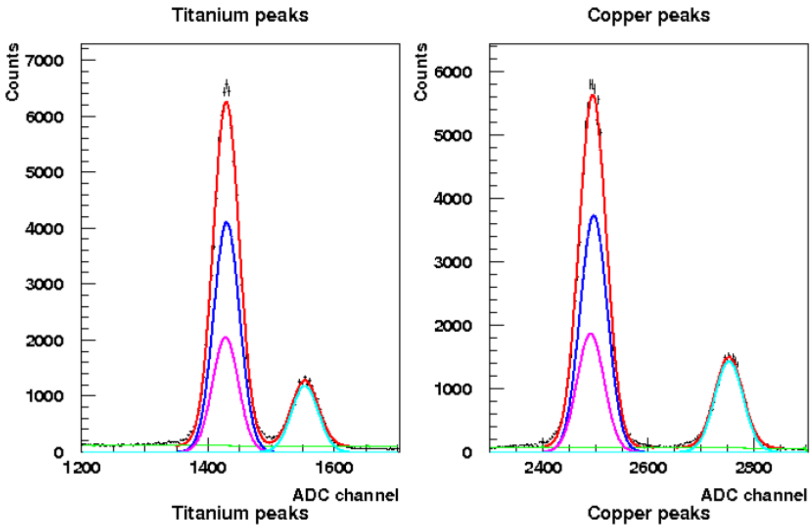

Figure 5: Typical calibration spectra for Ti and Cu; total fit (red), K_α (blue) and K_β (light blue) are plotted.

3.2 Kaonic helium spectra

In order to obtain the best kaonic helium spectrum, some cuts and selection have to be applied to the raw data:

- **SDD selection:** only the SDD having a good behaviour and working properly are selected;
- **Drift time selection:** using timing information coming from the Kaon Monitor scintillators, events related only with kaons can be identified. Drift time represents the time difference between a trigger from the Kaon Monitor and a hit on a SDD. Kaons related events are all lying under a peak and can be then selected (see fig. 6, top figure).
- **Kaons identification:** under the drift time peak, also events related to MIPs particles, mostly generated by e^- and e^+ lost from circulating beams and correlated in time with the kaons production, are present. These can be separated from the kaons using the time of flight information, as shown in fig. 7.

Applying all these cuts and selection, the final kaonic helium spectrum (fig. 6, bottom picture) can be obtained from the raw self trigger data (fig. 6, middle picture).

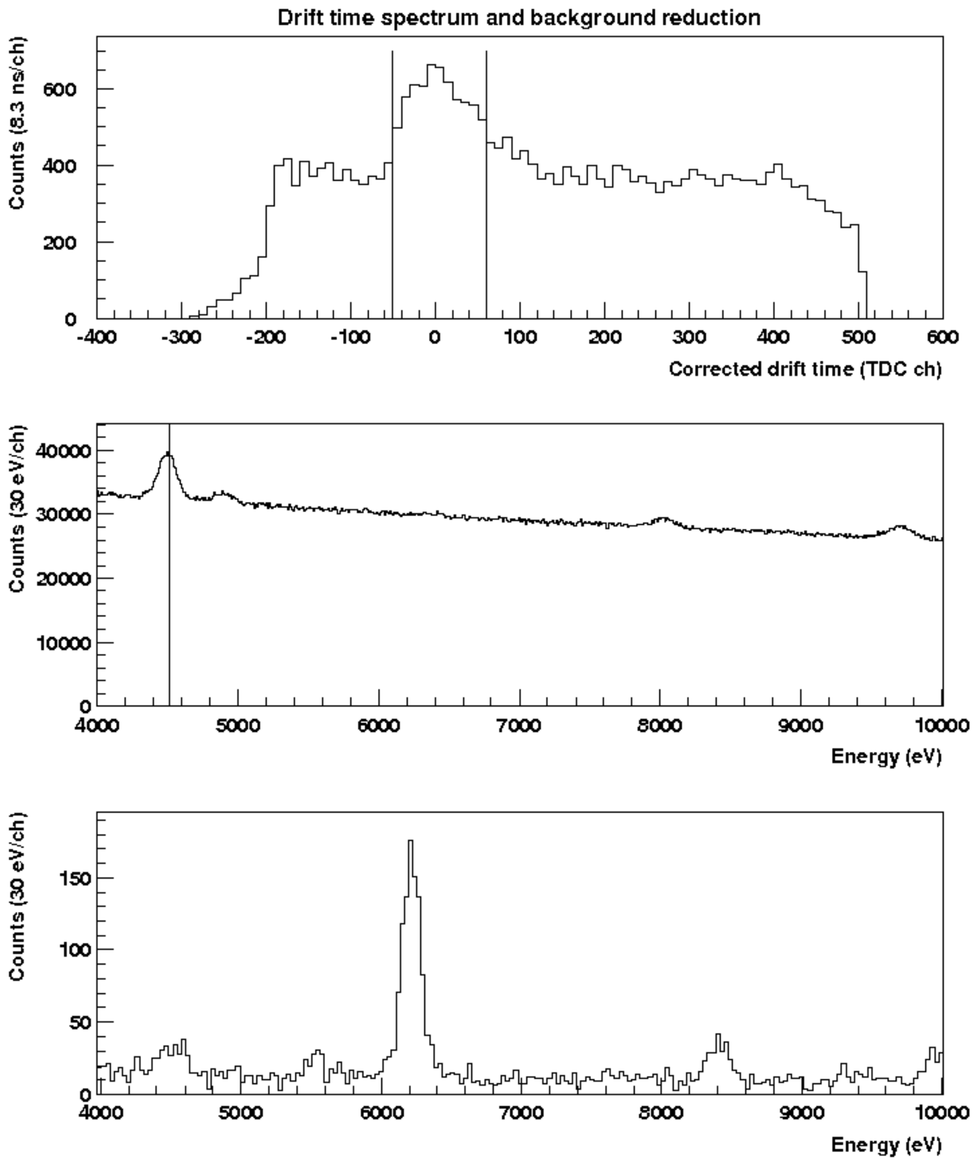

Figure 6: Drift time spectrum with kaons' peak selection evidenced (*up*), total self trigger spectrum (*mid*) and drift time cut spectrum (*bottom*).

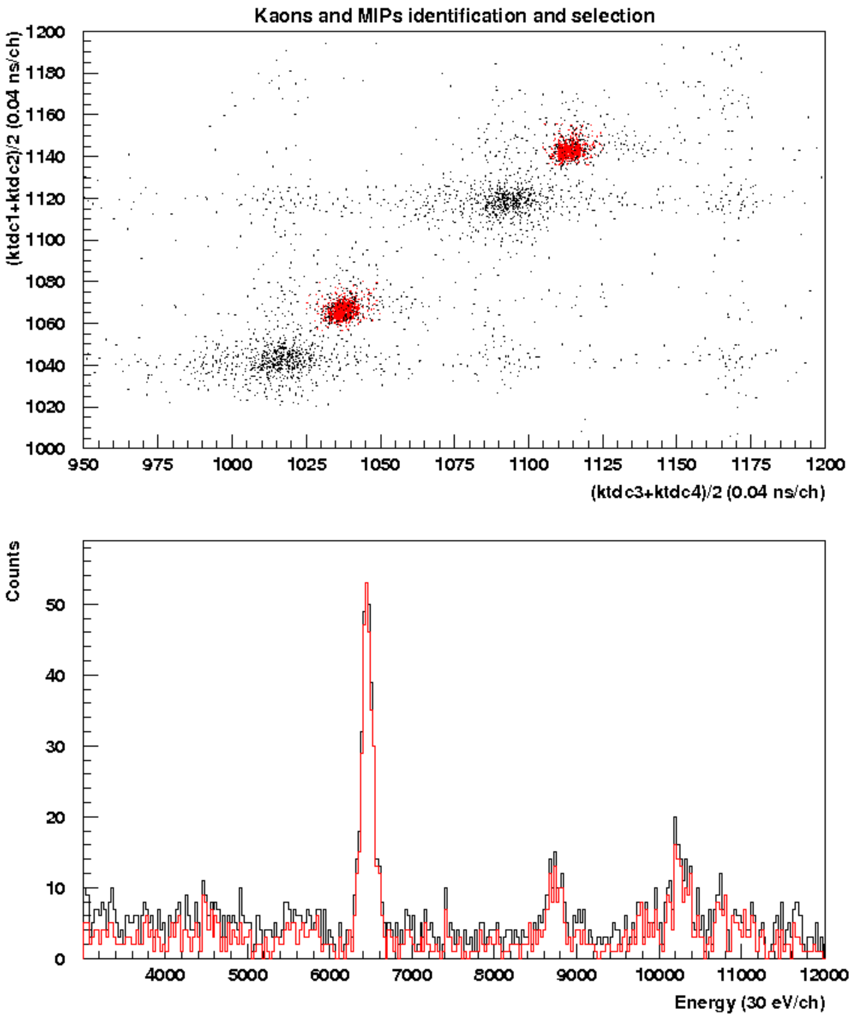

Figure 7: With (red) and without (black) kaons' selection spectra.

4. Results

Final $K-^{3}He$ and $K-^{4}He$ spectra have been fitted in order to obtain the values for the shifts and the relative yields and results are shown in fig. 8.

Together with the kaonic helium lines, other satellite lines are clearly visible and were included in the fit; these are due to X-rays coming from materials inside the setup like Copper, Titanium, Gold, Iron and Manganese (green lines) and from other kaonic atoms formed by the kaons stopped in the target cell walls like kaonic carbon, nitrogen and oxygen (blue lines). These satellite lines have also been taken into account while estimating systematic errors both on shifts and relative yields. For what concerns the relative yields, also a correction for the transmission coefficient of the target cell walls has been included [26].

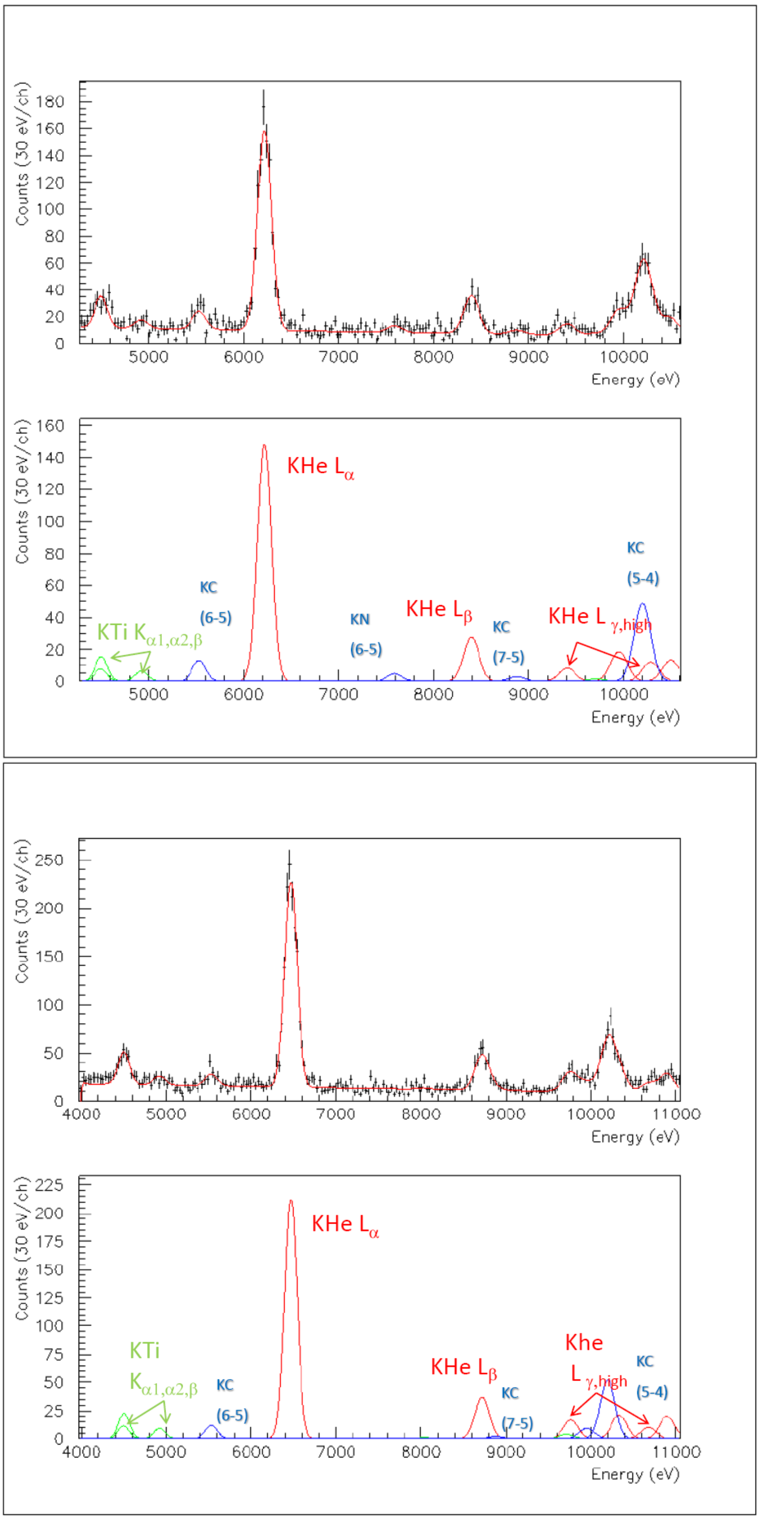

Figure 8: $K-{}^3He$ (up) and $K-{}^4He$ (down) final spectra; fit function (red) is superimposed to the histogram, while all satellite lines included in the fit are shown under each spectrum.

Final results for the shifts are

$$\varepsilon_{K-^3He} = (-2 \pm 3(stat) \pm 4(syst))\, eV \quad (4.1)$$
$$\varepsilon_{K-^4He} = (8 \pm 2(stat) \pm 4(syst))\, eV \quad (4.2)$$

while results on relative yields are summarized in tab. 2. To be mentioned that for yields these are preliminary results and refinements are going on.

Lines	$K-^3He$ Relative yield (%)	$K-^4He$ Relative yield (%)
$\frac{4\to2}{3\to2}$	$24.43 \pm 1.94(stat) \pm 0.001(sys)$	$25.97 \pm 1.67(stat) \pm 0.11(sys)$
$\frac{5\to2}{3\to2}$	$7.88 \pm 1.41(stat) \pm 0.003(sys)$	$12.40 \pm 1.45(stat) \pm 0.24(sys)$
$\frac{6\to2}{3\to2}$	$18.39 \pm 1.91(stat) \pm 0.04(sys)$	$16.48 \pm 2.02(stat) \pm 0.08(sys)$
$\frac{7\to2}{3\to2}$	$12.10 \pm 3.66(stat) \pm 0.25(sys)$	$7.79 \pm 1.00(stat) \pm 0.00(sys)$
$\frac{8\to2}{3\to2}$	$13.80 \pm 1.94(stat) \pm 0.03(sys)$	$16.04 \pm 2.51(stat) \pm 0.00(sys)$

Table 2: Preliminary results for relative yields values for $K-^3He$ and $K-^4He$; also values of the yields corrected by the target cell absorption coefficient are shown.

Concerning $K-^4He$, the obtained results are compatible with the KEK experiment [13] and are definitely rejecting the hypothesis of a large shift; the puzzle is then finally solved. For the $K-^3He$ we have performed the first measurement ever, and results have been published on PLB [27]. Presently, the kaonic helium results obtained by SIDDHARTA are being considered by theoreticians working in the field. Based on the success of the SIDDHARTA experiment, in particular on the happy marriage between excellent kaon beam quality from DAΦNE and efficient signal measurement by using triggerable detectors, we plan to perform an upgrade of the apparatus, becoming SIDDHARTA2, to continue and enrich this type of measurements [28].

The field of low-energy strangeness QCD has found a strong experimental support in the kaonic atoms measurements, as was shown in this work. The future of the field is making a transition from qualitative to quantitative precision measurements. The resonance of these results and of future planned experiments extends from particle physics to astrophysics, and will, for sure, help in a better understanding of the fundamental laws of Nature.

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Acknowledgement

We thank C. Capoccia, B. Dulach, and D. Tagnani from LNF-INFN; and H. Schneider, L. Stohwasser, and D. Stückler from Stefan-Meyer-Institut, for their fundamental contribution in designing and building the SIDDHARTA setup. We thank as well the DAΦNE staff for the excellent working conditions and permanent support. Part of this work was supported by Hadron- Physics I3 FP6 European Community program, Contract No. RII3-CT- 2004-506078; the European Community Research Infrastructure Integrating Activity "Study of Strongly Interacting Matter" (HadronPhysics2, Grant Agreement No. 227431) under the Seventh Framework Programme of EU; Austrian Federal Ministry of Science and Research BMBWK 650962/0001 VI/2/2009; Romanian National Authority for Scientific Research, Contract No. 2-CeX 06-11-11/2006; Grant-in-Aid for Specially Promoted Research (20002003), MEXT, Japan; and the Austrian Science Fund (FWF): [P20651- N20]

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