The DEAR experiment on DAΦNE

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DEAR is one of the first experiments at the new ϕ-factory DAΦNE at the Laboratori Nazionali di Frascati dell'INFN. The objective of the DEAR experiment is to perform a

precision measurement of the strong interaction shifts and widths of the K-series lines in kaonic hydrogen and the first measurement of kaonic deuterium. The aim is to obtain a precise determination of the isospin-dependent antikaon-nucleon scattering lengths, which will represent a breakthrough in $\bar{K}N$ low-energy phenomenology and will allow the determination of the kaon-nucleon sigma terms. Results on the first measurements with the DEAR setup installed on DAΦNE are reported.

1. Introduction

DEAR (DAΦNE Exotic Atom Research) [1]– one of the three approved experiments on the new ϕ-factory DAΦNE [2] of the Laboratori Nazionali di Frascati dell'INFN - will observe X rays from kaonic hydrogen and kaonic deuterium, using the "K^- beam" from the decay of ϕs produced by DAΦNE. The DEAR setup consists of a cryogenic pressurized gaseous target and Charge-Coupled Devices (CCDs) as x-ray detectors.

DEAR aims at a *precision* measurement of the strong interaction shifts and widths of the K-series lines in kaonic hydrogen and kaonic deuterium. K^-d will be measured for the first time. In this way, a precise determination of the isospin dependent $\bar{K}N$ scattering lengths will be obtained. This will allow to determine the kaon-nucleon sigma terms. The sigma terms give a direct measurement of chiral symmetry breaking and are connected to the strangeness content of the proton.

In Section 2, the DEAR scientific programme is discussed. Section 3 contains a description of the experimental setup. In Section 4 the results of the first measurements on DAΦNE are reported.

2. The DEAR scientific program

2.1. The physics of kaonic atoms

A kaonic atom is formed when a negative kaon enters a target, loses its kinetic energy through ionization and excitation processes of the atoms and molecules of the medium and eventually is captured, replacing the electron, in an excited orbit. Three processes then compete in the deexcitation of the newly formed kaonic atom: dissociation of the surrounding molecules, external Auger transitions and radiative transitions.

When a kaon reaches low-n states with small angular momentum, it is absorbed through a strong interaction with the nucleus. The strong interaction causes a shift in the energies of the low-lying levels from their purely electromagnetic values, while the decreased lifetime of the state results in an increase of the observed level width. 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 parts of the complex S-wave scattering length:

$$\epsilon + \frac{i}{2}\Gamma = 2\alpha^3 \mu^2_{K^-p} a_{K^-p} = (412\ eV\ fm^{-1}) \cdot a_{K^-p} \qquad (1)$$

where α is the fine structure constant and μ_{K^-p} is the reduced mass of the K^-p system. This expression is known as the Deser-Trueman formula [3]. A similar relation applies for the case of kaonic deuterium and the corresponding scattering length a_{K^-d}:

$$\epsilon + \frac{i}{2}\Gamma = 2\alpha^3 \mu^2_{K^-d} a_{K^-d} = (601\ eV\ fm^{-1}) \cdot a_{K^-d} \qquad (2)$$

where μ_{K^-d} is the reduced mass of the K^-d system.

These observable scattering lengths (a_{K^-p} and a_{K^-d}) are related to the isospin dependent scattering lengths (a_0 and a_1):

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

$$a_{K^-d} = 2(\frac{m_N + m_K}{m_N + m_K/2})a^{(0)} + C \tag{4}$$

where

$$a^{(0)} = \frac{1}{2}(a_{K^-p} + a_{K^-n}) = \frac{1}{4}(a_0 + 3a_1) \tag{5}$$

represents the lowest order impulse approximation and C contains higher order contributions, including three-body effects.

DEAR should reach a one order of magnitude improvement in the precision of the K^-p scattering length with respect to the most accurate value presently available from an experiment performed at KEK [4]. This will represent a breakthrough in the low-energy $\bar{K}N$ phenomenology and make possible the discrimination of different theoretical approaches and methods of analysis.

2.2. Chiral symmetry breaking and meson-nucleon sigma terms

An accurate determination of the K^-N isospin dependent scattering lengths will place strong constraints on the K^-N dynamics, which in turn constrains the SU(3) description of chiral symmetry breaking. Chiral symmetry holds if all quark masses were equal to zero. If quark masses were finite and equal, the exact unitary symmetry scheme SU(3) is valid, which means multiplets of particles degenerate in mass (for example, the pseudoscalar meson and baryon octets). In the world we live in, the quarks are massive and, furthemore, the quark masses are different: $m_s \gg m_u \cong m_d$. Thus, in the real world, chiral symmetry must be broken and the SU(3) symmetry is also broken to the extent required to obtain the experimentally observed mass spectrum. We do not know, on a fundamental level, the origin of the symmetry breaking: its nature, to which extent it is broken, which are the breaking mechanisms and, therefore, which models must be used to understand it.

There are two sources of information about SU(3) (and chiral) symmetry breaking. The first is the fact that the entire mass of a pseudoscalar meson comes from the symmetry breaking interaction. This, however, does not tell us much about the nature of the symmetry breaking interactions, except, when fitting the mass spectrum of pseudoscalar mesons, the magnitude of the free parameter in the symmetry violating piece of the strong interaction Hamiltonian.

By far more sensitive to the symmetry breaking mechanism are corrections to the so-called *low-energy theorems*. These theorems relate the symmetry breaking part of the total Hamiltonian to the scattering amplitude of massless particles: they would become exact in the limit where the pseudoscalar meson masses vanish and the axial vector currents are conserved. Therefore, more important tests of theories of chiral symmetry breaking come from studying low-energy theorems of meson-nucleon scattering, which just represent the "corrections" for the real world to the exact relations valid for zero mass particles -

corrections which evidently depend on a symmetry breaking mechanism. In practice, this means calculating the meson-nucleon *sigma terms* [5,6].

In order to define the sigma terms, consider the scattering process of a meson (M) with a nucleon (N):

$$M_a(q) + N(p) \to M_b(q') + N(p') \tag{6}$$

with the four momenta of the particles indicated in parenthesis and a, b denoting the SU(3) indices of the meson.

The meson-nucleon sigma term is the expectation value in the proton state $|p>$ of a double commutator of the symmetry breaking part of the strong-interaction Hamiltonian, H_{SB} [5]:

$$\sigma_{MN}^{ba} = i < p|[Q_b^5, [Q_a^5, H_{SB}]]|p > \quad , \tag{7}$$

where $Q_{a,b}^5$ is the axial-vector charge.

The corresponding low-energy theorem is [5]:

$$\sigma_{MN}^{ba} = -f_a f_b T_{ba}(0,0,0,0). \tag{8}$$

where $T_{ba}(\nu, t, q^2, q'^2)$ is the meson-nucleon scattering amplitude, the f's are the meson decay constants and ν, t, q^2, q'^2 are the kinematics invariants of the process, which all vanish in the soft-meson limit at which the low-energy theorem is defined.

The calculation of the σ-terms (they are two, corresponding to the isospin values $I = 0, 1$) from the scattering data requires an elaborate procedure [7]. The problem is that the σ-term is *not* an observable. One has to introduce an "experimental" sigma term Σ_{MN} which can be related to the experimental meson-nucleon amplitudes. This can be done in a favored point of the (t, ν) plane, the so-called Cheng-Dashen point ($t = 2\mu^2$, $\nu = 0$), by using dispersion relations. The last step consists in calculating Σ in the zero momentum point, where the σ-term is defined. The procedure is schematically shown in Fig. 1.

Presently, only estimates exist of the KN sigma terms. A measurement of $\bar{K}N$ scattering lengths at a percent level would enable the determination of the KN sigma terms with a precision of about 20% or less, to be compared with the 70% uncertainty of the present estimates [8].

The sigma terms are also especially important in connection with the strangeness content of the nucleon, that provides the SU(3) description of the nucleon beyond the SU(2) naive picture. Indeed, the SU(3) structure of the nucleon appears more explicitly in quantities associated with chiral symmetry breaking. The strangeness fraction is dependent on both kaon-nucleon and pion-nucleon sigma terms, but is more sensitive to the first one [9].

3. The DEAR experimental setup

The scientific program of DEAR consists of two stages: with an NTP (Normal Temperature and Pressure) target and with a cryogenic target (hydrogen and deuterium).

The NTP target setup is made of a pure nitrogen volume at room temperature and pressure, equipped with 4 CCD-05 chips. Its purposes are to measure background, compare the values to Monte Carlo calculations and to tune the degrader thickness in order to

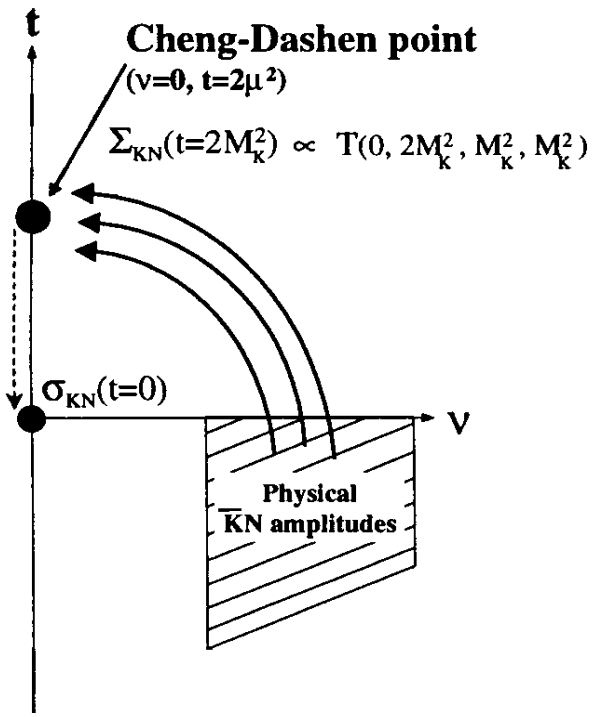

Figure 1. The phenomenological procedure to calculate the KN sigma term starting from the experimental data.

optimize the signal for the kaonic nitrogen $7 \rightarrow 6$ and $6 \rightarrow 5$ transitions at, respectively, ~ 4.6 and ~ 7.6 keV. The yield of the signal being higher than that of kaonic hydrogen, a faster feedback is possible.

Further details on the DEAR NTP setup can be found in ref. [10].

For the measurement of kaonic hydrogen, a pressurized cryogenic gaseous target was constructed in order to obtain a balance between a high stopped kaons rate in the target cell and the decreasing of the x-ray yield due to Stark mixing. The initial target conditions are a pressure of 3 bar and a temperature of 25 K, which results in a target density of 3.6×10^{-3} g/cm^3. After the kaon has been slowed down in the target, it is captured by a hydrogen atom and the cascade begins. Some K-series X rays exit the target and hit the CCD detectors. The CCDs are then read out by a set of custom electronics and the digitized data are transmitted via a fiber-optic link to the data acquisition computers in the DEAR control room. On-line diagnostic and analysis programs exist for real-time monitoring of the data. Compressed data are stored on magnetic-optical disks for further analyses.

Further details on the DEAR cryogenic setup can be found in ref [11].

4. Results of the measurements at DAΦNE with the NTP setup

The NTP setup was installed at DAΦNE in February 1999.

An extensive series of measurements with only electrons and/or positrons circulating; with beams colliding in the KLOE interaction point (IP), and vertically split in the DEAR IP; with beams colliding in DEAR and split in KLOE was performed [12–14].

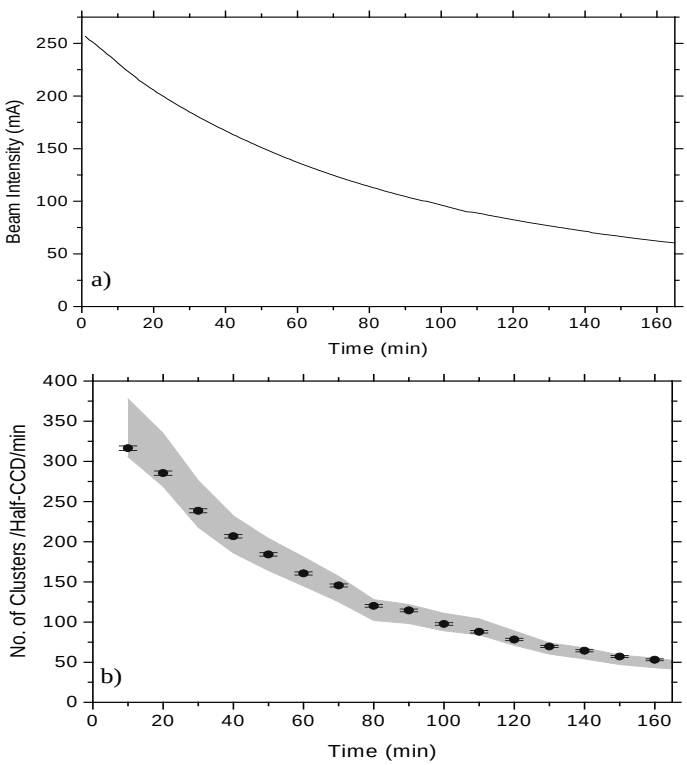

Figure 2. a) Electron beam intensity (mA) in the period 6:21 - 9:01 a.m. June 27, 1999 with only electrons circulating in the DAΦNE ring; b) Observed number of clusters per half - CCD per minute (filled circles) during the corresponding beam period. The shaded area shows the results of the DEAR Monte Carlo simulation.

In the period March-July 1999 measurements were performed with circulating, not colliding beams, in order to check the DEAR Monte Carlo routines. The background created in the DEAR setup by the particles lost from the beams was measured in terms

of "clusters", i.e. multi-pixels events, and then compared with the DEAR Monte Carlo simulation. Fig.2, from ref. [12], shows, as an example, the number of clusters per half-CCD per minute observed with electron beams circulating in DAΦNE. The time dependence is given in correlation with the injection time of the beam into the accelerator ring. The time between two adjacent points represents the exposure time, which was 10 minutes. The time behaviour of the number of clusters follows the time behaviour of the injected electrons. The simulations agree very well with the measurements.

A first period of data taking with collisions in the DEAR IP was performed in December 1999 [13]. The collisions could be investigated only for a short period (60 hours) during this run. However, a high level of background was measured, as well as a low luminosity.

A second period of runs with beams colliding in the DEAR IP was performed from August 24 to September 11, 2000 [14]. The beam period was devoted to two main goals, namely understanding and reducing the background in the DEAR region and increasing the luminosity, after major changes performed on the machine during the shutdown in Spring 2000.

Background reduction was tried by:

- using the horizontal scrapers on electrons and on positrons in the DEAR region, in order to cut the trajectories of the lost particles;
- using the vertical scrapers on electrons and on positrons in the DEAR region;
- using the horizontal scrapers on electrons and positrons in the KLOE region;
- changing the crossing angle in the DEAR IP, which should affect the rate of losses due to Touschek effect;
- changing the vertical direction of the trajectories in the DEAR interaction region.

The global reduction of background, measured in terms of number of clusters per beam loss in the measurement interval, turned out a factor of 3.3, with respect to the conditions found at the beginning of the runs. An x-ray energy spectrum collected in stable beam conditions is shown in Figure 3. It corresponds to a total integrated luminosity of 172.1 nb^{-1}. Many significant peaks, corresponding to electronic X rays from materials of the setup hit by the background particles, can be seen: the Al peak, produced essentially in the aluminum frame of the CCDs, the Si X rays coming from the bulk of the CCD chips, the Zr line originated in the zirconium foil put in the target cell, in order to have a full calibration of the energy scale. The positions of the 4.58 and 7.58 keV kaonic nitrogen lines are as well indicated in the Figure. The expected count rate in the peaks for the collected luminosity is by far too low to give a line which might be observed with the actual level of background.

5. Conclusions

The DEAR experiment has the aim to improve the precision in the measurement of the K^-p scattering length by about a factor of ten and make the first measurement of kaonic deuterium. A percent-level measurement of the isospin dependent $\bar{K}N$ scattering lengths will represent a breakthrough in the low-energy $\bar{K}N$ phenomenology, implying

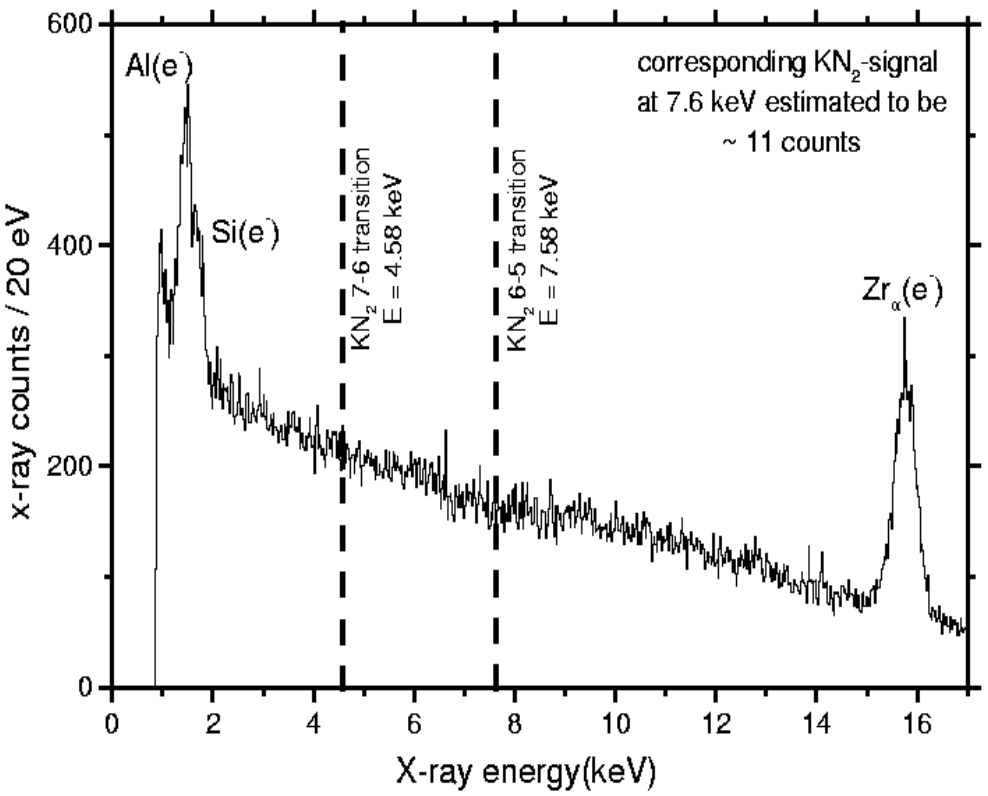

Figure 3. Energy spectrum of X rays observed in the period of beams colliding in the DEAR interaction region. Electronic x-ray lines from aluminum, silicon and zirconium are clearly visible. The calculated positions of two kaonic nitrogen transitions are indicated.

the possibility of discriminating between theoretical approaches and methods of analysis. Moreover, with a precision measurement of the $\bar{K}N$ scattering lengths, it will be possible to determine the kaon-nucleon sigma terms, which give the degree of chiral symmetry breaking and allow to obtain an indication of the strangeness content of the proton.

At the time of writing, the first stage of the DEAR scientific program is in progress. The NTP nitrogen target is installed on DAΦNE and took data with collisions in the DEAR IP. The DEAR NTP setup equipped with CCDs as x-ray detectors worked very well, however, the actual background level is too high for the present luminosity to allow an unambigous detection of a kaonic nitrogen signal. Further improvements in background reduction and increase of the signal (higher machine luminosity) are badly needed.

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