LABORATORI NAZIONALI DI FRASCATI
SIS-Pubblicazioni

LNF-98/002 (P)
28 Gennaio 1998

Strangeness in Nuclear Matter at DAΦNE

Paola Gianotti
INFN, Laboratori Nazionali di Frascati, P.O. Box 13, I-00044 Frascati, Italy

Abstract

The low energy kaons from the ϕ meson produced at DAΦNE offer a unique opportunity to study strangeness in nuclear matter. The interaction of kaons with hadronic matter can be investigated at DAΦNE using three main approaches: study of hypernuclei production and decay, kaons scattering on nucleons, kaonic atoms formation. These studies explore kaon-nucleon and hyperon-nucleon forces at very low energy, the nuclear shell model in presence of strangeness quantum number and eventual quarks deconfinement phenomena. The experiments devoted to study this physical program at DAΦNE are FINUDA and DEAR. The physics topics of both experiments are illustrated together with a detailed descriptions of the two detectors.

PACS: 21.80.+a, 13.75.Jz, 36.10

Presented at:
“International Symposium on Strangeness in Quark Matter 14-18 April 1997,
Thera (Santorini), Greece”
Published on J. Phys. G: Nucl. Part. Phys. **23** (1997) 2151-2159

1 Introduction

DAΦNE [1] is a high luminosity e^+e^- ϕ-factory that will be operational this year at the Frascati INFN laboratory. At the initial machine luminosity ($1.3 \cdot 10^{32} cm^{-2} sec^{-1}$) about 500 ϕ mesons are produced per second thus collinear pairs of K^+K^- and of $K^0_S K^0_L$, of very low momentum ($127 MeV/c$ and $110 MeV/c$ respectively), will be available. This will offer the opportunity of studying not only CP violation phenomena in the neutral kaon system and rare decay modes of both charged and neutral kaons, but also of exploring an interesting and wide hadronic physics program. This last item will be investigated mainly by two different experiments: FINUDA and DEAR. FINUDA is a high acceptance, high resolution magnetic spectrometer devoted mainly to hypernuclear physics; DEAR is a high resolution, background free, X-rays detector whose aim is to measure the kaon-nucleon scattering length.

In the following sections a detailed overview of the DAΦNE hadronic physics program main topics is given. Section 3 and 4 describe in detail FINUDA and DEAR detectors and illustrate the physics topics explored by both experiments.

2 Main topics of DAΦNE hadronic physics

The mono-chromatic charged kaons from ϕ decay can be used for studying quark degrees of freedom and basic QCD processes at very low energy. The main physics points studied at DAΦNE by FINUDA and DEAR are:

1. high resolution Λ-hypernuclei spectroscopy;
2. lifetime and decay modes of Λ particle inside nuclear matter;
3. low momentum kaon-nucleon and kaon-nucleus elastic scattering;
4. kaon-nucleon scattering length from 1*s* level in kaonic hydrogen and kaonic deuterium.

Hypernuclear spectroscopy can give important experimental information both for nuclear and particle physics. From the nuclear physics point of view, a Λ embedded inside a nucleus is expected to behave as a distinguishable baryon not affected by Pauli principle. Moreover, it has a weaker interaction with the nucleons than the *N*-*N* force and a negligible spin-orbit central potential, due to the zero isospin of the Λ particle which prevents it from exchanging an isovector meson (π, ρ) with a nucleon [2]. The relative weakness of Λ-*N* interaction implies that the nuclear shell structure is not disrupted by the insertion of a Λ and, moreover, the absence of Pauli exclusion constraints gives the Λ the possibility of populating all nuclear states. The validity of this scenario has been tested, up to now, with energy resolutions worse than $1MeV$. Thus, only pushing up the detector resolution can new effects be detected.

On the particle physics side Λ-hypernuclei allow to obtain information on the Λ-*N* interaction in the low momentum region, where direct scattering experiments cannot be done.

A very interesting result, arising from previous hypernuclear experiments, is the observation of new decay modes of the Λ when it is embedded in nuclear matter. This phenomenon is a consequence of the fact that the nucleons, produced by Λ mesonic decays (1), have a momentum ($\sim 100MeV/c$) lower than the Fermi one. The mesonic decays are then inhibited by the Pauli principle.

$$\Lambda \to \begin{cases} p + \pi^- \\ n + \pi^0 \end{cases} \tag{1}$$

Thus the Λ hyperon undergoes the non-mesonic (2), (3) decays when it is embedded in a nucleus:

$$\Lambda + p \to n + p \tag{2}$$

$$\Lambda + n \to n + n \tag{3}$$

Here the momentum of the produced nucleons is $\sim\ 400MeV/c$ and no Pauli blocking can appear. The study of non-mesonic Λ decays, which probe the high momentum parity conserving part of the weak interaction, can give an insight to the strangeness-exchanging weak interaction processes. In particular, it has been suggested [3] according to the analysis of hypernuclear data, that the $\Delta I = \frac{1}{2}$ empirical rule might be strongly violated in non-mesonic decays.

There are also some hints of a change of the Λ lifetime when it is produced inside a nucleus. The experimental values, available up to now, are scarce and affected by big errors. Then new measurements on a wide range of materials are needed.

Concerning kaon-nucleon interaction there are three main subjects that need new data in the DAΦNE energy range.

K^+N scattering is the appropriate system to study non-resonant nuclear forces. In fact the K^+ contains $u\bar{s}$ quarks which cannot annihilate with nucleon valence quarks. Then the K^+ cross-section should be quite independent from the projectile energy and the ratio $R_T = [\sigma(K^+A)/A]/[\sigma(K^+d)/2]$ should be near 1. Nevertheless, it has been experimentally observed that $\sigma(K^{+12}C)$ is about 6 times greater than $\sigma(K^+d)$ [4]. This effect can be interpreted as a swelling or partial deconfinement of the nucleon inside the nucleus [5], but more data are needed especially at low K^+ momenta.

The K^-N system shows a big inelasticity and a signal near threshold, the $\Lambda(1405)$, that need to be classified. In fact the nature of this subthreshold resonance is not well understood: *qqq* baryon, $\bar{K}N$ bound state or hybrid state.

Besides, to better understand non perturbative QCD and to give new hints to the open problem of the strangeness content of the proton, kaon-nucleon scattering length must be unambiguously determined. The present knowledge of this topic is poor. K^-p scattering data are available only for kaon momenta above $100 MeV/c$. These data [6–10] have been analysed using the K-matrix formalism and, under the assumption that the matrix elements are smooth functions of energy, have been extrapolated down to threshold and below, in order to infer the kaon-proton scattering length. The important feature that comes out from those analyses is the large negative real part of the K^-p scattering length; this suggests that the strong interaction between the kaon and the proton is repulsive. In these analyses a virtual *I* = 0 resonant $\bar{K}$ *N* bound state with $\Lambda(1405)$ parameters has to be introduced.

The direct way to obtain the kaon-proton scattering length, without any extrapolation at zero energy, is to measure the energy shift, from the purely electromagnetic values, of the X-rays emitted by kaonic hydrogen during the cascade through its atomic levels. The energy shift (ε) and the width (Γ) of the *1s* level, in kaonic hydrogen, is related to the real and imaginary part of the complex *s*-wave K^-p scattering length a_{K^-p}:

$$\varepsilon + \frac{i}{2}\Gamma = 2\alpha^3\mu^2 a_{K^-p} \tag{4}$$

where μ is the reduced mass of the system and α the fine structure constant. The measurements performed at the beginning of the 80's [11–13] of X-rays from kaonic hydrogen give results different and affected by big errors. Nevertheless, all experiments find a positive strong interaction shift of the *1s* level. This means that the strong interaction between the kaon and the proton should be attractive. However, in a recent KEK experiment [14], the value found for the energy shift for the 1*s* kaonic hydrogen level is $\varepsilon = -327 \pm 63 \pm 11 eV$ in agreement with the scattering data analyses.

This "kaonic hydrogen puzzle" needs to be definitely solved in order to understand the kaon-nucleon interaction

DAΦNE kaon beams have peculiar characteristics; low momenta, no pion contamination, good intensities. These features can be used to obtain high quality experimental data for all the topics previously mentioned. FINUDA and DEAR experiments have been especially designed to accomplish those tasks.

3 FINUDA experiment

3.1 Physics program

FINUDA (FI*sica* NU*cleare a* DAΦ*NE*) is a rare example of a nuclear physics experiment at a collider. The leading idea [15] is to stop the low energy K^- beam from ϕ-decay, tagged by the opposite K^+, to produce Λ-hypernuclei:

$$K^-_{stop} +^A Z \rightarrow^A_\Lambda Z + \pi^- \tag{5}$$

The spectrum of the emitted π^- provides the energy of the hypernuclear level. Low energy ($16MeV$) DAΦNE K^- can be stopped in a very thin target ($300\ mg/cm^2$); consequently, the outgoing π^- do not undergo significant momentum degradation making possible to obtain unachieved momentum resolution in hypernuclear spectroscopy.

The only drawback of such a kaon beam is its low intensity ($216K^-/s$ with a machine luminosity of $10^{32}cm^{-2}s^{-1}$), but FINUDA expected counting rate ($80\ hyp.ev./hour$) appears competitive with the new initiative on hypernuclear physics proposed at BNL AGS [16]. The rates foreseen for the two experiments are similar, but for opposite experimental reasons: in the AGS case a kaon beam of intensity $2 \cdot 10^4$ kaons per second is stopped on a nuclear target in order to produce hypernuclei through the reaction:

$$K^-_{stop} +^A Z \rightarrow^{(A-1)}_\Lambda Z + \pi^0 \tag{6}$$

The solid angle of the spectrometer, detecting the π^0, is $\sim 20msr$. In the case of FINUDA experiment the kaon flux is two order of magnitude lower, but this is compensated by the bigger detector acceptance ($\sim 2\pi sr$).

FINUDA apparatus will also detect hypernuclei decay products allowing the measurement of Λ lifetime and the study of its decay modes.

Λ lifetime can be directly measured as the difference between the arrival times, on the Time of Flight (TOF) detector, of the prompt π^-, produced after hypernucleus formation, and of the proton emitted after Λ decay. This time difference have to be corrected for the TOF of the particles. This will give a little contribution to the measurement uncertainty since momenta and trajectories are measured with good accuracy. With the time resolution of $500ps$ FWHM foreseen for the TOF system, the Λ lifetime will be measured with a 10% error collecting ~ 2000 events.

FINUDA wants also to look for possible violations of the $\Delta I = \frac{1}{2}$ rule in non-mesonic decays. This is an empirical rule that arises from the experimental decay branching ratios of the free Λ. These show a dominance of the channel with $\Delta I = \frac{1}{2}$ with respect to the one with $\Delta I = \frac{3}{2}$. To test this rule in non-mesonic decays it is necessary to measure precisely the two branching ratios (2), (3). At the initial DAΦNE luminosity FINUDA aspects to detect 6 non-mesonic decay of type (2) and 1 of type (3) per hour.

3.2 FINUDA detector

FINUDA is a magnetic spectrometer [17] (see fig. 1), with cylindrical geometry, optimised to have large solid angle, optimal momentum resolution and good trigger capabilities.

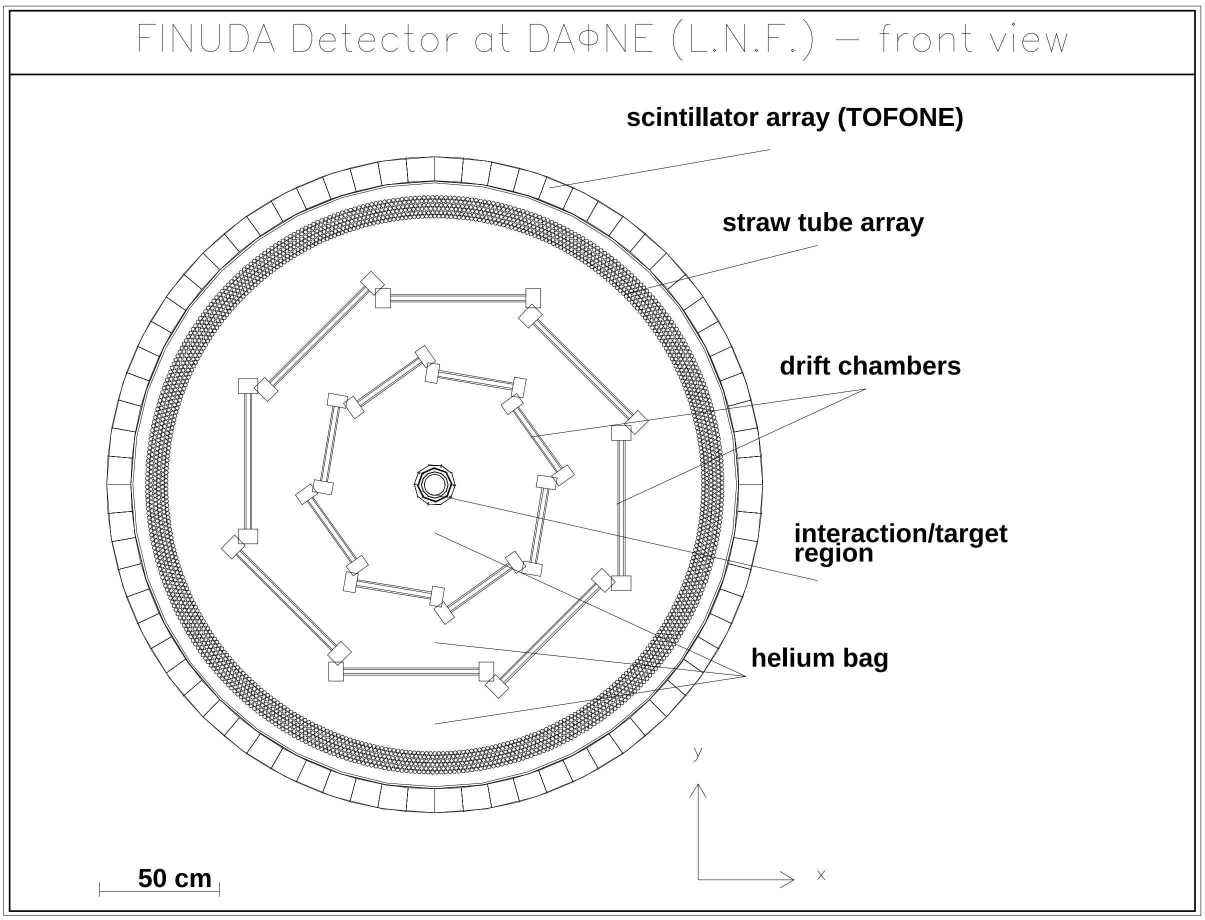

Figure 1: Cross section of the FINUDA spectrometer.

In fig. 2 the interaction/target region is shown. A barrel of 12 thin scintillators (TOFINO) is placed around the beam pipe with the primary aim of triggering on K^+K^- pairs.

The position of the K^-, before entering the nuclear target, is measured by an octagonal array of silicon microstrips (ISIM) with very high spatial resolution ($\sigma \sim 30-50\mu m$).

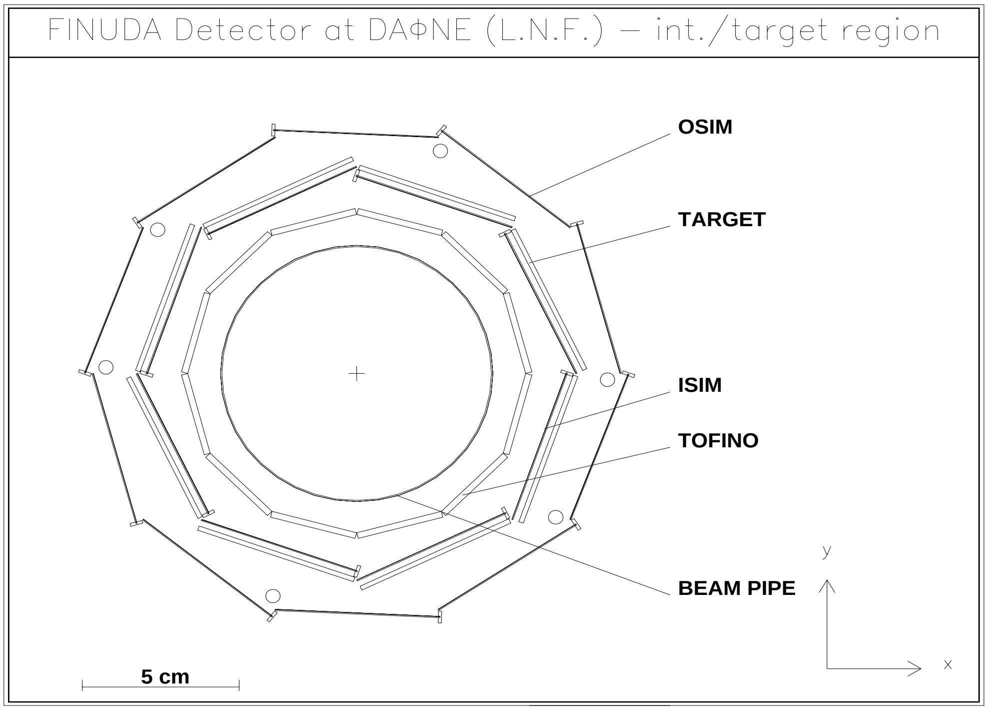

Figure 2: FINUDA interaction/target region.

The same detector can also provide particle identification, by measuring their energy loss, improving trigger capabilities to select K^+K^- pairs.

Finally, an external array of 10 silicon microstrips (OSIM) is used to measure the first point along the track of the π^- emitted after the hypernucleus formation.

The position of the interaction point of the K^- inside the target can be reconstructed, using the information of both ISIM and OSIM detectors, with an accuracy of $250\mu m$.

Going outwards from the interaction/target region we find a composite tracking device. As previously stated the first point along the charged tracks is given by OSIM detector. Then particles cross two octagonal layers of planar low mass drift chambers (LMDC) and a system of longitudinal (along the beam axis) and stereo (rotation angle $\pm 13^o$) straw tubes (ST). This tracking system is embedded in a helium atmosphere in order to minimise multiple scattering. For the same reason the drift chambers have very thin mylar walls (6 and 12 μm) and operate with a He-iC_4H_{10}(70/30) gas mixture.

The drift chamber spatial resolutions obtained in dedicated test beams are $150\mu m$ in the $\rho - \phi$ plane and $1cm$ along the z coordinate [18]; for the straw tubes a resolution of $100\mu m$ has been obtained for both x and y coordinates, $1mm$ for z coordinate [19].

The momentum resolution achievable with the FINUDA tracking system is 0.3% for π^- of momentum between $250 - 270 MeV/c$, which corresponds to a resolution of the hypernuclear energy level of $\sim\ 700 KeV$. For protons of $\sim\ 80 MeV$, coming from the hypernucleus non-mesonic decay, the energy resolution is $1.3 MeV$

The last FINUDA subdetector is an array of 72 scintillators (TOFONE) whose aim is to detect neutrons from hypernucleus non-mesonic decay and to perform fast trigger logics, based on time of flight measurements, in order to select hypernuclear events. The neutron detection efficiency is 15% with an energy resolution of $10 MeV$.

4 DEAR experiment

4.1 Physics program

The scientific goal of the DEAR experiment [20] (D*A*Φ*NE* E*xotic* A*tom* R*esearch*) is the measurement of the kaon-nucleon scattering length, through the precise measurement of the kaon-proton scattering length and, subsequently, the measurement of the kaon-neutron scattering length. These quantities are obtained by measuring the energy of the X-rays emitted in the transitions to the 1*s* level of kaonic hydrogen and kaonic deuterium.

In order to probe the kaon nuclear interaction at zero energy, two approaches can be considered: the first is to study kaons scattering on nucleons at the lowest possible momentum and then to extrapolate the results down to threshold; the second is to create a K^-N system nearly at rest.

The second way has been chosen by the DEAR experiment.

The negative kaons, entering a hydrogen(deuterium) target, lose energy by ionising target atoms and by colliding with atomic electrons, until they are captured and form a kaonic atom. This atom is produced in a state with high quantum number ($n \sim 25$) then it undergoes a cascade process through its atomic states. Auger emissions dominate the first deexcitation steps, then X-rays emissions become dominant. Finally, at small *n*, the nuclear absorption prevails and the kaon is captured. The energy spectrum of the X-rays emitted in the transitions to the 1*s* level (K-series) has an energy shift and a broadening of its width due to the strong interaction. By measuring the energy of the X-ray associated with the transition of the kaonic atom to the ground state 1*s* and comparing the obtained values with those calculated under the assumption of a pure electromagnetic interaction, ε and Γ for the 1*s* state can be obtained. Actually, the K_α line ($2p \to 1s$ transition) is the most important to determine ε and Γ, since the energy spacing between two adjacent lines of the K-series is smaller than the spacing between the K_α and K_β lines. Then, using eq. (4) $K^- p$ scattering length can be directly determined.

The QED calculations of atomic levels energies are extremely precise, errors are of the order of tenth of eV, however the experimental error on the kaon mass and the unknown kaon charge distribution function give an overall uncertainty, on the energy of the 1*s* state, of about 1 eV. Thus very precise X-rays detectors are necessary in this kind of experiment.

Another problem is the Stark effect suffered by the kaonic atoms, due to the electric field of neighbouring nuclei. This causes a mixing between the states with different angular momentum and consequently the kaon is absorbed from higher n states. Stark effect increases with the target density, but, on the other hand, it is not convenient to reduce too much the gas density otherwise the kaons could decay before they are captured to form a kaonic atom.

4.2 DEAR detector

The DEAR experimental set up [21] (fig. 3) has been designed in order to improve significantly all previous kaonic atom measurements. The first improvement is given by the high quality DAΦNE kaon beam. The second is given by the use of Charge Coupled Devices (CCD) that, up to now, are the best detectors available for soft ($\leq 10KeV$) X-rays spectroscopy in terms of energy resolution and background rejection.

DEAR apparatus is composed only by two elements: the target and the X-rays detector.

The DEAR target is a pressurised cryogenic target. This solution has been adopted in order to reduce the Stark effect, present with liquid hydrogen, without loosing too much in terms of kaonic atoms yield. The target density chosen is $\rho = 3.6 \cdot 10^{-3} gcm^{-3}$ (about 40 times the hydrogen NTP density) corresponding to a hydrogen pressure of $3\ atm$ and to a temperature of $25^o K$. Target dimensions are $150\ mm$ diameter and $140\ mm$ height. The berillum entrance window has a diameter of $125\ mm$ and a thickness of $400 \mu m$ in order to reduce the possibility of multiple scattering. The target is enclosed by an aluminum vessel to reduce helium consumption. Usually, stainless steel or copper is used to make cryogenic shields, but these materials have own X-rays emissions in the same energy region of kaonic hydrogen, so aluminum has been chosen in order to eliminate a source of background.

The X-rays detector consist of 8 CCD*s* having a resolution $\leq 150\ eV$ for X-rays of energy below $10KeV$. CCD*s* are solid state detectors [22,23] with a pixel structure. The

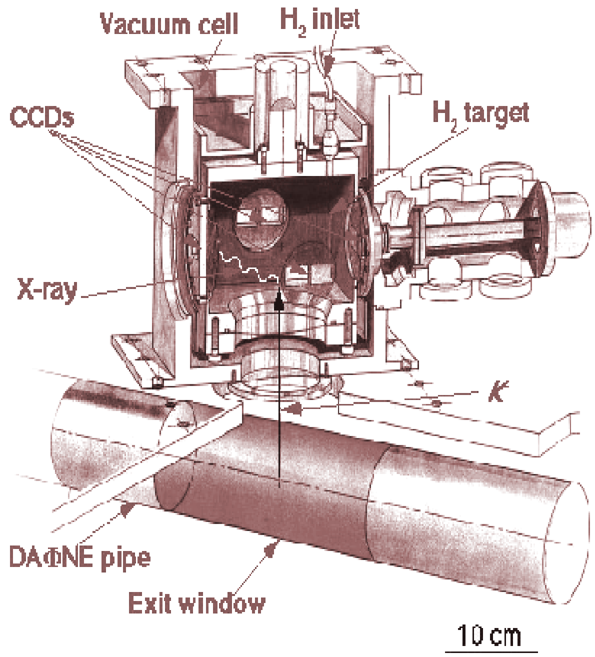

Figure 3: The DEAR experimental set up.

number of pixel per CCD is $770 \times 1152 \approx 887000$. Each pixel dimension is $22.5 \mu m^2$. Each CCD has an active area of about $17 \times 26\ mm^2 \approx 4.4\ cm^2$. The CCD detection efficiency for X-rays of energy $6.5 KeV$ is 60%. The good two dimensional spatial resolution of the CCD (pixel dimension) turns out to be crucial to extract the weak signal from the large background. The CCD*s* background rejection capability is indeed very good. This is due to the fact that an X-ray with energy between $1 - 10 KeV$ releases it in a single pixel. Charged particles, gammas and neutrons, on the contrary, give a signal on many pixels (~ 5). This is because in silicon an X-ray with energy less than $30 KeV$ interacts only by photoelectric effect, which is localised in space, whereas charged particles loose energy by ionising along their tracks.

Since a pixel has 8 neighbours, the usual way to distinguish a good X-ray event from background is to require that none of the 8 surrounding pixels have collected a charge above the noise level ($\approx 200\ eV$).

The two half of each CCD are readout simultaneously. The transfer and readout time per pixel is $64 \mu s$ thus the total readout time of the system is $\approx 28 s$, which excludes the possibility of triggering a CCD. Accumulation of data continues during the readout.

An important parameter to tune is the readout frequency in order to exclude that the same 8 pixel cluster could be hit twice by a good X-ray event. To be safe the number of hit pixels should not exceed 5%, which corresponds to 4000-5000 background events per $\frac{1}{2}$

CCD. With DAΦNE machine background conditions this give an exposure time of $10\,min$.

With the numbers given above for the target density and CCDs efficiency the expected number of K_α X-rays is $\approx 20/hour$.

5 Final remarks

The unique characteristics of the kaons form DAΦNE ϕ's, low momentum, zero contamination, good momentum resolution and intensity, together with the special features of the FINUDA and DEAR detectors, allow to explore open problems in particle an nuclear physics.

Fine hypernuclear spectroscopy, Λ lifetime measurements in nuclear matter, tests of weak interactions, low energy kaon-nucleon scattering will be explored by the FINUDA detector, with the aim to obtain data of superior quality and reliability.

The DEAR set up, which takes advantage of the best performances of CCD detectors for soft X-rays, in terms of background rejection and energy resolution, will precisely determine the kaon-nucleon scattering length by measuring X-rays spectra of kaonic hydrogen and kaonic deuterium. This will allow to obtain fundamental information on physics open problems: the nature of the strange resonance $\Lambda(1405)$ and the kaon-nucleon sigma term, which is directly connected to the strangeness content of the nucleon.

DEAR and FINUDA will be the first experiments to take data at DAΦNE in '98 after machine installation and tuning.

References

[1] Vignola G it et al1996 *Proc. 5th European Particle Accelerator Conference (Sitges)* vol 1 S Myers it et al(London: Institute of Physics Publishing) p 22

[2] Molinari A Feshbach H 1995 *The Second Daϕne Physics Handbook* vol II L Maiani it et al(Frascati: SIS-LNF) p 713

[3] Schumacher R A 1992 *Nucl. Phys.* **A547** 143c

[4] Krauss R A it et al1992 *Phys. Rev.* **C46** 655

[5] Siegel P B it et al1985 *Phys. Rev.* **C31** 2184

[6] Sakitt M it et al1965 *Phys. Rev.* **B139** 719

[7] Kim J K 1967 *Phys. Rev. Lett* **19** 1074

[8] von Hippel F and Kim J K 1968 *Phys. Rev. Lett* **20** 1303

[9] Martin A D and Ross G G 1970 *Nucl. Phys* **B16** 479

[10] Martin A D it et al1981 *Nucl. Phys.* **B179** 33

[11] Davies J D it et al1979 *Phys. Lett* **B83** 55

[12] Izycki M it et al1980 *Z. Phys.* **A297** 11

[13] Bird P M it et al1983 *Nucl. Phys* **A404** 482

[14] Iwasaki M it et al1997 *Phys. Rev. Lett.* **78** 3067

[15] Bressani T 1991 *Proc. Workshop on Physics and Detectors for DAΦNE (Frascati)* Pancheri G (Frascati: SIS-LNF) p 475

[16] Thiessen H A and Peng J C 1994 *Investigation of Light Hypernuclei Using the* (K^-_{stop}, π^0) *Reaction* AGS PROPOSAL (Brokhaven)

[17] Agnello M it et al1993 *FINUDA a detector for Nuclear Physics at DAΦNE* LNF-93/021 (IR) (Frascati:SIS-LNF)

Agnello M it et al1995 *FINUDA technical report* LNF-95/024 (IR) (Frascati:SIS-LNF)

[18] Agnello M it et al1996 *Nucl. Instr. Meth.* **A379** 411

[19] Benussi L it et al1996 *Nucl. Instr. Meth.* **A379** 429

[20] Guaraldo C it et al1995 *Proc. Second Workshop on Physics and Detectors for Da*ϕ*ne '95* Baldini R it et al(Frascati: SIS-LNF) p 349

[21] Baldini R it et al1995 *DAΦNE Exotic Atom Research. The DEAR Proposal* LNF-95/055 (IR) (Frascati:SIS-LNF)

[22] Beynon J D E and Lamb D R 1980 *Charge-coupled devices and their applications* (London: Mc-Graw Hill)

[23] Boyle W S and Smith G E 1970 *Bell Syst. Tech. Journal* **49** 587