Kaonic atoms measurements at the DAΦNE accelerator: the SIDDHARTA experiment

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Abstract. Kaonic Hydrogen and Helium X-ray measurements play nowadays a fundamental role in testing the reliability of the Chiral Perturbation Theory as a realisation of the Quantum Chromodynamics at low energies. Dictated by both electromagnetic and strong interaction, X-ray transitions at lower energy levels of these complex bound systems offer indeed the unique opportunity to perform a threshold measurements of zero-energy meson-nucleon scattering. Nowadays the SIDDHARTA experiment at DAΦNE collider is the only apparatus which can provide such kind of measurements with the high precision needed to disentangle different theoretical calculation scenarios. In this work we present the SIDDHARTA experiment performances and results, with a focus on the main topics of light kaonic atom physics.

1. Introduction
The light kaonic atoms, matter of study of the SIDDHARTA experiment at the DAΦNE collider, are bound systems made of a light target atom and a $K^-$ meson captured in an external atomic orbital, with a lifetime of the order of $10^{-12}\text{s}$. The difference between the atomic binding energies of these light systems (in the keV range) and the hadronic scale (about 1GeV) make them a very useful tool to perform experiments equivalent to scattering at vanishing energies: this allows, in the strangeness sector, to check the nature of the three flavor Chiral Symmetry Breaking through a real threshold measurement.
The experimental challenges of this kind of physics are strictly related to four main processes that occur during the lifetime of these bound systems: the capture, the formation, the cascade and the absorption process (see ref.[1] for an exhaustive description). After the capture of the $K^-$ and the formation of the bound system, the meson starts a series of radiative transitions towards the lower lying levels (cascade process): in the last ones, when the meson is nearest to the nucleus, an X-ray with the energy emission dictated by both the electromagnetic and strong interaction occurs, bringing us information about the strong force contribution at very low energy. A high precision spectroscopic X-ray measurement of the lines related to these transitions allows to evaluate their shift ($\epsilon$) and width ($\Gamma$) respect to the pure electromagnetic case. Recognising these parameters ($\epsilon, \Gamma$) respectively as the real and the imaginary part of a complex scattering length through the Deser-Truemann formula [2], we can relate them to the effective chiral lagrangian using the Bethe-Salpeter equation [3]. From the experimental point of view the capture and the cascade process are the most important. The capture probability is maximum when the $K^-$ kinetic energy is comparable to the kinetic energy of the atomic electron in the capturing orbital (13.6 eV for the Kaonic Hydrogen (KH)), a very low-energy monochromatic $K^-$ beam is needed. The cascade process is the most important one for the spectroscopic measurement itself: after the depletion of all low lying atomic electrons till a formation of a hydrogenoid system nucleus - $K^-$, in the last part of the cascade, namely the Particle-Nucleus interaction regime (when the meson is nearest to the nucleus), the X-ray transitions of experimental interest occur [1]. Moreover during this process several processes compete, causing the loss of the signal: the most important are the coulombian de-excitation, the elastic scattering and the Stark mixing, that increase with density (see ref.[4]).

In the next section the SIDDHARTA apparatus is described, with a focus on how it can satisfy these requirements.

2. The SIDDHARTA experiment at the DAΦNE collider

The ideal low-energy monochromatic $K^-$ beam to produce kaonic atoms in the target of the SIDDHARTA experiment is provided by the DAΦNE $e^+e^-$ collider of the Laboratori Nazionali di Frascati, tuned on the $\Phi$ resonance at rest (1020 MeV). With a branching ratio of 49.2% the $\Phi$ decays in $K^+K^-$ emitted back to back, with a momentum of 127 MeV/c and a spread $\Delta p/p$ of 0.1%. These particular characteristics offer several advantages for the SIDDHARTA experiment: first, the low kaons momentum allows to use a thin plastic degrader to slow them without enhance the energy spread, second the particular topology of the $\Phi$ decay allows to implement a trigger system to disentangle the kaons and the MIPs (Minimum Ionizing Particles). Moreover, a new collisional scheme implemented on the DAΦNE collider enhance the machine luminosity to $5 \times 10^{32} cm^{-2}s^{-1}$ through the Crab-Waist collisions, accounting nowadays the DAΦNE collider the ideal machine to perform this kind of physics [5]. To detect the particular topology of the $\Phi$ decay, the SIDDHARTA trigger system is constituted by two scintillators, placed immediately below and above the Interaction Point (IP). Through a TOF measurement, it allows to disentangle kaons from synchronous background with a separation of about 1 ns. In order to correlate the passage of a produced kaon with an X-ray emission coming from a kaonic atom, to reduce the background in the spectroscopic measurement, a very fast detector for high precision spectroscopy is needed. The Silicon Drift Detectors (SDD) combine a fast response with a good energy resolution (FWHM=150eV@5.9KeV): 144 SDDs with 1 cm$^2$ of active area surround the SIDDHARTA target, to detect the X-rays [6]. They were continuously monitored during the data taking with in-situ calibrations, one every 4 hours, using a sandwich of Ti and Cu foils and an X-ray tube. The produced $K^-$, passing through the scintillator of the trigger system and the plastic degrader, enters in the SIDDHARTA target cell, placed in the vacuum chamber and surrounded by the SDDs. To enhance the mean free path of the kaonic atoms in the target cell minimising the contribution of the competitor processes, SIDDHARTA
uses a gaseous target. The temperature and the pressure of the target are carefully set, because the capture probability is proportional to the density of the target itself. In particular, for the different SIDDHARTA targets (kaonic H, $^4$He (K$^4$He) and $^3$He (K$^3$He)), the temperature and the pressure were set as follow: 23 K and 10$^5$ Pa for the KH, 20K and 10$^5$ Pa for the K$^3$He and 27K and 10$^5$ Pa for the $^4$He. For a detailed description of the SIDDHARTA apparatus see ref.[7]. In the next section we present the SIDDHARTA results on these different light kaonic atoms.

3. SIDDHARTA results

- Kaonic Hydrogen (ref.[8]) : A set of data for a total amount of 340 pb$^{-1}$ has been collected and analysed. The result for the shift $\epsilon$ and the width $\Gamma$ for the transition $K_{\alpha}$ is: $\epsilon_{1s} = -283 \pm 36(stat) \pm 6(syst)$eV and $\Gamma_{1s} = 541 \pm 89(stat) \pm 22(syst)$eV. Nowadays it is the best result available in literature.

- K$^3$He (ref.[7]): A set of data for a total amount of 20 pb$^{-1}$ has been collected and analysed. A source of $^{55}$Fe has been used during the data taking to check the systematics. The results for the shift $\epsilon$ for the transition $L_{\alpha}$ is: $\epsilon = 0 \pm 6(stat) \pm 2(syst)$. This is the first result obtained using a gaseous $^4$He target, that confirm the result obtained in a previous experiment with a liquid target (see ref. [10]).

- K$^4$He (ref.[9]): A set of data for a total amount of 15 pb$^{-1}$ has been collected and analysed. The results for the shift $\epsilon$ for the transition $L_{\alpha}$ is: $\epsilon = -1.7 \pm 2.7(stat) \pm 4(syst)$. This is the first measurement in the world for this light kaonic atom.

4. Conclusions and outlooks

Thanks to the monochromatic low-energy kaons beam delivered by the DAΦNE collider, which allowed the choice of a gaseous target and the use of very-fast and high-precision detector for spectroscopy (SDDs), the SIDDHARTA experiment obtained a unique-quality results on light kaonic atoms. Presently an upgrade of the SIDDHARTA apparatus is ongoing for the SIDDHARTA-2 phase. The aim of this project is to study an enlarged scientific case, in particular the Lyman series of kaonic deuterium (Kd) and of K$^3$He and K$^4$He, never done before. This will allow to have an overall view of the strong interaction at low-energy in the strangeness sector in system with one, two, three and four nucleons.

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References

[1] Gotta D 2004 Progress in Particle and Nuclear Physics 52 133
[2] Truemann T L et al. 1961 Nucl. Phys. 26 57
[3] Itzykson C Zuber J 1980 Quantum Field Theory (New York, McGraw-Hill)
[4] Jensen T S et al. 2002 Eur. Phys. J. D 19 165
[5] Boscolo M et al. 2010 Nucl. Instr. and Meth. A 621 121
[6] SIDDHARTA Collaboration, Marton J In the Proceedings of International Symposium on Detector Development for Particle, Astroparticle and Synchrotron Radiation Experiments (SNIC 2006), Menlo Park, California, 3-6 Apr 2006, pp 0196.
[7] SIDDHARTA Collaboration, Bazzi M et al. 2009 Phys. Lett. B 681 310
[8] SIDDHARTA Collaboration, Bazzi M et al. 2011 Phys. Lett. B 704 113
[9] SIDDHARTA Collaboration, Bazzi M et al. 2011 Phys. Lett. B 697 199
[10] Okada S et al. 2007 Eur. Phys. J. B 653 387