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The DEAR physics programme

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ABSTRACT

The DEAR experiment installed at DAΦNE is dedicated to perform a precise determination of the isospin dependent antikaon-nucleon scattering lengths via the percent level observation of the strong interaction shift and width of the K_α x-ray transition in kaonic hydrogen and the first measurement of kaonic deuterium. This will drastically change the present status of $\bar{K}N$ phenomenology and will allow important tests of theories of chiral symmetry breaking.

1 Introduction

The new electron-positron collider DAΦNE [1] at the Frascati National Laboratories has made available a unique "beam" of negative kaons providing unprecedented conditions for the study of the low-energy kaon-nucleon interaction, a field experimentally still largely unexplored.

The DEAR experiment [2] [the acronym stands for DAΦNE Exotic Atom Research], one of the three approved experiments on DAΦNE, aims at the precision determination of the isospin dependent antikaon-nucleon scattering lengths via the measurement of the strong interaction shifts and widths of the x-ray lines due to transitions to the ground levels of kaonic hydrogen and kaonic deuterium atoms.

DEAR represents the most powerful effort ever launched to study the low-energy kaon-nucleon physics. This is due to three major ingredients:

• the expected kaon beam delivered by DAΦNE, which has low energy (16.3 MeV), is almost monochromatic (δp/p $\cong 10^{-3}$), has high purity (π:K ratio $\cong$ 1:1) and an intensity of 1.1×10^3 kaons per second at the design luminosity of 5×10^{32} $cm^{-2}s^{-1}$;

• the x-ray detectors used, the Charge-Coupled Devices (CCDs), which have an unprecedented background rejection capability and good energy resolution [3];

• the use of a moderate-density gas cryo-target, in order to maximize the x-ray yield by reducing Stark-mixing which causes strong kaon absorption from high atomic states.

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

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

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

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

where the error of 1 eV is dominated by the uncertainty of the kaon mass. This error directly contributes to the uncertainty of ϵ. The challenging aim of DEAR is to measure ϵ in kaonic hydrogen with a precision of a few eV, which corresponds to a ~ 1 % measurement . Kaonic deuterium will be measured for the first time.

The scientific program of DEAR will be developed in two stages: with an NTP (Normal Temperature and Pressure) target filled with nitrogen, and with a cryogenic target with hydrogen (deuterium).

The NTP target consists of a pure nitrogen volume at room temperature equipped with four CCD-05 chips. The purpose is to measure background, compare it to the Monte Carlo calculation, and tune the degrader thickness by optimizing the signal coming from the kaonic nitrogen transitions: $7 \rightarrow 6$ at ~ 4.6 keV and $6 \rightarrow 5$ at ~ 7.6 keV. The yields of these transitions being higher (by a factor of 10) than the one of the kaonic hydrogen a faster feedback is possible. Kaonic nitrogen x-ray transitions have been never measured and will be *for the first time* measured with DEAR.

For the measurement of kaonic hydrogen (deuterium), a pressurized cryogenic target was built, to achieve a balance between high kaon stopping power in the target cell and the loss of x-ray yield due to the Stark mixing effect. The target will operate at a hydrogen pressure of 3 bar and temperature of 25 K. X-ray detectors are 16 CCD-22.

According to newly initiated cascade calculations [4] and the recent KEK result [5], the expected yield of K_α X rays per stopped kaon in the mentioned conditions is (1 - 3) %.

We refer the reader to J. Zmeskal's contribution [6] for a description of the DEAR experimental setup and the composition of the DEAR collaboration. Further details regarding the NTP setup can be found in [7].

Since the first beams circulated in the DAΦNE main rings, DEAR has started to investigate the background in the experimental area. In spring 1999 the NTP setup was installed in the interaction region. The background with circulating electrons, positrons, and both beams present but separated in the DEAR interaction region, was investigated. Good agreement between the measured background rates and those derived from the DEAR Monte Carlo simulation was obtained [7].

In December 1999 the first 3 days of collisions in the DEAR interaction region were achieved.

It is of paramount importance for DEAR that, in the region of interest around the expected kaonic hydrogen K_α peak at $\sim$ 6.15 keV, no line structure can be seen. This would pose severe problems for the identification of the interesting x-ray lines because x-ray background signals cannot be rejected. No structures at the energies of the electronic x-ray transitions originating from manganese and iron - materials present in normally available aluminum alloys - were visible in the spectrum from the collected data. Long periods of data taking with circulating beams have also shown [7] the total absence of unwanted structures in the region of interest. This demonstrates the high purity of the aluminum selected for each component of the setup.

Extensive studies have been performed to constrain the possible systematic errors of the measurement coming from energy calibration, detector stability and linearity, as well as analysis and fitting procedures.

If the DAΦNE luminosity will reach the design value, DEAR is ready to perform the planned precision measurements.

2 The physics of kaonic atoms

A kaonic atom is formed when a negative kaon enters an atomic target, for instance hydrogen or deuterium, looses its kinetic energy through ionization and excitation of the atoms and molecules of the medium and eventually is captured in an excited orbit, replacing an electron. Various collisional cascade processes and radiative transitions deexcite this kaonic atom to the ground state.

When the kaon reaches low-n states with small angular momentum, it is absorbed through a strong interaction with the nucleus. This strong interaction causes a shift in the energies of the low-lying levels from their purely electromagnetic values, while the finite lifetime of the state is evident in an increase in 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 part of the complex s-wave scattering length, a_{K^-p}:

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

(Deser-Trueman formula [8]), where α is the fine structure constant and μ the reduced mass of the K^-p system.

A similar relation applies to the case of kaonic deuterium and the corresponding scattering length, a_{K^-d}:

$$\epsilon + \frac{i}{2}\Gamma = (601\,\mathrm{eV\ fm^{-1}}) \cdot a_{K^-d} \quad . \tag{2}$$

These simple relations are known to hold quite accurately for these atoms [9], their corrections being smaller than 1 %. The higher order corrections tend to cancel between the two sides of each expression, and the Coulomb correction is quite small in these charge-one systems. We can thus safely consider these relations to be exact and regard the precision in determining the scattering lengths a_{K^-p} and a_{K^-d} to be that of the shift and width measurements.

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

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

The kaonic deuterium scattering length is related to a_0 and a_1 in the following way:

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

where

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

corresponds to the (t-channel) isoscalar $\bar{K}N$ scattering length. The first term in Eq.(4) represents the lowest-order impulse approximation – K^- scattering from each (free) nucleon. The second term, C, includes all higher-order contributions, representing all other physics associated with the K^-d three-body interaction. Note that the kinematic factor in the parentheses of Eq.(4) is due to the shift in the center of mass from the $\bar{K}N$ system to the $\bar{K}d$ system. Numerically, C is not negligible and, in fact, is larger than the first term.

The determination of the $\bar{K}N$ scattering lengths requires the calculation of C. It is well known that a three-body problem is solvable by the use of Faddeev equations when the two-body interactions among them are specified. The K^-d three-body problem includes the further complication that the K^-p and K^-n interactions involve significant inelastic channels. The K^-p and K^-n scattering lengths are thus complex with large magnitudes of the imaginary parts, and so is the K^-d scattering length. Incorporating $\bar{K}N$ 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 account of coupling among the multi-channeled interactions.

3 Low-energy kaon-nucleon phenomenology

A measurement at the level of percent of kaonic hydrogen, together with the first measurement of kaonic deuterium will represent a dramatic step forward in the investigation of low-energy kaon-nucleon interactions.

Three measurements of kaonic hydrogen X rays were carried out at CERN and RAL [10] about twenty years ago, claiming to observe a signal with positive energy shift and hence an attractive strong interaction between kaon and proton. This was in striking contradiction to results of low-energy scattering data extrapolated down to threshold, which showed a *repulsive* contribution of the strong interaction: the so-called *"kaonic hydrogen puzzle"* was born. The theoretical understanding of the observed behaviours was indeed complicated by the existence of a resonance just below the threshold, $\Lambda(1405)$. No reasonable explanation of the "puzzle" could be achieved.

The recent observation of a faint but clear K_α-signal by the KpX experiment at KEK [5] solved this longstanding mystery with an observation in agreement with the scattering experiments. Due to the low overall statistics it is, however, not a real constraint and challenge for the theoretical description of low-energy $\bar{K}N$ phenomenology.

Figure 1 illustrates the actual experimental situation: it refers only to kaonic hydrogen, since no data on kaonic deuterium exist so far. Presently available data on shift and width of the K_α line, as obtained directly from x-ray measurements or deduced, via the Deser-Trueman relation, from scattering data analyzed with various approaches, are reported. The predictions of some theoretical models are also shown. The recent, most reliable result [5] has an uncertainty of about 30 % in the shift and 70 % in the width. The expected precision of DEAR is about 1 % in the shift and 5 % in the width. This order of magnitude in precision will drastically change the present status of the low-energy $\bar{K}N$ phenomenology. The confirmation of the KEK result with a precision measurement of the repulsive shift of the hydrogen K_α line is theoretically significant. Moreover, the DEAR measurement will also give the possibility of selecting among the different methods to analyze scattering data, as well as of discriminating the various theoretical approaches.

4 Understanding low-energy strong interaction dynamics

Quantum Chromo Dynamics (QCD) is regarded as the basic theory of the strong interaction. The theory possesses the important feature of asymptotic freedom: as the distance scale becomes smaller, or as the momentum transfer becomes higher, the QCD constant becomes weaker and the interaction diminishes. In this high-energy domain, perturbative QCD has been successfully applied. In the low-energy domain, however, the (running) QCD coupling constant becomes stronger and the theory exhibits the confinement of color. The quarks and gluons are thus confined in the hadrons, which become the relevant degrees of freedom at low energies. At this point, perturbative QCD ceases to be a useful tool to understand strong interaction dynamics. At energies equal to or smaller than the scale of strong interactions ($\sim$ 1 GeV), one must simplify the whole theory. This can be done by introducing models which approximate the low-energy region of QCD, being an admixture of QCD and phenomenological treatments of confinement. Another way is to perform lattice calculations, where the space-time continuum is replaced by discrete values

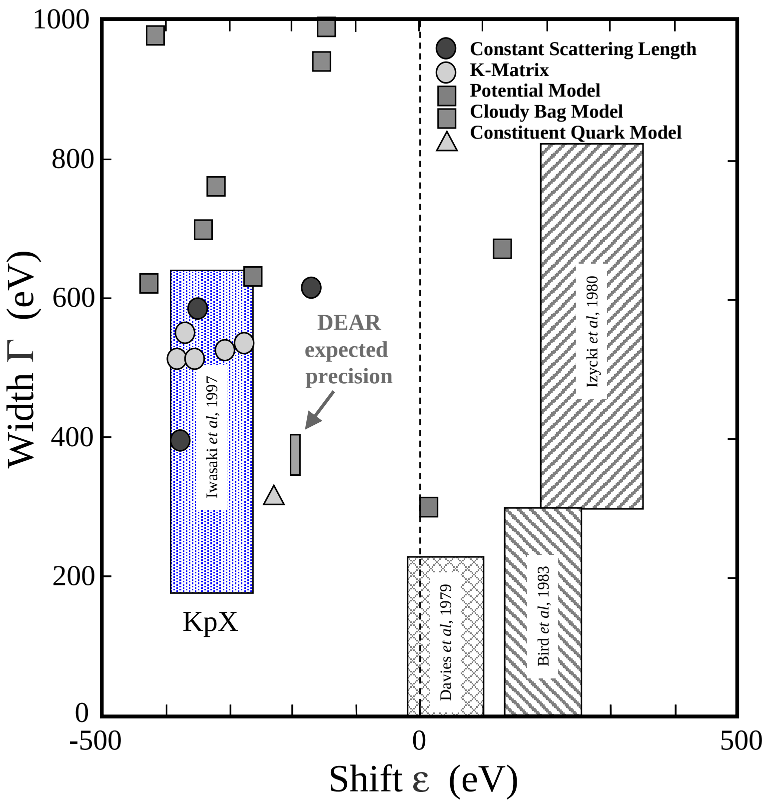

Figure 1: *(reproduced from* [5] *with permission of the authors). Presently available data on shift and width of the K_α line of kaonic hydrogen, as obtained from x-ray measurements or deduced from scattering data analyzed through various approaches, together with some theoretical models. The DEAR expected precision is also shown.*

of space and time.

At very low energies, a great simplification occurs. Below the resonance region ($E < M_\rho$) the hadronic spectrum contains only the pseudoscalar particles (π, K, η), whose interactions can be most easily understood from *global symmetry* considerations. 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 (for example, the pseudoscalar meson and baryon octets) degenerate in mass. In the world we live in, the quarks are massive and, furthermore, 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 what extent it is broken, which are the breaking mechanisms and, therefore, which models must be used to understand it. The final goal of the DEAR experiment is to perform a measurement which can be used to investigate such primary problems.

4.1 Chiral symmetry breaking and meson-nucleon sigma terms

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 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 "correction" 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 term.*

The meson-nucleon sigma terms are quantities of fundamental importance to non-perturbative QCD. Their main interest lies in the fact that they provide a measure of the chiral symmetry breaking and vanish in the massless quark chiral limit of QCD. They 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.

In order to define them, consider the scattering process

$$M_a(q) + N(p) \rightarrow M_b(q') + N(p') \quad , \tag{6}$$

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

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} [11]:

$$\sigma^{ba}_{MN} = i < p|[Q^5_b, [Q^5_a, H_{SB}]]|p > \quad , \tag{7}$$

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

How to derive from the definition of the sigma term the corresponding low-energy theorem? The double commutator in Eq.(7) - sigma commutator (it derives its name from the so-called σ-model [12]) - is nothing else than the equal-time commutator of the axial vector current, associated with Q_a^5, with its divergence $\delta_\mu A_a^\mu$ [11]. The partially conserved axial vector current (PCAC) hypothesis identifies then this divergence with the pseudoscalar meson field. In such a way, the sigma commutator in Eq.(7) is replaced by the product of the two meson fields allowing one to connect the sigma term - therefore H_{SB} - to the meson-nucleon scattering amplitude $T_{ba}(\nu, t, q^2, q'^2)$ and, finally, to obtain the low-energy theorem in the soft-meson limit q^2,$q'^2 \to 0$ together with $\nu = 0$ and $t = 0$:

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

where the f's are the meson decay constants and the kinematic invariants of the process are defined by:

$$s = (q+p)^2, \quad t = (q-q')^2, \quad u = (q-p')^2, \quad \nu = (s-u)/2M_N \quad . \tag{9}$$

The calculation of the sigma term from the scattering data requires an elaborate procedure. The problem is that the sigma term is *not* an observable. One has then 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 (C-D) point ($t = 2\mu^2$, $\nu = 0$, μ being the meson mass).

The Cheng-Dashen point is on mass-shell but lies outside the physical meson-nucleon scattering region ($t < 0$). Therefore, in order to obtain $\Sigma(2\mu^2)$ from the experimental amplitudes one has to *extrapolate* them to the C-D point, with a procedure commonly based on dispersion relations. Then the last step consists in calculating Σ in the zero momentum point, where the kinematic variables all vanish and the sigma term is defined by equation (8).

The pion-nucleon sigma term has been obtained by following this phenomenological approach. The same procedure, in principle, might be used to evaluate the KN sigma terms (there are two, in correspondence with the isospin states I=0 and I=1 of the $\bar{K}N$ system). The procedure is schematically shown in figure 2.

The situation is, however, much less favourable than in the pion case. On the experimental side, this is due to the poor bulk of $K^{\pm}N$ scattering data. On the theoretical side, complications arise from the fact that there are open channels below threshold, from the existence of a resonance, $\Lambda(1405)$, just below threshold,

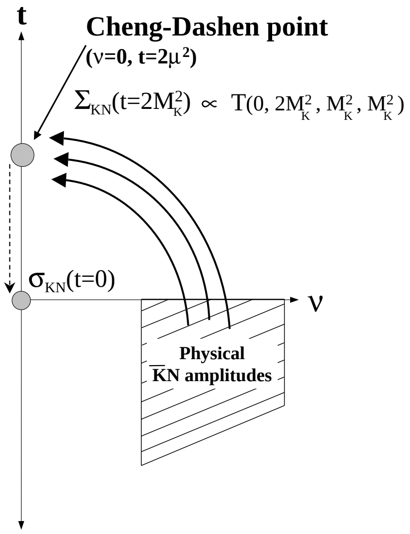

Figure 2: How to determine the sigma term from experiment.

from uncertainties in the phenomenological procedure (note that the distance from threshold to the C-D point is considerably larger than in the πN case: the difference $\Sigma(2M_K^2) - \Sigma(0)$ is expected to be rather large, eventually larger than the quantity of interest, which means that there is no reliable connection between the points $t = 2M_K^2$ and $t = 0$).

See the detailed agenda of topics still to be investigated in J. Gasser's contribution to this conference [13].

The result is that presently only estimates of KN sigma terms exist.

Which is the precision in determining the KN sigma terms from a percent measurement of the $\overline{K}N$ scattering lengths? What is the impact of DEAR? The planned DEAR result will not only fix precisely the scattering amplitude at threshold, it will place, at the same time, a strong constraint on the extrapolations to zero energy which are required in any analysis of scattering data. Consequently, the s-wave K^-N amplitudes will be determined more accurately, below and above threshold. This will provide a tighter constraint on the p-wave parameters from experimental data and, eventually, reduce the uncertainty in the phenomenological procedure used to calculate the sigma terms.

Based on the above considerations, it can be argued that a 1 % precision measurement in kaonic hydrogen (together with a precise measurement of deuterium), combined with a significantly improved analysis of low-energy $K^\pm N$ scattering data, would enable the determination of the KN sigma terms with an uncertainty of about 20 % or less, to be compared with the 70 % uncertainty of the present estimates [14].

4.2 Strangeness content of the proton

Spin-dependent deep inelastic scattering experiments have demonstrated that nucleon structure functions cannot be fully described by valence quark models based on the SU(2) scheme. A strange quark fraction in the nucleon is the most probable hypothesis. While several parity-violating electron scattering experiments are either under way or planned, another way to look for the strangeness content of the nucleon is represented by the determination of the meson-nucleon sigma terms. Indeed, the SU(3) structure of the nucleon appears more explicitly in quantities associated with chiral symmetry breaking.

The complementary approach of using the meson-nucleon sigma terms to determine the strangeness content of the nucleon has its source in the fact that the symmetry breaking Hamiltonian, H_{SB}, to which sigma terms are directly connected, is the quark mass term of the total Hamiltonian:

$$H_{SB} = m_u\overline{u}u \ + \ m_d\overline{d}d \ + \ m_s\overline{s}s \tag{10}$$

$$\begin{aligned}\approx \ & \frac{1}{3}(m_s + 2\bar{m})(\bar{u}u + \bar{d}d + \bar{s}s) - \\ & \frac{1}{3}(m_s - \bar{m})(\bar{u}u + \bar{d}d - 2\bar{s}s) = H_0 + H_8 \ ,\end{aligned} \tag{11}$$

where $\overline{m} = m_u = m_d$ by assuming isospin invariance. The singlet term H_0 preserves SU(3) symmetry, the octet term H_8 breaks it.

One can then define the sigma terms through quark masses and quark scalar densities [15)]

$$\sigma_{KN}^{(1)} = \frac{1}{2}(\bar{m} + m_s) < p| \ \bar{u}u + \bar{s}s \ |p > \tag{12}$$

$$\sigma_{KN}^{(0)} = \frac{1}{2}(\bar{m} + m_s) < p| - \bar{u}u + 2\bar{d}d + \bar{s}s \ |p > \tag{13}$$

$$\sigma'_{KN} = \frac{1}{4}(3\sigma_{KN}^{(1)} + \sigma_{KN}^{(0)}) \tag{14}$$

$$\sigma_{\pi N} = \bar{m} < p| \ \bar{u}u + \bar{d}d \ |p > \ . \tag{15}$$

The fraction y of strange quark content of the proton is defined as:

$$y = \frac{2 < p|\bar{s}s|p >}{< p|\bar{u}u + \bar{d}d|p >} \ . \tag{16}$$

This quantity can be expressed through the sigma terms:

$$y = \frac{4\bar{m}}{\bar{m} + m_s}\frac{\sigma'_{KN}}{\sigma_{\pi N}} - 1 \ . \tag{17}$$

It turns out that y is particularly sensitive to σ_{KN} (more than to $\sigma_{\pi N}$) [16]. Therefore DEAR can contribute to a better determination of the strangeness content of the nucleon.

5 Conclusions and perspectives

DAΦNE has unique features as a kaon source, which is intrinsically clean and at low momentum, a situation unattainable with a fixed target machine, especially suitable for a kaonic atom experiment. The DEAR experiment combines newly available techniques to initiate a renaissance in the investigation of low-energy kaon-nucleon interaction: at the DAΦNE design luminosity, with the cryogenic pressurized target, DEAR can collect in *one week* a number of kaonic hydrogen K_α events which will exceed the present world data set by an order of magnitude; moreover, it will measure kaonic deuterium for the first time. The CCD detectors have an unprecedented background rejection capability, orders of magnitude better than that of any silicon device used up to now in kaonic hydrogen measurements. DEAR is regarded to have the potential for a breakthrough in the low-energy kaon-nucleon phenomenology and should give a precision test for theories of chiral symmetry breaking.

At the time of this writing, the DEAR NTP setup is awaiting a proper tuning of the machine in the DEAR interaction point, in order to optimize the signal-to-background ratio. Kaonic nitrogen will be the first exotic atom to be observed in Frascati: it will also represent the first measurement of this system. Then the precision measurement of kaonic hydrogen is planned, followed by the measurement of kaonic deuterium. The measurement of kaonic helium, to study the behaviour of the subthreshold resonance $\Lambda(1405)$ in nuclear matter, gives an additional interesting perspective for the future.

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