Status of the DEAR Experiment

presented by Ross King
on behalf of the DEAR Collaboration:

M. Augsburger[j], G. Beer[b], S. Bianco[c], A. M. Bragadireanu[c,i], M. Bregant[d], W. H. Breunlich[a], M. Cargnelli[a], D. Chatellard[j], J. -P. Egger[k], F. L. Fabbri[c], B. Gartner[a], C. Guaraldo[c], R. S. Hayano[f], M. Iliescu[c,**], T. Ishiwatari[e], T. M. Ito[l], M. Iwasaki[e], R. King[a], P. Knowles[j], T. Koike[h], B. Lauss[c,*], V. Lucherini[c], J. Marton[a], E. Milotti[d], F. Mulhauser[j], S. N. Nakamura[g], C. Petrascu[c,**], T. Ponta[i], A. C. Sanderson[b], L. A. Schaller[j], L. Schellenberg[j], H. Schneuwly[j], R. Seki[l,m], D. Tomono[e], T. Yoneyama[e], E. Zavattini[d], J. Zmeskal[a]

[a] *Institute for Medium Energy Physics, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria*
[*] *on leave of absence from above*
[b] *Univ. of Victoria, Dept. of Physics and Astronomy, P.O. Box 3055 Victoria, BC V8W 3P6, Canada*
[c] *INFN - Laboratori Nazionali di Frascati, C.P. 13, Via E. Fermi 40, I-00044 Frascati , Italy*
[d] *Univ. degli Studi di Trieste, Dip. di Fisica and INFN Sezione di Trieste, Via A. Valerio 2, I-34127, Trieste, Italy*
[e] *Tokyo Institute of Technology, 2-12-1 Ookayama Meguro, Tokyo 152, Japan*
[f] *Univ. of Tokyo, Dept. of Physics, 7-3-1 Hongo, Bunkyo, Tokyo 113, Japan*
[g] *Inst. of Physical and Chemical Research (RIKEN), 2-1 Hirosawa, Wako, Saitama 351-01, Japan*
[h] *KEK, High Energy Accelerator Research Organization, Tanashi Campus 3-2-1 Midori, Tanashi, Tokyo 188, Japan*
[i] *Inst. of Physics and Nuclear Engineering "Horia Hulubei", Dept. of High Energy Physics, P.O. Box MG-6 R-76900 Magurele, Bucharest, Romania*
[**] *on leave of absence from above*
[j] *Univ. de Fribourg, Inst. de Physique, Bd. de Perolles, CH-1700 Fribourg, Switzerland*
[k] *Univ. de Neuchatel, Inst. de Physique, 1 rue A.-L. Breguet, CH-2000 Neuchatel, Switzerland*
[l] *W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA*
[m] *Department of Physics and Astrophysics, California State University, Northridge, CA 91330, USA*

1 Introduction

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 status and plans of the DEAR experiment are also discussed.

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. It is our hope that precision measurements of this type will invigorate many areas related to meson-nucleon interactions, from cascade processes in mesic atoms to the SU(3) chiral effective Lagrangian approach.

2 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 related to the isospin scattering lengths a_0 and a_1 in the following way:

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

$$a_{K^-d} = \frac{1}{2}\left(\frac{m_N + m_K}{m_N + m_K/2}\right) \cdot (a_0 + 3a_1) + C \tag{3}$$

In the case of deuterium, the first term represents the lowest-order impulse approximation in which the kaon scatters from each "free" nucleon. The second term, C, contains all

higher-order contributions, including three-body effects. This term is not negligible; on the contrary, it is larger than the first term. Thus the extraction of the two isospin scattering lengths from an observation of the kaonic hydrogen and kaonic deuterium scattering lenghts requires an involved analysis.

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 ($\sigma_{KN}^{(0)}$, $\sigma_{KN}^{(1)}$) [3], defined by:

$$\sigma_{KN}^{(0)} = \frac{1}{2}(\bar{m} + m_s)\langle p| - \bar{u}u + 2\bar{d}d + \bar{s}s|p\rangle \tag{4}$$

$$\sigma_{KN}^{(1)} = \frac{1}{2}(\bar{m} + m_s)\langle p|\bar{u}u + \bar{s}s|p\rangle \tag{5}$$

where $\bar{m} = m_u = m_d$ is assumed. 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.

The strangeness content of the proton, y, is directly related to the sigma terms in the following way:

$$y = \frac{2\langle p|\bar{s}s|p\rangle}{\langle p|\bar{u}u + \bar{d}d|p\rangle} = \frac{4\bar{m}}{\bar{m} + m_s}\frac{\sigma_{KN}^{'}}{\sigma_{\pi N}} - 1 \tag{6}$$

where

$$\sigma_{KN}^{'} = \frac{1}{4}(\sigma_{KN}^{(0)} + 3\sigma_{KN}^{(1)}) \tag{7}$$

and

$$\sigma_{\pi N} = \bar{m}\langle p|\bar{u}u + \bar{d}d|p\rangle \tag{8}$$

is the pion-nucleon sigma term [4].

The strangeness fraction y is dependent on both kaon-nucleon and pion-nucleon sigma terms, but is more sensitive to the kaon-nucleon terms [5].

3 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 [6]:

$$\epsilon = -327 \pm 63(stat.) \pm 11(syst.)\, eV \tag{9}$$

$$\Gamma = 407 \pm 208(stat.) \pm 100(syst.)\, eV \tag{10}$$

Table 1: Comparison of two kaon sources.

	DAΦNE	KEK
Rate (kaons/s)	1100	3000
Momentum (MeV/c)	127	600
$\delta P/P$	0.1%	4%
π:K ratio	1:1	90:1

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 [7]. A comparison of some relevant quantities can be found in table 1.

It is clear that DAΦNE is not an outstanding kaon source as far as the rate in concerned, which, even at full design luminosity ($5 \times 10^{32}\, cm^{-2}s^{-1}$) is not better than KEK. 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 and essentially monoenergetically (limited only by the spread in beam energy). This in turn means that the stopping efficiency for a gaseous 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.

The second innovation of DEAR is the use of CCD (Charge-Coupled Device) detectors [8] 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 (2 to 10 keV) 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 [9]. This means that the CCDs can take data without a trigger, which leads to another large improvement in overall efficiency.

The DEAR project will employ two types of CCD chips, both produced by the firm EEV [10]. The first type, the CCD-05-20, has been used extensively in previous experiments (for examples, see [11]). However, this particular model is no longer manufactured or commercially available. The second device, the CCD-22, was developed jointly by EEV and the University of Leicester, and has recently been made available by special arrangement to the DEAR experiment. The characteristics of these CCDs are compared in table 2. The primary advantage of the CCD-22 is that, due to the larger pixel size, we can double our detector acceptance without substantially changing our readout system. There is also an advantage in efficiency, due to the deeper depletion layer.

The combination of these two innovations, DAΦNE as a unique kaon source, and

Table 2: Essential characteristics of two CCD chips.

	CCD-05-20	CCD-22
Depletion Depth	≤ 30 μm	≤ 40 μm
Pixel Size	22.5 μm x 22.5 μm	40 μm x 40 μm
Number of Pixels	1152 x 770	600 x 600
Effective Area	2.6 x 1.7 cm^2	2.4 x 2.4 cm^2

CCDs as x-ray detectors, will allow DEAR to collect K_α x rays with an unprecendented efficiency.

4 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%.

Concentrating now on the particle of interest, a K^- meson exits the machine vacuum through a special beam pipe that was manufactured for the DEAR experiment. It consists of a thin (250 μm) aluminum pipe, 690 mm long, surrounded by a 650 μm carbon-fiber reinforcing layer. The inner diameter of the pipe is 90.00 ± 0.01 mm. 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 100 μm aluminum entrance window of the target isolation vacuum. The isolation vacuum, maintained below 10^{-5} mbar using a wide-range turbomolecular pump (Varian 300 HT), is required in order to maintain the low temperature ($\sim$ 25 K) of the cryogenic target volume.

Kaons enter the cryogenic target volume through a 150 μm Hostaphan window. The cryogenic target itself is constructed of a special alloy (AlMgSi 0.5) with low manganese content (less than 0.1%) The target is cooled by a two-stage closed-cycle helium refrigerator (APD-Cryogenics DE-204SLB). The initial target conditions will be 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 captured by a hydrogen atom and the cascade chain begins, some K-series photons will exit the cryogenic target (attenuation in the hydrogen itself is negligible) through 50 μm Kapton windows (transmission efficiency $\simeq$ 90%) and interact with the CCD detectors.

The CCD chips themselves are cooled by two separate single-stage compressors (APD Cryotiger) to a temperature of 160 K. The CCDs are read out by a set of custom electronics [9]. The digitized data are transmitted over a fiber-optic link to the two data acquisition computers (PCs running Windows 3.11) 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 and rough analysis of the data.

Further details and a complete description of the DEAR setup can be found in [12].

5 Status and Plans

The DEAR installation will proceed with four target stages: the NTP target, the initial cryogenic target, the upgraded cryogenic target, and the final cryogenic target. The time scale of a target installation is one or two days.

The NTP (normal temperature and pressure) target consists of a 2700 cm^3 pure nitrogen volume at room temperature. Four CCD-05 chips are installed on this target. 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 with this target. At the time of this writing (April 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 initial cryogenic target, which consists of gaseous hydrogen at 25 K and 3 bar, with eight CCD-05 detectors.

At the same time, laboratory tests will continue on an upgraded target and the new CCD-22 chips. When these tests are complete, the initial cryogenic target will be replaced by the upgraded cryogenic target. This target also operates at 25 K and 3 bar, but allows for up to 16 CCD detectors. In the third phase, we will install eight new CCD-22 chips and leave four of the old CCD-05 chips. This system will improve the detection efficiency by a factor of 2.5 relative to the initial cryogenic target. The goal with this setup is to measure the shift of K_α in kaonic hydrogen to 5%.

In the fourth and final phase, 16 CCD-22 chips will be installed on the upgraded cryogenic target. This system will improve the detection efficiency by a factor of four relative to the initial cryogenic target. 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.

6 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 allow us to determine the strangeness content of the proton, 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 second stage (cryogenic hydrogen target) is ready for installation, and an upgrade, with a final potential efficiency improvement of a factor of four, is being tested and will be ready for installation in 1999.

References

[1] S. Deser *et al.*, Phys. Rev. **96** (1954) 774;
T.L. Trueman, Nucl. Phys. **26** (1961) 57;
A. Deloff, Phys. Rev. **C13** (1976) 730.

[2] R. Seki, Phys. Rev. **182** (1969) 1773.

[3] B. Di Claudio *et al.*, Lett. Nuovo Cimento **26** (1979) 555;
A.D. Martin and G. Violini, Nuovo Cimento **30** (1981) 105.

[4] J.F. Gunion, P.C. McNamee, and M.D. Scadron, Nucl. Phys. **B123** (1977) 445.

[5] R.L. Jaffe and C.L. Korpa, Comments Nucl. Part. Phys. **17** (1987) 163.

[6] M. Iwasaki *et al.*, Phys. Rev. Lett. **78** (1997) 3067;
S.N. Nakamura *et al.*, Nucl. Inst. and Meth. **A408** (1998) 438;
T.M. Ito *et al.*, Phys. Rev. **C58** (1998) 2366.

[7] T.M. Ito, *Observation of Kaonic Hydrogen X Rays*,
Ph.D. Thesis, University of Tokyo, 1997.

[8] G. Fiorucci *et al.*, Nucl. Inst. and Meth. **A292** (1990) 141;

[9] D. Varidel *et al.*, Nucl. Inst. and Meth. **A292** (1990) 147.

[10] EEV (English Electric Valve), Waterhouse Lane,
Chelmsford, Essex, CM12QU, United Kingdom.

[11] B. Lauss *et al.*, Phys. Rev. Lett **76** (1996) 4693;
D. Chatellard *et al.*, Nucl. Phys. **A625** (1997) 855;
S. Tresch *et al.*, Phys. Rev. **A 58** (1998) 3528.

[12] S. Bianco *et al.*, *The DEAR Case*, LNF-98/039.
To be published in *Rivista del Nuovo Cimento*.