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KAONIC ATOMS EXPERIMENTAL STUDIES AT DAΦNE

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Abstract

The DAΦNE electron-positron collider at the Frascati National Laboratories has made available a unique "beam" of negative kaons. The DEAR (DAΦNE Exotic Atom Research) experiment at DAΦNE and its successor SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) aim at a precision measurement of the strong interaction energy shift and width of the $1s$ level, via the measurement of the X-ray transitions to this level, for kaonic hydrogen and kaonic deuterium. The final aim is to extract the isospin dependent antikaon-nucleon scattering lengths which contribute to the understanding of aspects of non-perturbative QCD in the strangeness sector. Other hadronic atoms transition measurements possible at DAΦNE are under study.

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1 Introduction

The DAΦNE [1] electron-positron collider at the Frascati National Laboratories produces the ϕ-resonance, which decays with a probability of about 50% in K^+K^-, providing low energy kaons (16 MeV of kinetic energy) which can be used used for the study of the low-energy kaon-nucleon interaction, a field still largely unexplored. By making use of the K^- from DAΦNE, the DEAR (DAΦNE Exotic Atom Research) experiment [2] at DAΦNE and its successor SIDDHARTA (SIlicon Drift Detector for Hadronic Atom Research by Timing Application) [3] aim at eV precision measurement of the strong interaction energy shifts and widths of the 1s level, via the measurement of the X-ray transitions to this level, for kaonic hydrogen and kaonic deuterium. The final goal is to extract, for the first time, the isospin dependent antikaon-nucleon scattering lengths, fundamental quantities for the understanding of aspects of chiral symmetry breaking in the strangeness sector.

In practice, in studying kaonic hydrogen (deuterium) in order to measure the strong interaction component of the kaon-nucleon force, one measures the energy shift ϵ of the K_α line ($2p \rightarrow 1s$ transition) from the one calculated from a purely electromagnetic interaction:

$$\epsilon = |E_{2p\rightarrow 1s}^{measured}| - |E_{2p\rightarrow 1s}^{e.m.}| \tag{1}$$

and the width (broadening) Γ of the 1s level given by the strong interaction.

The electromagnetic transition energy in kaonic hydrogen is calculated with 1 eV precision by solving the corresponding Klein-Gordon equation and applying the corrections for finite size and vacuum polarization. The resulting value is:

$$E_{2p\rightarrow 1s}^{e.m.} = (6480 \pm 1)\ eV \tag{2}$$

where the 1 eV error is dominated by the uncertainty of the kaon mass [4].

Until the advent of DAΦNE, the kaonic hydrogen parameters were measured at KEK [5], where the following results were found:

$$\epsilon = -323 \pm 63(stat.) \pm 11(syst.)\ eV \tag{3}$$

$$\Gamma = 407 \pm 208(stat.) \pm 100(syst.)\ eV \tag{4}$$

This measurement, which solved the so-called “kaonic hydrogen puzzle”, showed clearly that the antikaon-nucleon interaction is of repulsive type, but cannot be considered a precision measurement. The challenging aim of the DEAR/SIDDHARTA experiment is, therefore, to measure the kaonic hydrogen transition with a precision at the eV level. The kaonic deuterium, fundamental to determine the two antikaon-nucleon isospin dependent scattering lengths (as will be shown in the next Section), will be measured for the first time. These results will represent a breakthrough in the study of the low-energy antikaon-nucleon interaction.

In Section 2, the DEAR/SIDDHARTA scientific case will be discussed. Section 3 contains the presentation of the SIDDHARTA setup, while the paper ends with Section 4, dedicated to Conclusions.

2 The DEAR/SIDDHARTA scientific case

The aim of the experiment is a precise determination of the isospin dependent antikaon-nucleon scattering lengths, through an eV measurement of the K_α line shift and width in kaonic hydrogen, and, for the first time, a similar measurement of kaonic deuterium. SIDDHARTA measures the X-ray transitions occurring in the cascade processes of kaonic atoms. A kaonic atom is formed when a negative kaon (from the decays of ϕs, produced at DAΦNE) enters a target, loses its kinetic energy through the ionization and excitation of the atoms and molecules of the medium, and is eventually captured, replacing the electron, in an excited orbit. Via different cascade processes (Auger effect, Coulomb deexcitation, scattering, electromagnetic transitions) the kaonic atom deexcites to lower states. Whenever a small angular momentum state is reached, the strong interaction with the nucleus comes into play. This strong interaction is the reason for a shift in energy of the lowest-lying level from the purely electromagnetic value and for a finite lifetime of the state, due to nuclear reaction of the kaon.

For kaonic hydrogen and deuterium the K-series transitions are of primary experimental interest since they are the ones mostly affected by the strong interaction (the shift of the energy due to the presence of strong interaction is at the level of hundred(s) of eV). The K_α lines are clearly separated from the higher K transitions. The shift ϵ and the width Γ of the 1s state of kaonic hydrogen are related in a fairly model-independent way to the real and imaginary part of the complex s-wave scattering length, a_{K^-p} :

$$\epsilon + i\Gamma/2 = 412 a_{K^-p}\ eV\ fm^{-1} \tag{5}$$

This expression in known as the Deser-Trueman formula [6]. A similar relation applies to the case of kaonic deuterium and to its corresponding scattering length, a_{K^-d}.

The observable scattering lengths a_{K^-p} and a_{K^-d} can be expressed in terms of the $\overline{K}N$ isospin dependent scattering lengths a_0 (I=0) and a_1 (I=1). The kaonic hydrogen scattering length is simply the average of the two:

$$a_{K^-p} = 1/2(a_0 + a_1) \tag{6}$$

while the kaonic deuterium scattering length a_{K^-d} is related to a_0 and a_1 in the following way:

$$a_{K^-d} = 2(\frac{m_N + m_K}{m_N + m_K/2})a^{(0)} + C \tag{7}$$

where

$$a^{(0)} = \frac{1}{2}(a_{K^-p} + a_{K^-n}) = \frac{1}{4}(3a_1 + a_0) \tag{8}$$

corresponds to the isoscalar $\overline{K}N$ scattering length. The first term in eq. (8) represents the lowest-order impulse approximation, i.e. K^- scattering from each (free) nucleon. The second term, C, includes all higher contributions related to the physics associated to the K^-d three-body interaction.

The determination of the $\overline{K}N$ scattering lengths requires the calculation of C. This is a well-known three-body problem, solvable by the use of Faddeev equations, when the two-body interactions are specified. The K^-d three-body problem includes the complication that the K^-p and K^-n interactions involve significant inelastic channels. The K^-p and K^-n scattering lengths are thus complex and so is the K^-d scattering length. Incorporating $\overline{K}N$ scattering data and its sub-threshold behavior, the two-body potentials are determined in a coupled-channel formalism including both elastic and inelastic channels. Three-body Faddeev equations are then solved by the use of the potentials, taking into account the coupling among the multi-channel interactions.

An accurate determination of the K^-N isospin dependent scattering lengths will place strong constraints on the low-energy $\mathrm{K^-N}$ dynamics, which in turn constrains the SU(3) description of chiral symmetry breaking [7].

In 2002, the DEAR experiment performed the most precise measurement to date of kaonic hydrogen X-ray transitions to the 1s level [8]:

$$\epsilon = -193 \pm 37(stat.) \pm 6(syst.)\ eV \tag{9}$$

$$\Gamma = 249 \pm 111(stat.) \pm 30(syst.)\ eV \tag{10}$$

This measurement has triggered new interest from the theoretical groups working in the low-energy kaon-nucleon interaction field, and as well it is related to non-perturbative QCD tests [9–13].

The new experiment, SIDDHARTA, aims to improve the precision obtained by DEAR by an order of magnitude and to perform the first measurement ever of kaonic deuterium. Other measurements (kaonic helium, sigmonic atoms, precise determination of the charged kaon mass) are also considered in the scientific program.

3 The SIDDHARTA experiment

SIDDHARTA represents a new phase in the study of kaonic atoms at DAΦNE. The DEAR precision was limited by a signal/background ratio of about 1/70. To significantly improve this ratio, a breakthrough is necessary. An accurate study of the background sources present at DAΦNE was redone. The background includes two main sources: synchronous background, coming together with the kaons – related to K$^-$ interactions in the setup materials and also to the ϕ-decay processes; it can be defined as hadronic background; asynchronous background, final products of electromagnetic showers in the machine pipe and in the setup materials originating from particles lost from primary circulating beams either due to the interaction of particles in the same bunch (Touschek effect) or due to the interaction with the residual gas. Accurate studies performed by DEAR showed that the main background source in DAΦNE is of the second type, which shows the way to reduce it. A fast trigger correlated to a kaon entering into the target would cut the main part of the asynchronous background.

X rays were detected by DEAR using CCDs (Charge-Coupled Devices) [14], which are excellent X-ray detectors, with very good energy resolution (about 140 eV FWHM at 6 keV), but having the drawback of being non-triggerable devices (since the read-out time per device is at the level of 10 s). A recently developed device, which preserves all good features of CCDs (energy resolution, stability and linearity), but additionally is triggerable - i.e. fast (at the level of 1μs), was implemented. This new detector is a large area Silicon Drift Detector (SDD), specially designed for spectroscopic application. The development of the new 1 cm^2 SDD device is partially performed under the Joint Research Activity JRA10 of the I3 project "Study of strongly interacting matter (HadronPhysics)" within FP6 of the EU.

The trigger in SIDDHARTA will be given by a system of scintillators which will recognize a kaon entering the target making use of the back-to-back production mechanism of the charged kaons at DAΦNE from ϕ decay: of the type: $e^+e^- \to \phi \to K^+K^-$.

Monte Carlo simulations, together with tests on the Beam Test Facility (BTF) of LNF-INFN extrapolated to SIDDHARTA conditions, showed that the S/B ratio in the region of interest for kaonic hydrogen is about 20/1 for the asynchronous background, which is mainly due to the Touschek effect. Taking into account the synchronous background contribution as well, we can estimate a total S/B ratio of about 4/1.

The SIDDHARTA setup will contain 216 SDD chips of 1 cm^2 each, grouped in chips containing 3 SDDs (Fig. 1), organized in units containing 18 cm^2 SDDs (Fig. 2). The SDDs are placed around a cryogenic cylindrical

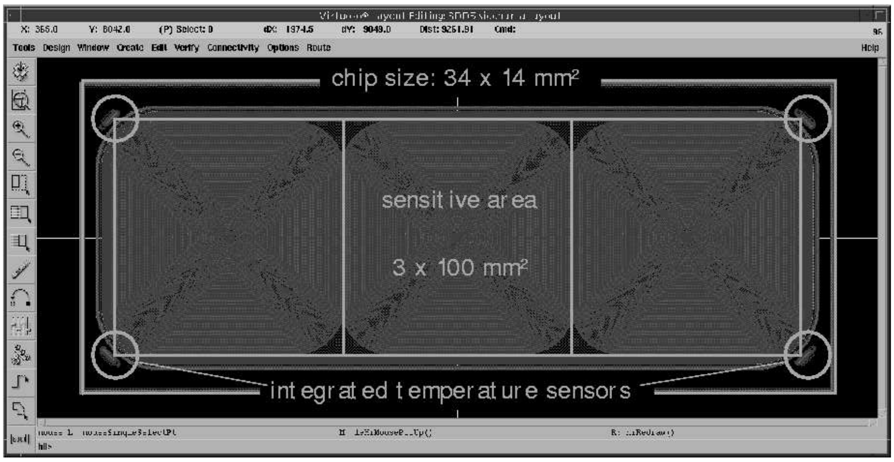

Figure 1: SDD layout on the readout side: 3 SDD cells, read independently, each of 1 cm^2 area, monolithically integrated on one chip.

target, containing high density gaseous hydrogen (deuterium). The target is going to be made of kapton, 75μm thick, reinforced with an aluminium grid.

SDDs together with the readout electronics were intensively tested. The tests proved a very good experimental resolution, Figure 3, and a stability of the order of 2-3 eV at 6 keV (by using a 1 mV stabilized power supply developed in the framework of SIDDHARTA). 12 SDD 18 cm^2 units will be placed all around the target cell, as shown in Figure 4. The setup will be installed above the beam pipe; in Figure 5 there is a drawing of the final setup in the DAΦNE interaction region.

SIDDHARTA is being assembled and it's going to be installed at DAΦNE by the end of 2007; a period of DAQ will follow in 2008, with the plan to collect 400 pb^{-1} integrated luminosity for kaonic hydrogen and about 600 pb^{-1} for kaonic deuterium, such as to obtain few eV precision for the parameters ϵ and Γ.

4 Conclusions

DAΦNE has unique features as a kaon source which is intrinsically clean and of low momentum – a situation unattainable with fixed target machines – especially suitable for kaonic atom research.

The SIDDHARTA experiment combines the newly available techniques of large area triggerable SDD detectors with the good kaon beam quality to initiate a renaissance in the investigation of the low-energy kaon-nucleon

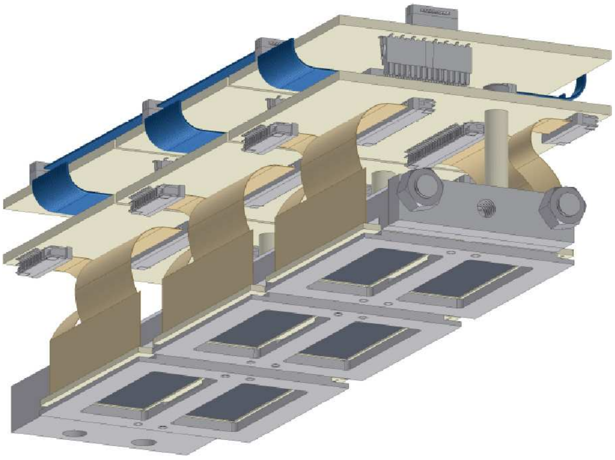

Figure 2: An 18 cm^2 SDD unit, containing 18 SDD individual chips.

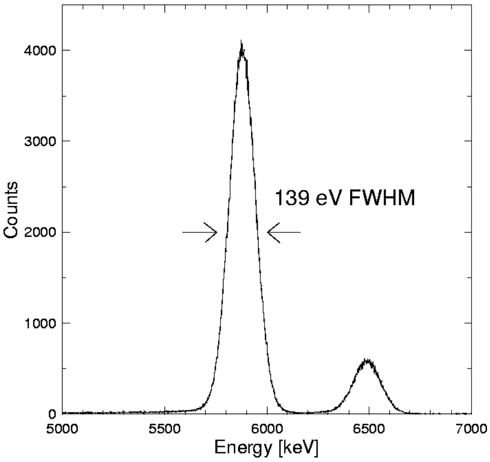

Figure 3: The X-ray spectrum from an Iron source as measured in the laboratory with a 1cm^2 SDD chip prototype. Te experimental resolution, FWHM (Full Width Half Maximum) at 5.9 keV is 139 eV.

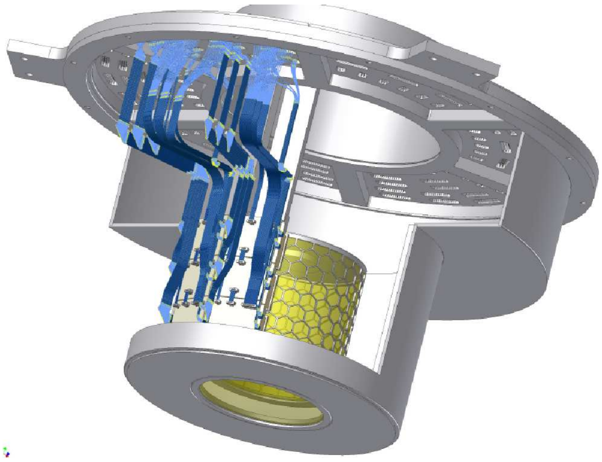

Figure 4: The SIDDHARTA target cell surrounded by SDD units (detail).

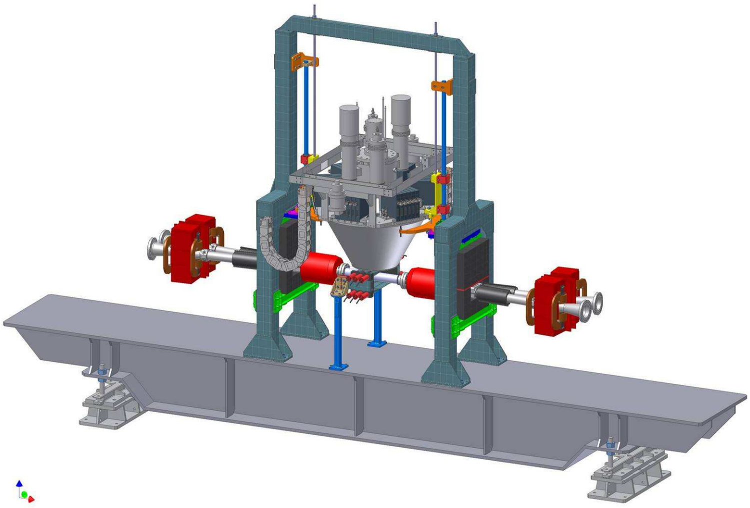

Figure 5: The schematic drawing of the SIDDHARTA setup in the Interaction Region of DAΦNE.

interaction. DEAR has performed the most precise measurement of kaonic hydrogen; the eV precision measurement of the strong interaction shift and width of the ground state in kaonic hydrogen will be performed by SIDDHARTA. The first measurement of kaonic deuterium is also planned. It will be then possible to extract the isospin dependent antikaon-nucleon scattering lengths, which will open new windows in the study of the kaon-nucleon interaction.

The measurement of kaonic helium (with ^{3}He and ^{4}He), feasible in SIDDHARTA, allows to study of the behaviour of the subthreshold resonance $\Lambda(1405)$ in nuclei. Such measurements are of utmost importance, considering the recent KEK precision measurement on kaonic helium (^{4}He) [15], consistent with the optical model calculations (see contributions to the present conference). Other light kaonic atoms can be studied in SIDDHARTA as well.

The precision measurement of the charged kaon mass by using kaonic nitrogen transitions, proved to be possible by DEAR, is as well under study.

DAΦNE proves to be a real and ideal "kaonic atom" factory.

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