Proc. 8th Int. Conf. Quarks and Nuclear Physics (QNP2018)
JPS Conf. Proc. **26**, 023012 (2019)
https://doi.org/10.7566/JPSCP.26.023012

Probing Strong Interaction with SIDDHARTA-2

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(Received March 31, 2019)

The antikaon-nucleon interaction close to threshold provides crucial information on the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD involving strangeness. The unique feature of DAΦNE, namely the production of low-energy kaons, has led to a series of successfully conducted experiments with light kaonic atoms like SIDDHARTA, where the most precise value for the antikaon-proton scattering length was determined. Kaonic deuterium X-ray spectroscopy is still missing and with SIDDHARTA-2 the ground state *1s*-level shift and width should be measured with a precision of 30 eV and 75 eV, respectively.

KEYWORDS: low-energy QCD with strangeness, chiral symmetry, kaonic atoms, X-ray spectroscopy

1. Introduction

Confinement implies that QCD in the low-energy limit is realized as a theory of hadronic degrees of freedom rather than on the quark-gluon level. Spontaneous chiral symmetry breaking implies further that the appropriate framework is Chiral Effective Field Theory (ChEFT) [1-5], a systematic approach describing the interactions of the pseudo-scalar Nambu-Goldstone bosons amongst each other and with baryons. In the hierarchy of quark masses in QCD the strange quark is very special, their masses of ~ 100 MeV/c^2 is well separated on the mass scale from light *u* and *d* quarks (with current quark masses of only a few MeV/c^2) as well as from heavy *c*, *b* and *t* quarks (with masses in the GeV/c^2 range). The strengths of the attractive *s*-wave antikaon-nucleon interaction at threshold can be expressed by the kaon mass and the pseudo-scalar decay constant. The appearance of the pseudo-scalar decay constant (~ *100* MeV/c^2) is characteristic of spontaneously broken chiral symmetry in low-energy QCD, while the kaon mass reflects explicit breaking of chiral symmetry by the non-vanishing (strange) quark mass. Measurements of the antikaon–nucleon interaction close to threshold provides crucial information on the interplay between spontaneous and explicit chiral symmetry breaking in low-energy QCD.

Therefore, kaonic atoms offer an ideal framework to study strong interaction physics. Of particular interest are studies of kaonic systems formed with hydrogen isotopes, which will give access to the basic low-energy parameters like the antikaon-nucleon scattering lengths. Kaonic atoms allow to perform experiments at vanishing relative energies between the antikaon and the nucleon, because their atomic binding energies are in the keV range, far below the lowest energies of extracted beams for scattering experiments.

2. Formation of kaonic hydrogen atoms

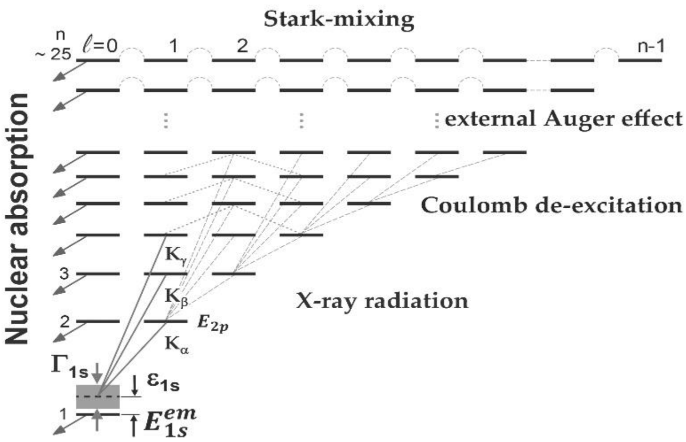

Fig. 1. Cascade processes for kaonic hydrogen down to the *1s* ground state, which is shifted due to strong interaction and broadened due to nuclear absorption of the kaon by the proton.

When a negatively charged kaon enters a target it is slowed down to a kinetic energy of a few tens of eV by ionizations and excitations of the target molecules. Finally, it will be captured into an outer atomic orbit by replacing an electron and thus forming a kaonic atom. The initial principal quantum number n of the kaonic atom is given by the reduced mass μ and the electron mass m_e with the principal quantum number n_e of the outermost electron shell:

$$n \approx \sqrt{\frac{\mu}{m_e}} \cdot n_e \tag{1}$$

For kaonic hydrogen the kaon starts from an outer shell with a main quantum number, n ~ 25 to cascade down to the *1s* ground state (Fig.1). During cascade processes, especially for kaonic hydrogen atoms, the Stark effect is strongly density dependent and will become important. Stark-mixing occurs when the exotic atom passes through the Coulomb field of another target atom. The electric field mixes the *l*-states with the same principal quantum number. For kaonic atoms, this means that the kaon-nuclear absorption may occur even from higher *n*-orbits in *s*-states. Stark mixing is therefore mainly responsible of a drastic reduction of the X-ray yield with increasing target density.

3. The antikaon-nucleon scattering length

The study of the strong interaction effects with strangeness was the major motivation for performing experiments with kaonic atoms. The electromagnetic interaction with the nucleus is very well known, the energy levels can be calculated by solving the Klein-Gordon equation and then applying finite size and vacuum corrections, achieving a value for the *2p–1s* transition of ΔE_{2p-1s}^{QED} = 6479.6 eV [6].

By measuring the transition X-ray energies $\Delta E_{2p-1s}^{meas.}$ to the *1s* ground state of kaonic hydrogen atoms (K^-p) the deviation ε_{1s} from the purely electromagnetic value can be determined with high precision:

$$\varepsilon_{1s} = \Delta E_{2p-1s}^{meas.} - \Delta E_{2p-1s}^{QED} \tag{2}$$

The values ε_{1s} and the energy broadening Γ_{1s} can be related to the K^-p complex scattering length a_{K^-p} by the so-called Deser-Trueman formula [7,8]. However, it turns out that isospin-breaking corrections in the case of kaonic hydrogen are important and much larger than e.g. for pionic hydrogen. The improved Deser formula [9,10], derived from non-relativistic effective field theory (EFT) includes isospin breaking corrections and writes as follows:

$$\varepsilon_{1s} - \frac{i}{2}\Gamma_{1s} = 2\alpha^3\mu^2 a_{K^-p}(1 - \alpha\mu[\ln\alpha - 1]a_{K^-p}) \tag{3}$$

with the fine structure constant α and the reduced mass μ.

The *s*-wave complex scattering length a_{K^-p} and a_{K^-d} are related to the $\bar{K}N$ isoscalar and isovector scattering lengths a_0 and a_1, through:

$$a_{K^-p} = \frac{1}{2}(a_0 + a_1), \quad a_{K^-n} = a_1 \tag{4}$$

$$a_{K^-d} \sim \left(a_{K^-p} + a_{K^-n}\right) \sim \frac{1}{2}(a_0 + 3a_1) \tag{5}$$

Therefore, to obtain the isospin dependent scattering lengths one has to determine the kaonic deuterium scattering length, which will provide information on a different combination of a_0 and a_1 (4, 5).

4. SIDDHARTA setup and results

The SIDDHARTA (Silicon Drift Detector for Hadronic Atoms Research with Timing Applications) experiment determined the kaonic hydrogen shift ε_{1s} and width Γ_{1s} of the *1s* ground state of kaonic hydrogen, with the highest precision up to now [11]. The SIDDHARTA experiment was performed at the DAΦNE electron-positron collider at the Laboratori Nazionali di Frascati of INFN (Italy). DAΦNE produces ϕ-mesons almost at rest, which decay into K^+ and K^- emitted back-to-back, with a branching ratio of about 49%. These monochromatic low-energy kaons (~ 16 *MeV*) are stopped efficiently in a gaseous target forming kaonic hydrogen atoms.

To detect the back-to-back correlated K^+ and K^- from ϕ decay, with one of the kaons moving in direction of the target cell, two plastic scintillation counters were mounted above and below the e^+e^- interaction point. The coincidence signal of the two scintillators defines the kaon trigger, which is a good indication that a kaon will stop in the target cell.

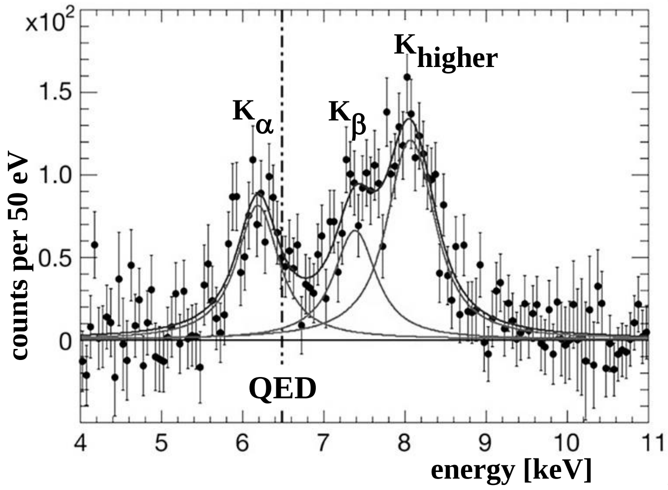

Fig. 2. Final kaonic hydrogen spectra after background reduction, showing the K_α, K_β and the sum of all other higher transitions to the 1s ground state.

This trigger condition was used to build a triple-coincidence including a measured X-ray event in the Silicon Drift Detectors (SDDs) to suppress uncorrelated background events by almost 3-orders of magnitude.

The SDDs [12] were developed within a European research project (EU-FP6 framework program: Hadron-Physics) devoted to this experiment. Each of the 144 SDDs used in the apparatus has an area of 1 cm^2 and a thickness of 450 μm. The SDDs, operated at a temperature of ~ 170 K have an energy resolution of 185 eV (FWHM) at 8 keV and a timing resolution below 1 μsec, in contrast to the CCD detectors used in DEAR [13] which had no timing capability.

Data were accumulated with integrated luminosity of ~ 340 pb^{-1} for the kaonic hydrogen measurement over six months in 2009, with the background subtracted spectrum shown in Fig. 2. The SIDDHARTA results [12] for shift ε_{1s} and width Γ_{1s} of the kaonic hydrogen *1s*-level are:

$$\varepsilon_{1s} = -283 \pm 36(\text{stat}) \pm 6(\text{sys})\ \text{eV} \tag{6}$$
$$\Gamma_{1s} = 541 \pm 89(\text{stat}) \pm 22(\text{sys})\ \text{eV} \tag{7}$$

5. Kaonic deuterium with SIDDHARTA-2

Although the importance of kaonic deuterium X-ray spectroscopy has been well recognized for more than 30 years (*Dalitz et al.* [14]), no experimental results have yet been obtained due to the difficulty of the X-ray measurement. The experimental challenges of SIDDHARTA-2 are the very small kaonic deuterium X-ray yield as well as the larger width of the *1s* ground state compared to kaonic hydrogen and, in addition, the

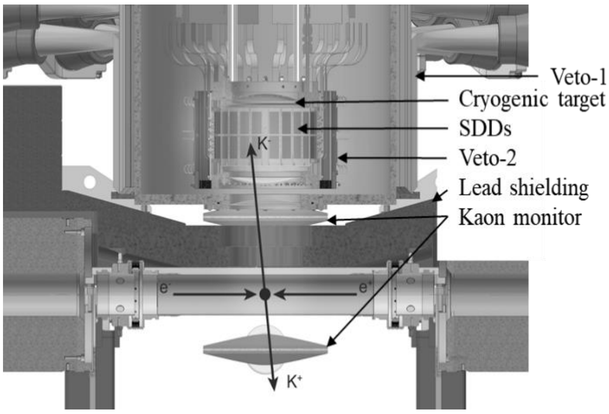

Fig. 3. Sketch of the SIDDHARTA-2 apparatus, showing the main components: SDDs, cryogenic target, veto detectors.

difficulty to perform X-ray spectroscopy in the high bremsstrahlung environment of the DAΦNE collider. Therefore, it is crucial to improve the X-ray detection efficiency, as well as to control the signal-to-background ratio for a successful observation of the kaonic deuterium X-rays. Dedicated Monte Carlo simulations as well as R&D work on the detector side lead to the finally developed SIDDHARTA-2 apparatus (Fig. 3), with the three main improvements, essential for a successful kaonic deuterium X-ray experiment:

- A lightweight cryogenic target with a sidewall thickness < 150 μm, made of 2 layers of 50 μm Kapton glued together with an epoxy adhesive, allowing for an X-ray transmission of approximately 90% for 8 keV X rays. The working temperature of the target cell is 30 K with a maximum working pressure of 0.3 MPa.
- Recently developed robust SDDs with an active area as large as 246 cm^2 and a drastic improved active to total area ratio, with excellent timing capability (< 500 ns) and energy resolution (~ 170 eV).
- A charged particle veto detector system consisting of two veto systems: Veto-1, an outer veto detector as active shielding and Veto-2, an inner veto detector for the suppression of charged particles. Additionally, for both veto systems an excellent time resolution about 500 ns (FWHM) is required to distinguish between kaons stopped in the gaseous target cell or kaons stopped in the target entrance window.

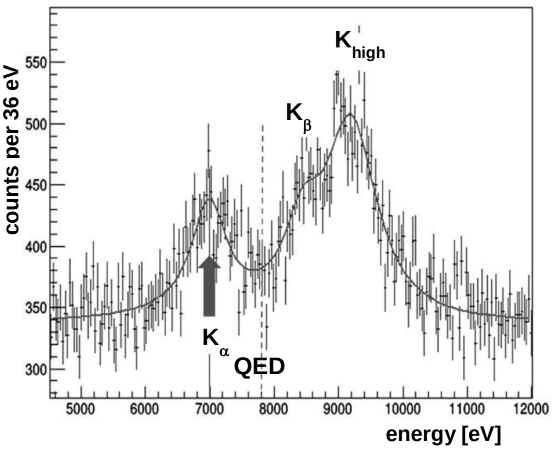

Fig. 4. The anticipated peak of the *2p-1s* (K_α) transition and the position of the pure electromagnetic *2p-1s* (QED) transition are indicated.

Dedicated Monte Carlo studies have been performed showing that with the new designed experimental apparatus the K^-d experiment is feasible at DAΦNE (and at J-PARC as well). The following main assumptions were used as input for the Monte Carlo (Geant4) simulation: shift $\varepsilon_{1s} = -800$ eV, width $\Gamma_{1s} = 800$ eV and X-ray yield = 0.1 % (a factor of ten less than measured for kaonic hydrogen).

In addition, the dedicated shielding structure and veto detector devices have been included in the SIDDHARTA-2 Monte Carlo simulations, leading to a signal to background ratio of 1:4. The performed Monte Carlo simulation in Fig. 4 shows the expected spectrum shape. By fitting theses produced spectra, the precision of shift and width was evaluated to be 30 eV and 75 eV, respectively for an integrated luminosity of 800 pb^{-1}. These experimental results will lead to essential constraints in theory [10,15-19] and will set the physics focus on the low-energy antikaon-neutron interaction, which is up to now an open question.

6. Conclusions

The kaonic deuterium X-ray measurement will provide the most important experimental information missing in the field of the low-energy antikaon-nucleon interactions today. The detector and target system are ready to be installed at DAΦNE, which is foreseen for Spring 2019.

Acknowledgment

We thank C.Capoccia, G.Corradi, B.Dulach and D.Tagnani from LNF-INFN; D.Pristauz-Telsnigg, H.Schneider, L.Stohwasser and M.Pruckner from Stefan Meyer Institute for their important contributions in designing and building the detector system.

Part of this work was supported by the Austrian Science Fund (FWF) (P24756-N20); Austrian Federal Ministry of Science and Research BMBWK 650962/0001 VI/2/2009; the Grantin-Aid for Specially Promoted Research (20002003), MEXT, Japan; Croatian Science Foundation under Project IP-2018-01-8570; Ministero degli Affari Esteri e della Cooperazione Internazionale, Direzione Generale per la Promozione del Sistema Paese (MAECI), StrangeMatter project; Polish National Science Center through grant No. UMO-2016/21/D/ST2/01155; Ministery of Science and Higher Education of Poland grant no 7150/E-338/M/2018.

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