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KAON–NUCLEON INTERACTION STUDIED BY KAONIC X RAYS WITH DEAR AT DAΦNE*

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The scientific program and the experimental setup of the DEAR (DAΦNE Exotic Atom Research) experiment on the new ϕ-factory DAΦNE of Laboratori Nazionali di Frascati, are presented. The objective of DEAR is to perform a 1% measurement of the shift, due to the strong interaction, of the K_α line of kaonic hydrogen and a similar precision measurement, performed for the first time, on kaonic deuterium. The aim is to investigate the low-energy $\bar{K}N$ physics and to understand SU(3) chiral symmetry breaking. DEAR looks as the major effort ever performed to study low energy $\bar{K}N$ interaction, capable to produce a real breakthrough in the field.

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1. Introduction

The low energy kaon-nucleon interaction is still a largely unexplored field on the experimental side. The lack of experimental inputs has a negative impact on theoretical developments: in addition to the poorly determined low-energy parameters, a vital non-perturbative QCD quantity, the KN sigma term, has remained virtually undetermined, thus creating a serious disparity with the recent theoretical efforts based on QCD chiral effective Lagrangians.

DEAR (DAΦNE Exotic Atom Research) is one of the first experiments collecting data on the new ϕ-factory DAΦNE of Laboratori Nazionali di Frascati dell'INFN. DEAR will observe X-rays from kaonic hydrogen and kaonic deuterium, using the "K^- beam" from the decay of ϕs produced in DAΦNE; a cryogenic pressurized gaseous target and Charge-Coupled Device (CCD) as detectors. The experiment has all the distinctive features to represent the most powerful effort ever performed for studying kaon-nucleon physics. Moreover, it will perform the first absolute measurement on kaonic deuterium.

The objective of DEAR is to perform a 1% measurement of the K_α line shift, due to the strong interaction, in kaonic hydrogen and a similar precision measurement on kaonic deuterium. This will drastically change the present status of the low energy $\bar{K}N$ phenomenology, and also provide a clear assessment of the SU(3) chiral effective Lagrangian approach.

2. The DEAR scientific case

The DEAR scientific case, based on a 1% measurement of the K_α line shift in kaonic hydrogen and on a similar precision measurement on kaonic deuterium, shows many relevant reasons of interest.

The first goal of DEAR is the study of the low energy $\bar{K}N$ interaction, a field in which for nearly a quarter of a century no significant progress has been made, apart the great step forward done with the KpX experiment at KEK [1], which solved the discrepancy between scattering data and kaonic X-ray data. The real performance, however, will be the first absolute measurement on kaonic deuterium.

The 1% precision measurements of the K_α line shifts in kaonic hydrogen and kaonic deuterium will yield the $\bar{K}N$ scattering lengths with a 2–5% precision. This will drastically change the present status of low energy $\bar{K}N$ phenomenology.

An important consequence of the DEAR experiment is that one will be able to determine a vital quantity in non-perturbative QCD, the kaon nucleon sigma term. The KN sigma term is a quantity which gives an indication of chiral symmetry breaking. In SU(3) description, it is strongly correlated with the strangeness content of the proton, in a more sensitive way with respect to the πN sigma term, as emphasized by Jaffe and Korpa [2]. Only *estimates* of the KN sigma terms exist so far, basically due to very poor KN scattering data at low energies. This has generated a serious disparity within the recent theoretical efforts based on QCD chiral effective Lagrangians.

The KN sigma terms are determined from KN data by means of dispersion relations and by a continuation of the scattering amplitudes from the physical into the unphysical region of the t-channel. A 1% measurement at zero energy from DEAR will give a strong constraint to the bulk of low energy $\bar{K}N$ data, thus enabling a better determination of the KN sigma terms. According to Jaffe and Korpa if one might determine the KN sigma term at a level of precision of about 20% this would allow a determination of the strangeness content of the proton to a precision of about 5%.

It is worthy to mention again that deuterium scattering data do not exist at all below a momentum of about 400 MeV/c, and one has to replace them with extrapolations which cover a quite sizeable energy interval.

Furthermore, scattering data on deuterium are perhaps even more interesting *per se* [3], as a testing ground of multichannel three-body calculations, which one cannot avoid for evaluating the multiple scattering *correction term* in the expression of the kaon-deuteron scattering length.

3. The DEAR experimental setup

The DEAR experimental setup was designed taking into account the characteristics of the DAΦNE [4] "kaon beam": low momentum (127 MeV/c), K^- emitted with a $\sin^2\theta$ law all around the beam axis (where θ is the angle measured respect to the beam pipe axis).

The kaon exit window from the machine pipe extends between the two quadrupoles which face the interaction point in the so called DAY-ONE configuration of the interaction regions of DAΦNE. It is a thin pipe, 690 mm long, made of 250 μm aluminium with a 650 μm carbon fiber reinforcement. The diameter is 90.00±0.01 mm. A plastic degrader, 300 mm long, 2.35 mm thick, is placed around the pipe in order to slow down the kaons.

The cryogenic target ($T = 25$ K and $p = 3$ atm) is placed at $\theta = 90^o$ above the beam pipe.

The hydrogen density was selected by seeking a balance between the number of stopped kaons and the decrease of X-ray yield due to Stark mixing. The choice was: hydrogen pressure 3 atm, temperature 25 K. The resulting target density is 3.6×10^{-3} g/cm^3 ($\simeq 40\rho_{STP}$). According to cascade calculations [5], the expected yield of K_α X-rays per stopped kaon in these conditions turns out to be (1–3)%, depending on the values of cascade parameters.

In total 8 CCD [6] detectors are arranged in 4 pairs, each at 90° with respect to the adjacent pair, all around the lateral wall of the cylindrical target cell. The two CCDs of a pair, each 1.7 cm high and 2.5 cm wide, are placed horizontally, one next to the other, separated by 8 mm. The distance from the bottom of the target cell to the center of each CCD pair is 8 cm, and corresponds to the mean position of the stopped K^-s, thus maximizing the acceptance for the emitted X-rays.

A pictorial view of the DEAR experimental setup is shown in Fig. 1.

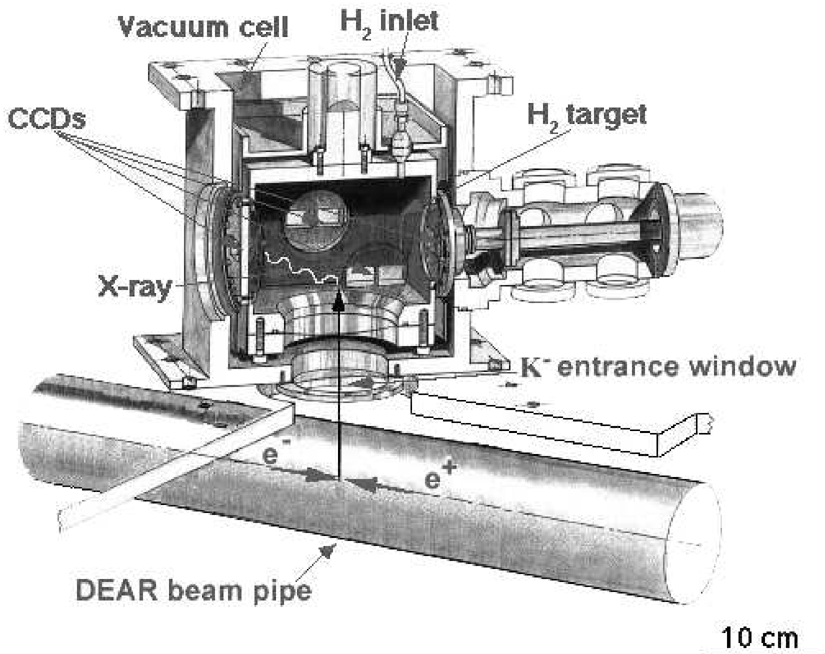

Fig. 1. The DEAR experimental setup

4. Expected rate and background

A Monte Carlo program was performed in the framework of the CERN simulation package GEANT3 [7], using an improved version of the 3.21 code, in order to simulate the physical processes involved in a kaonic hydrogen experiment and to optimize the experimental setup as far as geometry and performances are concerned.

The reliability of the code depends critically on its performance at very low energies. In particular, the behaviour of photons, electrons and positrons must be accurate below the low energy cut-off (10 keV) of the standard GEANT package. Regarding the photon interaction, it was verified that the GEANT program remains accurate also below 10 keV. In particular this aspect regards the photoelectric process, which is the relevant one for energies below 100 keV.

For what concerns the Bremsstrahlung process, the total cross section values (as calculated by the routine GBRSGE) are unreliable when the cut-off parameter k_c is fixed below 10 keV. Therefore, in order to recover the expected logarithmic increasing behaviour of the Bremsstrahlung cross section as a function of the electron energy T, the GBRSGE routine was modified for $k_c < 10$ keV [8].It was estimated that the error on this approximation is not worse than the 10-15% error quoted for the GEANT code between 10 keV and 1 MeV.

At the luminosity $L = 1.2 \cdot 10^{32}$ cm^{-2} s^{-1} (30 bunches) the annihilation cross section of about 4.4 μb at the ϕ-resonance produces a $K^{\pm}$ flux of about 220 s^{-1}, at a central momentum of 126.9 MeV/c, with a momentum spread $\delta p/p \simeq 10^{-3}$.

Within the geometry of the DEAR setup, the following results, concerning the kaon flux, are obtained from the DEAR Monte Carlo simulation:

— number of K^- entering the target volume: $N_{\rm in}^K = (12.5 \pm 0.2)$/s, corresponding to (5.7 ± 0.1) % of the produced kaons;

— number of K^- stopped in the hydrogen gas: $N_{\rm st}^K = (8.6 \pm 0.1)$/s, corresponding to (68.8 ± 1.4) % of the kaons entering the target.

As far as K_α events are concerned, at the working conditions: $\rho_H = 3.6 \times 10^{-3}\ g/{\rm cm}^3$, $\varepsilon_{\rm CCD}(6.5\ keV) = 60\%$, $Y(2p \to 1s)$ =(1–3)%, one obtains:

— number of K_α events: $N(K_\alpha)$ =(7–21)/hour.

The background on CCDs can be divided into two categories: the first one is the background which affects the operational conditions of a CCD causing its "blindness", *i.e.*, it is connected to the maximum number of pixels which can be involved in a CCD avoiding "double hits". This background is directly given by the number of ionizing particles which hit the surface of 1/2 CCD (since the readout takes into account half CCD) and therefore determines the readout time. In the operational limit in which the CCDs will be used in the DEAR experiment a read-out time of about 5 minutes, dictated by the CCD "blindness", is expected.

The second kind of background to be considered is the "true"-background: the soft X-rays (below 10 keV) in the energy region of the signal. This background cannot be eliminated, as the CCD is a non-triggerable detector.

The main source is the "machine background", consisting of the products of the electromagnetic cascades generated by the electrons and positrons lost from the primary beams circulating in the rings. The beam losses are due to the Touschek effect [9] and to beam-gas interactions [10] (large angle Coulomb scattering and Bremsstrahlung on the residual gas). There is also the background generated by ϕ-decay products, among which an important role is played by the hadronic interaction of the stopped K^-. This has been defined as the "hadronic background". It was evaluated and its value is one order of magnitude less than the "machine background".

For what concerns the X-ray background level, coming from hadronic interactions and machine background a value between 60% and 80% level is expected. This value can be further reduced (by at least a factor of 3) by adopting adequate shielding solutions.

5. Precision of the measurement

The precision of the measurement is controlled by the statistical error and by many possible sources of systematic error.

For a given number of collected events, the statistical error depends on the level of background.

Sources of systematic errors are: uncertainty in the calculation of the position of the unperturbed (purely electromagnetic) K_α line; non-linearity of CCD detectors; energy calibration of the CCD detectors; uncertainty in the fitting procedure.

A careful study of systematics, based on laboratory mani-facets tests (CCD linearity, short- and long-term stability tests of CCD energy scale calibration), was performed [11–14].

The expected systematic error in the measurement, taking into account all the above-mentioned sources of systematic errors, turns out about 3 eV, or a relative error of slightly less than 1% (depending on the value of the shift).

Extensive Monte Carlo studies have been done [11] in order to estimate the statistical errors on the shift and width under a variety of background and luminosity assumptions. For a number of about 10000 K_α events and a background level of about 30% (attainable using an appropriate shielding solution) the statistical error in the measurement is about 4 eV, or a relative error of about 1%, *i.e.* at the same level of systematic error.

6. Conclusions

DAΦNE has *unique features as a kaon so urce.* The kaon beam is intrinsically clean, a situation unattainable with a fixed target machine.

DEAR has unique features for the observation of kaonic atoms. With a suitable choice of the gas density, adopting a pressurized cryogenic gaseous target, the number of K_α events collected in *one week* of work with kaonic hydrogen, at the $10^{32}\text{cm}^{-2}\text{s}^{-1}$ luminosity, will exceed the present world data set by an order of magnitude.

A breakthrough in the field of the low-energy $\bar{K}N$ interaction appears realistic with DEAR.

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