The DEAR Case

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This report gives an overview of the DEAR (**D**AΦNE **E**xotic **A**tom **R**esearch) project, one of the first experiments that will collect data at the new DAΦNE ϕ-factory at the Laboratori Nazionali di Frascati dell'INFN. The objective of the DEAR experiment is a precise determination of the isospin-dependent kaon-nucleon scattering lengths, through a 1% measurement of the K_α line shift in kaonic hydrogen and the first observation of the same shift in kaonic deuterium.

1 DEAR Physics

When a negative kaon enters a hydrogen target, it loses kinetic energy through ionization and excitation of the hydrogen molecules. Eventually, it is captured, replacing the electron, in an excited orbit ($n \simeq \sqrt{\mu/m_e}$, where μ is the reduced mass of the kaon-proton system). A variety of processes occur during the subsequent cascade, some of which lead to the emission of photons. When the kaon reaches a low-n state with small angular momentum, it is absorbed through a strong interaction with the proton. This strong interaction causes a shift in the energies of the low-lying levels from their purely electromagnetic values, and the finite lifetime of the state corresponds to an increase in the observable 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, a_{K^-p}

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

where α is the fine structure constant and μ is the reduced mass of the K^-p system. This expression is known as the Deser-Trueman formula [1]. A similar relation applies to the case of kaonic deuterium and the corresponding scattering length, a_{K^-d}. These equations are expected to be accurate at a level of 1% [2].

These observable scattering lengths are in turn related to the isospin scattering lengths a_0 and a_1. An accurate determination of the isospin scattering lengths will place strong constraints on low-energy K^-N dynamics, which in turn constrains the SU(3) description of chiral symmetry breaking. In particular, the determination of these scattering lengths is one of the primary uncertainties in the phenomenological procedure used to calculate the kaon-nucleon sigma terms ($\sigma^{(0)}_{KN}$, $\sigma^{(1)}_{KN}$) [3]. We estimate that these sigma terms can be extracted at the level of 20%, by combining the DEAR results at zero energy with the other most recent analyses of low-energy $K^{\pm}N$ scattering data. These sigma terms are also important inputs for the deterimination of the strangeness content of the proton. The strangeness fraction is dependent on both kaon-nucleon and pion-nucleon sigma terms, but is more sensitive to the kaon-nucleon terms [4].

2 DEAR Innovations

The DEAR experiment is not the first attempt to observe x rays in kaonic hydrogen. Most recently, the KpX experiment at KEK reported the following results for the strong interaction shift and width [5]:

$$\epsilon = -327 \pm 63(stat.) \pm 11(syst.)\, eV \tag{2}$$

$$\Gamma = 407 \pm 208(stat.) \pm 100(syst.)\, eV \tag{3}$$

We expect that the DEAR experiment will decrease the uncertainty on these observables by a factor of ten. This will be contigent upon two important innovations: the DEAR kaon source, and the DEAR x-ray detector.

As a kaon source, DAΦNE has some unique properties, which can be emphasized by comparing to other sources, such as the KEK K3 beam line used in the KpX experiment [6]. DAΦNE is not the best kaon source in terms of the rate, which is 1100 kaons/s at full design luminosity ($5 \times 10^{32}\ cm^{-2}s^{-1}$) - less than the 3000 kaons/s available from the K3 line. Rather, the main advantage of DAΦNE kaons is that they result from a two-body decay of the ϕ-meson, which means they are produced with low momentum (127 MeV/c) and essentially monoenergetically (δP/P = 0.1%, limited only by the spread in beam energy), compared to the 600 MeV/c kaons with δP/P of 4% at KEK. This means that the kaon stopping efficiency in DEAR's gas target is greatly increased relative to the KpX experiment. In addition, backgrounds in an electron-positron collider are inherently lower than those in a hadron machine, as is suggested by the pion-to-kaon ratio in the two beams: about 1:1 for DAΦNE and 90:1 for KEK.

The second innovation of DEAR is the use of CCD (Charge-Coupled Device) detectors [7] to detect the K_α x rays from transitions in kaonic hydrogen. The characteristics of the CCD pixel array - pixel size and depletion depth - are such that x rays in the region of interest deposit all of their energy in a single pixel with a reasonably high efficiency ($\simeq$ 60% at 6 keV). This permits a very effective background-reduction scheme based on a single pixel analysis. By accepting signals in pixels that are surrounded only by dark pixels (those whose signal is consistent with the dark noise or pedestal level), an enormous background reduction can be achieved [8]. This means that the CCDs can take data without a trigger, which leads to another large improvement in overall efficiency.

The combination of these two innovations, DAΦNE as a unique kaon source, and CCDs as x-ray detectors, will allow DEAR to collect K_α x rays with an unprecendented efficiency.

3 Experimental Setup

ϕ mesons are produced at rest by the collision of 510 MeV electrons and positrons at the interaction point. The ϕ mesons decay into a pair of charged kaons with a branching ratio of 49%. A K^- meson exits the machine vacuum through a special beam pipe that was manufactured for the DEAR experiment. A plastic degrader is placed around the pipe to further slow the kaons and to adjust their stopping distribution in the target. After passing through the beam pipe and degrader, the kaon travels through three centimeters of air before encountering the entrance window of the target isolation vacuum. The isolation vacuum, maintained below 10^{-5} mbar, is required in order to maintain the low temperature ($\sim$ 25 K) of the cryogenic target volume.

The initial target conditions will consist of a pressure of 3 bar and a temperature of 25 K, resulting in a target density of $3.6 \times 10^{-3} g/cm^3$. After the kaon has been slowed down in the target, is captured by a hydrogen atom, and the cascade chain begins, some K-series photons will exit the target and interact with the CCD detectors. The CCD chips themselves are cooled to a temperature of 160 K to suppress dark current noise. The CCDs are read out by a set of custom electronics [8]. The digitized data are transmitted over a fiber-optic link to the two data acquisition computers in the control room. Compressed raw CCD data are stored on magnetic-optical disks for later analysis; online diagnostic and analysis programs also exist for real-time monitoring of the data.

Further details and a complete description of the DEAR setup can be found in [9].

4 Status and Plans

The DEAR installation will proceed in two target stages: the NTP (normal temperature and pressure) target, and the cryogenic target. The NTP target consists pure nitrogen volume at room temperature. The purpose is to observe backgrounds, compare to Monte Carlo calculations, and to tune the degrader thickness by optimizing the signal from the kaonic nitrogen 7-6 transition at 4.5 keV. The yield of this signal is at least ten times higher than that of the kaonic hydrogen K_α , so a much faster feedback is possible. At the time of this writing (July 1999), the NTP target is already installed in the north interaction region of DAΦNE and is awaiting kaon production.

Once the machine vacuum conditions (and hence the principal background from beam-gas scattering) have reached tolerable levels, and luminosity has increased as well, we will install the cryogenic target, with sixteen CCD chips. The goal with this setup is a 1% measurement of ϵ in kaonic hydrogen, followed by the first observation of the shift and width in kaonic deuterium.

5 Summary

The DEAR experiment will improve the measurement of the K^-p scattering length by a factor of ten, and make the first measurement of the corresponding scattering length in kaonic deuterium. These observations are critical inputs for the determination of the kaon-nucleon sigma terms, which will reveal the degree of chiral symmetry breaking and will hopefully revitalize the field of low-energy meson-nucleon interactions.

At the time of this writing, the first stage (NTP nitrogen target) is installed on DAΦNE and is awaiting kaons. The cryogenic hydrogen target is being tested in the laboratory and is ready for installation in 1999.

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