The FINUDA Experiment at DAΦNE

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FINUDA is a large acceptance, high resolution magnetic spectrometer dedicated to hypernuclear physics. The experiment is in an advanced stage of construction and will run in 1997 at DAΦNE, the Frascati ϕ–Factory. Motivations, physics goals and expected performance are illustrated.

1. INTRODUCTION

The DAΦNE collider, proposed in 1990 [1], is now being built at the Laboratori Nazionali di Frascati of INFN. DAΦNE will run in 1997 at the center of mass energy of the ϕ meson with an initial luminosity of $\mathcal{L} = 1 \times 10^{32}$ cm^{-2}s^{-1} and a final luminosity one order of magnitude larger.

The $\phi(1020)$ meson is produced in $e^+ e^-$ collisions with a peak cross section

$$\sigma(e^+ e^- \rightarrow \phi) \sim 5\,\mu b \tag{1}$$

which translates into a production rate of

$$R_\phi = (5 \times 10^2 \rightarrow 5 \times 10^3)\, s^{-1} \tag{2}$$

from initial to final luminosity, with a 30:1 S/N ratio with respect to the hadronic production.

The ϕ then decays at rest into K^+K^- (49%), $K^0_SK^0_L$ (34%), $\rho\pi$ (13%), $\pi^+\pi^-\pi^0$ (2.5%) and $\eta\gamma$ (1.3%). Therefore a ϕ–factory is a unique source of monochromatic, collinear, quantum–defined and tagged neutral and charged kaons. The detection of one K out of the two produced in the ϕ decay determines the four–momentum of the other ("tagging").

The neutral kaon decay mode will supply an abundant rate of $K^0_SK^0_L$ systems to the KLOE [2] experiment, where this unique possibility will be exploited for a measurement of $\mathcal{R}(\epsilon'/\epsilon)$ to 10^{-4} and of other CP violating parameters in the $\bar{K}$K system.

The most frequent charged kaon decay mode will provide low–energy (16 MeV), monochromatic, background free and tagged K^+ and K^- to the FINUDA experiment. A third experiment recently approved, DEAR [3], will also use K^- to measure X–rays from the (K^- p) atoms.

An overview of the FINUDA detector and associated physics is given, as well as a status report and construction schedule.

2. THE FINUDA EXPERIMENT

FINUDA (standing for *FIsica NUcleare a DAΦne*) is an experiment dedicated to Nuclear Physics topics carried out at an ($e^+\,e^-$) collider. This sounds contradictory in itself and indeed herein lies the uniqueness of the idea [4]: charged kaons from ϕ decays are used as a monochromatic, slow, tagged, background–free, beam on a thin target surrounding the beam pipe. The possibility of stopping low–momentum monochromatic K^- in a thin target (typically 0.5 g cm^{-2} of Carbon) is unique to DAΦNE: K^-'s can be stopped, with minimal straggling, very near the target surface, so that outgoing prompt pions do not cross significant amount of target and undergo minimum momentum degradation. This feature provides unprecedented momentum resolution as long as very transparent detectors are employed before and after the target.

The FINUDA detector is optimized to perform high–resolution studies of hypernuclear production and decays with a large acceptance spectrometer, typical of collider experiments. Furthermore, different from fixed target experiments, the K^- direction is completely tagged by the K^+ detection and viceversa.

Negative kaons stopping inside the target produce a Λ–hypernucleus via the process

$$K^-_{stop} + {}^A\,Z \rightarrow {}^A_\Lambda Z + \pi^- \qquad (3)$$

where the momentum of the outgoing π^- is directly related to the energy level of the hypernucleus formed (two body reaction). The large momentum transferred to the produced Λ–hyperon (250 MeV/c) in reaction (3) is of the same order of magnitude of the Fermi momentum of nucleons in nuclei, and thus production of Λ–hypernuclei is expected both in ground and excited states. Thanks to the better resolution and larger production rate than in present Hypernuclear Physics experiments, a substantial step forward in hypernuclear spectroscopy is expected, in particular in the medium–high mass region, for which the present information is rather scarce.

It is well known that for all but the lightest (A$\leq$4) Λ–hypernuclei the following weak

interaction decays are strongly favoured:

$$\Lambda + n \rightarrow n + n \tag{4}$$

$$\Lambda + p \rightarrow n + p \tag{5}$$

with the nucleus undergoing the non–mesonic (NM) decays:

$${}^{A}_{\Lambda}Z \rightarrow {}^{(A-2)}Z + n + n \tag{6}$$

$${}^{A}_{\Lambda}Z \rightarrow {}^{(A-2)}(Z-1) + n + p. \tag{7}$$

In spite of the strong physical interest of these processes, recently renewed by claims of a possible violation of the ΔI=1/2 rule in reactions (6) and (7), the experimental information is scarce and of poor statistical significance. Thanks to the high production rate of Λ–hypernuclei in the ground state and to the large acceptance for detecting neutrons and protons from decays (6) and (7) with a high transparency, it can be expected that FINUDA will allow a real breakthrough in the study of NM decays. Relative branching ratios for (6) and (7) will be obtained with a statistical precision better than 5% in inclusive measurements (i.e. without identification of the final nuclear state). For some selected cases, like

$${}^{6}_{\Lambda}He \rightarrow {}^{4}He + n + n, \tag{8}$$

exclusive (i.e. with identification of the final nuclear state) NM decays of Λ–hypernuclei will be measured for the first time [5]. The lifetime of Λ in different hypernuclei will also be measured thanks to the excellent timing properties of the detector. Finally, the production of neutron–rich hypernuclei through the reaction:

$$K^{-}_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}(Z-2) + \pi^{+} \tag{9}$$

will also be investigated.

Following the initial idea, FINUDA was formally proposed in May 1993 [6], rapidly approved and funded at the end of 1993.

3. STRUCTURE OF THE FINUDA DETECTOR

The FINUDA detector is a high resolution magnetic spectrometer with cylindrical geometry, optimized for large geometrical acceptance ($> 2\pi$ sr) and momentum resolution ($\Delta p/p \leq 0.3\%$ FWHM), exploiting dedicated triggers.

Fig. 1 shows a sketch of the detector, consisting of a superconducting solenoid, providing a homogeneous magnetic field of 1.1 T inside a cylindrical volume of 146 cm radius and 211 cm length. The (e^{+}, e^{-}) collide at the center of the magnet and the current distribution in the coil as well as the shape of the iron yoke and of the end-caps were designed in such a way as to have a 1% homogeneity inside a tracking volume shaped as a clepsydra.

The following functional sub-structures of the detector, each consisting of different arrays of sub-detectors, may be defined:

- the interaction/target region;

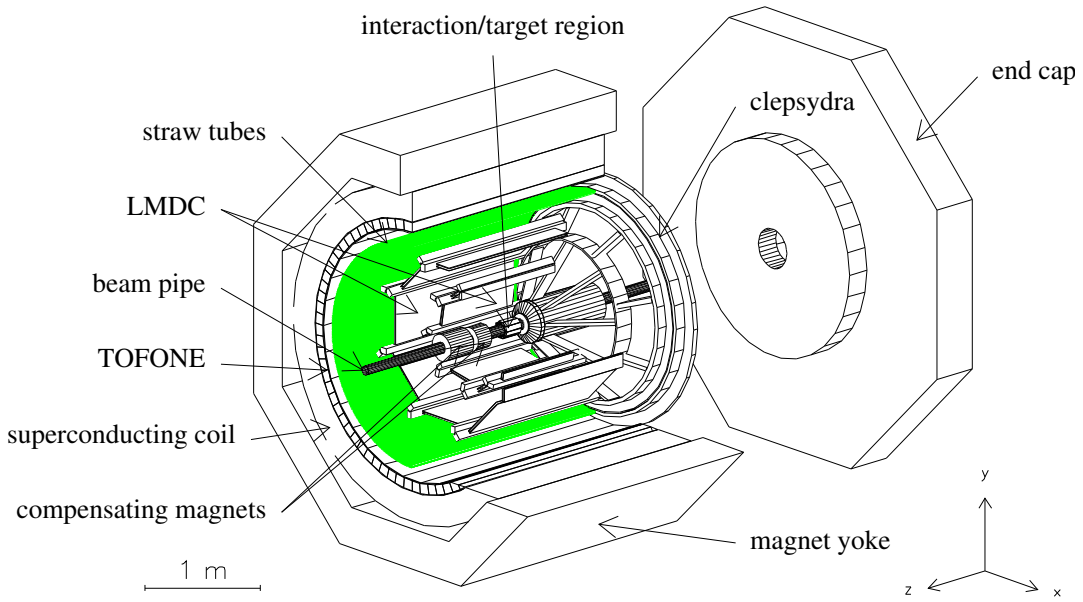

Figure 1. Schematic view of the FINUDA apparatus; the "right" end-cap has been shifted outward, while the "left" end-cap and the "left" part of the mechanical structure (clepsydra) have not been drawn.

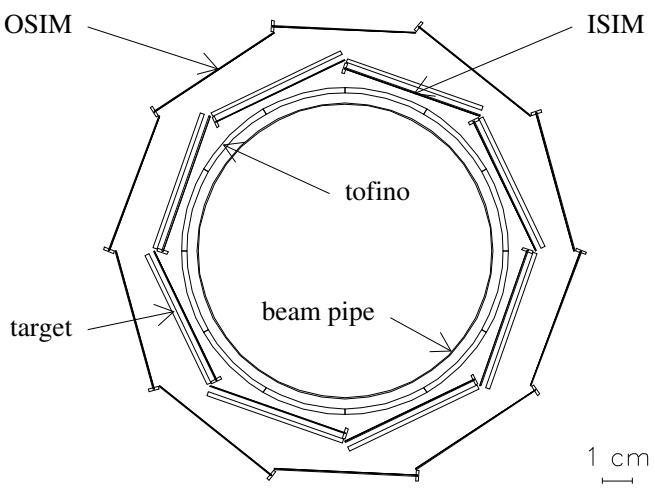

Figure 2. Schematic frontal view of the interaction/target region.

- the tracking device;

- the external scintillator barrel.

Fig. 2 shows a sketch of the interaction/target region. The role of the detectors arranged around the Be beam pipe (radius = 5.5 cm, thickness = 400 μm) is to select the (K^+, K^-) pairs from the ϕ-decay and to provide the first level trigger. There is a first barrel of scintillators (tofino), 2 mm thick, sliced in 12 slabs viewed at both ends by Hybrid PhotoDiodes (HPD) through suitably shaped Lucite light guides. (K^+, K^-) pairs crossing the barrel are very efficiently selected at trigger level by $\Delta E/\Delta x$ measurements and back-to-back correlation. There is furthermore an array of Si μ-strip detectors (ISIM), arranged following the sides of an octagonal prism, with bi-dimensional read-out. It localizes, with a precision better than 50 μm, the K^- (K^+) before stopping in the nuclear target, facing ISIM at a distance of less than 2 mm. In addition ISIM allows a further $\Delta E/\Delta x$ measurement of the particle, very useful for the pattern recognition and the determination of the interaction vertex. The thickness of the nuclear targets (solid materials, ranging from Li to Pb) is such as to stop the K^- (K^+); its magnitude varies between 200 and 300 mg/cm^2. The total length (17 cm) of the detectors surrounding the beam pipe is such that $\sim 90\%$ of the K^- from ϕ–decay are detected.

The tracking device must allow the determination of the π^- momenta from equation (3) with a $\Delta p/p$ of 0.3 % FWHM. It consists of three different types of sub-detectors, all of them immersed in a Helium atmosphere, in order to minimize the multiple Coulomb scattering, which strongly affects the momentum resolution in a non-focusing spectrometer like FINUDA. The π^- emitted isotropically from the nuclear targets encounters a first array of Si μ-strip detectors (OSIM), arranged following the sides of a decagonal prism.

Beyond these, there are (see Fig. 1) two layers of Low-Mass, high precision planar Drift Chambers (LMDC), arranged following again the sides of an octagonal prism. A He-iC_4H_{10} (70/30) gas mixture will be used. A systematic study performed on a real-scale prototype has shown that the performance is the same, or even better, than that obtained with Ar–based mixtures [7], whose radiation length is one order of magnitude lower. The precision on the localization is 100 μm across the drift cell, and, by the charge division method, 1 cm along the wire. The two prisms are rotated by an angle of 11° and firmly held in position by a stiff Al structure (clepsydra). This geometry ensures the best acceptance for π^- of 250 $\div$ 280 MeV/c from reaction (3).

The last array of the tracking device consists of six layers of aluminized mylar straw tubes. There are three super-layers (one axial and two $\pm$ 12° stereo super-layers) each with two layers of staggered straws. The choice for this kind of detector was dictated by the fact that particles hit the last array of detectors with a large angle ($\geq 50°$). Extensive tests on prototypes showed excellent localization properties (better than 100 μm) [8].

A scintillator barrel (TOFONE) composed of 72 elements, 10 cm thick, encloses the tracking device: it is used for trigger purposes and is very useful in reducing the machine–induced background. Simulations based on calculated beam losses in the target region (mostly Touschek scattering) showed that this background would be lower than 1 Hz at $\mathcal{L}$ = 10^{32} $cm^{-2}s^{-1}$. Furthermore, TOFONE will detect neutrons emitted following the NM decay of the produced hypernuclei. The energy of neutrons (ranging up to $\sim$ 80 MeV) will be determined by time-of-flight, with a $\sim$ 500 ps FWHM time resolution and a $\sim$ 15%

efficiency. These features will allow an unprecedented step forward in the experimental study of these decays.

The Data Acquisition system will allow to write more than 200 events per second on tape.

None of the proposed sub-detectors is fully innovative, but each one exhibits some new performance or non-standard utilization: excellent HPD timing performance (Δt start-stop $\leq$ 1 ns), large LMDC safely and continuously operated with He-based mixtures [7], utilization of ISIM for $\Delta E/\Delta x$ measurements, first operation of a large array ($>$ 2400 elements) of straw tubes [8], full reliability of a large array of scintillators for neutron detection.

The present schedule of the FINUDA installation is the following:

- end 1996: completion of delivery and tests of all sub-detectors;
- mid 1997: delivery of the super-conducting solenoid to INFN National Laboratory of Frascati, installation of the apparatus in the pit;
- end 1997: end of the debugging of the apparatus with beam, start of data taking.

4. FINUDA PERFORMANCE

The momentum resolution of the apparatus is its most crucial feature. In fact, the momentum resolution of the π^- emitted in the hypernucleus formation is directly connected to the resolution of the hypernuclear energy levels. For a π^- of 270 MeV/c, an uncertainty of 0.1% in momentum corresponds to an energy resolution of 230 KeV on the hypernuclear level. Hence, to fulfill the physical expectations, FINUDA must feature not more than 0.3% FWHM in momentum resolution, which corresponds to $\sim$ 700 KeV in energy.

The design of the spectrometer, as described in Sec. 3, was largely driven by these considerations. Extensive simulations were carried out, with a Monte Carlo program based on the GEANE package, and with a very detailed description of all the elements of the spectrometer and of the sub–detectors response as determined by the experimental results on the prototypes. The momentum resolutions are evaluated to be 0.28% for π^- of 270 MeV/c, 0.79% for protons of 417 MeV/c (typical value for the NM decay [5]) and 0.24% for μ^+ of 236 MeV/c (they correspond to $K^+_{\mu 2}$ decay). As mentioned in Sec. 2, the thinness of the target allows the high momentum resolution of the spectrometer to be fully exploited. In any case, a correction of the pion momentum for the energy lost in the target can be efficiently applied, since both the K^- interaction point and the exit point of the π^- from the target can be reconstructed with an uncertainty of some hundreds of microns.

The aim of the trigger logic is to select hypernuclear events from background ones. In hypernuclear events, the ϕ decays in K^+K^-, the K^- stops in the target and forms a hypernucleus with emission of a prompt π^- (3). To be useful for high resolution spectroscopy, the π^- must cross the full spectrometer and, therefore, must produce hits on one or more slabs of TOFONE at the end of its trajectory. Background events are Bhabha scattering and other decays of the ϕ. Table 1 shows typical triggering efficiency for hypernuclear events and residual background contamination calculated by Monte Carlo simulation.

The trigger efficiency for hypernuclear events is very high and is limited essentially by the geometrical acceptance of the spectrometer.

Table 1
Trigger rates at $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}

	Hz
Hypernucleus formation ($10^{-3}/\mathrm{K}^-_{stop}$ capture rate)	$8{\cdot}10^{-2}$
Bhabha	$<4{\cdot}10^{-2}$
$\phi \rightarrow \mathrm{K}_S\mathrm{K}_L$	$5{\cdot}10^{-2}$
$\phi \rightarrow \rho\pi$	$2{\cdot}10^{-2}$
$\phi \rightarrow \pi^+\pi^-\pi^0$	10^{-3}
K^- interaction without hypernucleus formation	15

The background events are efficiently rejected and only the K^- interactions without formation of a hypernucleus produce an important rate. For these events the fast coincidence from TOFONE is, in general, provided by the detection of a μ^+ from $\mathrm{K}_{\mu 2}$ decay. The $\mathrm{K}_{\mu 2}$ events will provide a very useful continuous on–line calibration of the spectrometer with particles of well defined momentum.

Accounting for the percentage of triggered events for which the π^- is measured with high resolution ("forward" pions, not crossing the interaction region before entering the spectrometer) and assuming a chamber transparency of about 80%, the trigger rate of 8×10^{-2} Hz at $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1} provides about 80 events/hour useful for high resolution hypernuclear spectroscopy.

Last but not least, FINUDA will also allow a direct measurement of the lifetime of the different hypernuclei in the ground state. Assuming a time resolution of $\sim$ 500 ps FWHM, a Monte Carlo simulation has shown that, thanks to the large acceptance of the FINUDA apparatus for the hypernucleus decay products, the lifetime of a hypernucleus can be determined with a 10% statistical error with $\sim$2000 events reconstructed for the hypernucleus ground state peak. Assuming a production rate of $10^{-3}/\mathrm{K}^-_{stop}$, this number of events can be obtained in one day of data taking at $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}. More details on the performance of FINUDA can be found in [9–11].

5. OUTLOOK AND CONCLUSIONS

FINUDA will be installed in 1997 in DAΦNE and will be ready to start its large program of hypernuclear physics at the end of 1997. The main physics priorities of the experimental program can be briefly summarized as follows:

- the first item will be the re–measurement of the excitation spectrum (with resolution $<$1 MeV), decay modes and lifetime of ${}^{12}_{\Lambda}$C, which is one of the hypernuclei most extensively studied up to now.

- high statistics study of the production, decay and lifetime of the p–shell hypernuclei ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{10}_{\Lambda}$B. ${}^{6}_{\Lambda}$He will be studied too using a ^{6}Li target.

- high statistics survey of the production of higher mass hypernuclei, with ^{27}Al, ^{51}V, ^{133}Cs, ^{165}Ho and ^{209}Bi targets.

Finally, it is worth to notice that other physics issues will be studied, as a by–product of the hypernuclear physics data taking runs. The cross section for the

$$K^- + p \rightarrow K^0 + n \tag{10}$$

charge–exchange reaction never measured at momenta around 100 MeV/c and quite important for testing chiral symmetry theories, will be determined with a precision better than 5%. Furthermore the relative branching ratio $\Gamma(K^+ \rightarrow e^+\nu_e)/\Gamma(K^+ \rightarrow \mu^+\nu_\mu)$ will be measured with a statistical precision improved by at least a factor 3 [12].

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