Experiments at the DAΦNE ϕ–factory

The KLOE Collaboration †

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The Frascati e^+e^- collider, DAΦNE, operates at a center of mass energy of ~ 1020 MeV, the mass of the ϕ-meson. Three detectors have been realized, KLOE, DEAR, and FINUDA. The first two are presently collecting data in the two DAΦNE interaction regions (IR), while the third is being assembled in its pit inside the DAΦNE hall and will take data in the IR occupied by DEAR. The KLOE experiment, which is designed to measure CP and CPT violation parameters in the K_SK_L system, has collected so far ~ 300 pb^{-1}. Measurements obtained using the year 2000 data sample will be presented, which are focussed on K_S physics and ϕ radiative decays. The DEAR experiment aims at studying the scattering lengths of the kaon-nucleon system, through a precise measurement of the K_α line shifts in kaonic hydrogen and kaonic deuterium. With 2001 and 2002 data-taking periods the DEAR collaboration has demonstrated the capability of creating and detecting exotic atoms using the kaon flux from DAΦNE, by measuring the X-ray spectrum of kaonic nitrogen. The present status and perspectives of the DEAR experiment will be discussed. A brief report will be given at the end on the FINUDA physics program, aiming at the study of the Λ-hypernuclei levels and lifetimes.

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1. The Frascati ϕ–factory complex

The main physics interest motivating the construction of DAΦNE is the measurement of the CP-violation parameter ε'/ε using the KLOE detector. The accelerator will also have two other experiments, FINUDA and DEAR, aimed at performing high-precision measurements in nuclear and atomic physics, to operate sequentially.

DAΦNE is an e^+e^- collider, operating at a center of mass energy of $\sim$ 1020 MeV, the mass of the ϕ-meson. At the design peak luminosity of $5 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$, the machine will produce $\sim$ 1.5 kHz of ϕ-mesons. The DAΦNE complex consists of an injection system and a collider, composed by two main rings, in which electron and positron beams circulate separately. Two interaction regions (IR) house the experiments: KLOE on one side, DEAR on the opposite one.

The injection system is based on a 60 m long Linac, which accelerates electrons and positrons up to the nominal energy of 510 MeV. An intermediate 33 m long accumulator ring is used to damp the transverse and longitudinal emittances of the Linac beam, thus relaxing the injection requirements in the collider.

The strategy used to achieve a high luminosity, is based on accumulating high-current electron and positron beams (5 A at maximum), consisting of 120 bunches each. Two main rings are therefore needed in order to minimize perturbations due to beam-beam electromagnetic interactions. The beams intersect at the two IR's with a horizontal crossing angle of $\sim$ 25 mrad, thus the ϕ's will be produced with a small momentum ($P_\phi \sim$ 13 MeV/c) in the laboratory frame.

In the present running conditions, DAΦNE peak luminosity is $5.5 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$, still an order of magnitude less than the design value. This is obtained with $\sim$ 800 mA circulating beam currents. The luminosity delivered to KLOE is on average 2.5 pb^{-1} per day (3 pb^{-1} at maximum), while 1 pb^{-1} only is integrated by DEAR. This difference is due to KLOE being able to operate in the "top-up" injection mode, *i.e.* injecting electrons and positrons with colliding beams every fifteen minutes. This mode of operation is well suited for DAΦNE, because of its short beam lifetimes, which are reflected in a steep drop-off of the luminosity with time.

KLOE had three different data-taking periods: the first was in 1999, mostly spent in machine and detector commissioning. In year 2000 the machine delivered to KLOE a total of 23 pb^{-1}, which has produced the first batch of published results. In year 2001 a total integrated luminosity of 180 pb^{-1} has been collected. Further improvements are expected in year 2002; data taking has resumed in May with comparable luminosity but with much improved machine background conditions, which is another key issue for many physics measurements. A total of 90 pb^{-1} has been integrated up to June; a reasonable expectation is to reach 300 pb^{-1} at the end of the data-taking period.

The DEAR experiment collected the first useful data sample during year 2001, consisting of 2 pb^{-1}. Big improvements have been achieved in the performances of the DAΦNE-DEAR setup, which allowed them to acquire 20 pb^{-1} during April 2002.

2. The KLOE experiment

The KLOE scientific program [1] is focussed on the study of CP and CPT symmetries with neutral kaons. These will be studied via the "double ratio" and by looking at the quantum-mechanical interference patterns in the $K_S K_L$ system [2]. To reach accuracies of the order of 10^{-4}, an integrated luminosity in the range of several fb^{-1}'s is needed. Meanwhile, a lot of topics are within the present statistical reach. The analysis on the year 2000 data set has produced new results on the ϕ radiative decays into scalar (f_0, a_0) and pseudoscalar (η, η') mesons, on the K_S semileptonic decay, and on the ratio of K_S decays into charged and neutral pion pairs. Using the year 2001 data set (180 pb^{-1}), the goal is to improve the accuracy on the Cabibbo angle (V_{us}) through a precise measurement (0.5%) of K_L and charged kaon semileptonic decays; a 0.6% measurement of the e^+e^- hadronic cross section below 1 GeV using the radiative return, and several measurements of rarer K_S and K_L decays.

The KLOE detector [3] has been designed to maximize the number of reconstructed K_L decays. It consists of a large tracking chamber, a hermetic electromagnetic calorimeter and a superconducting magnet providing a solenoidal field of ∼0.52 T. The beam pipe in the interaction region is spherical in shape, 10 cm in radius, and made of an Aluminum-Beryllium alloy.

The large, 2 m radius and 3.7 m long, tracking volume is instrumented with a drift chamber [4] operating with a low-Z, 90%He-10%iC_4H_{10} gas mixture, enclosed by Carbon-fiber/Epoxy walls. The light A, Z materials have been chosen to optimize the chamber resolution, and to reduce both the photon conversions (0.01 X_0) and $K_L \to K_S$ regeneration. The 58 concentric layers of wires (52140 wires, 12582 readout channels) are strung in an all-stereo geometry. The momentum resolution is $\sigma(p_\perp)/p_\perp \simeq 0.4\%$, from a single measurement resolution of $\sigma_{r\phi} \sim 150$ μm (σ_z ∼2 mm).

The electromagnetic calorimeter [5] is a sampling calorimeter made of lead and scintillating fiber layers, 15 X_0 thick. The solid angle coverage (98%) is ensured by barrel modules surrounding the drift chamber and by modules of two endcaps, which are bent outwards to eliminate dead zones in the overlap region between barrel and endcap. The calorimeter modules are read out at the two ends by a total of 4880 photomultipliers. The calorimeter has been designed to measure time and energy for photons of energy as low as 20 MeV, with resolutions of 54 ps/$\sqrt{E} \oplus 50$ ps (E in GeV) in time and 5.7%/$\sqrt{E}$ in energy.

2.1. K_S physics results

Neutral kaons at a ϕ–factory are produced in a coherent $J^{PC} = 1^{--}$ quantum state, which is a superposition of $K_S K_L$ states with opposite momenta. This allows the tagging of pure and almost monochromatic kaon beams: the detection of a K_L (K_S) tags the presence of a K_S (K_L) in the opposite hemisphere of the apparatus. In particular, a very robust K_S tag is provided by the interactions of K_L in the calorimeter: in about 30% of the cases the K_L does not decay in the detector, reaches the calorimeter barrel and interacts therein. A time-of-flight measurement then allows a clean selection of these interactions since $\beta_{K_L} \sim 0.218$. Results from the 2000 data set come from 5.4×10^6 tagged K_S.

Two topics have been addressed: the first one is the measurement of the ratio $BR(K_S \to \pi^+\pi^-(\gamma))/BR(K_S \to \pi^0\pi^0)$ with 0.7% accuracy, which is a step towards the determination of $Re(\varepsilon'/\varepsilon)$ with the double ratio method. This precise measurement of the single ratio is also relevant for the extraction of the isospin $I = 0$, $I = 2$ amplitudes and phases, since soft radiation emitted in $\pi^+\pi^-\gamma$ decays is correctly taken into account. The second result is the measurement of $BR(K_S \to \pi^\pm e^\mp \bar{\nu}(\nu))$ with 5% accuracy, based on the largest sample collected so far. The study of semileptonic decays allows one to perform a test of the $\Delta S = \Delta Q$ rule validity, by comparing K_S and K_L decay rates integrated on the final lepton charge. To improve the present limits on $Re(x)$ [6], it is necessary to reach 2% accuracy on the measurement of the K_S semileptonic branching ratio. This will be accomplished by KLOE when the ongoing analysis over the whole 2001 data sample will be concluded.

From the sample of tagged K_S decays the ratio of $\pi^+\pi^-(\gamma)$ and $\pi^0\pi^0$ branching ratios is extracted by selecting two categories of events: 2 tracks from the IR for $\pi^+\pi^-$ decay mode, and at least three prompt photons for the $\pi^0\pi^0$. While the selection acceptance has been evaluated from the Monte Carlo simulation, all other efficiencies, such as the track reconstruction efficiency and the photon detection efficiency have been evaluated from data sub-samples.

Moreover, special care has been devoted in the assessment of the $\pi^+\pi^-(\gamma)$ selection efficiency as a function of the center of mass photon energy E^*_γ, from zero to the maximum allowed energy of ∼170 MeV. In order to perform a fully inclusive measurement, the selection efficiency has been evaluated from Monte Carlo and folded into the theoretical E^*_γ spectrum [7]. The corrected ratio is then [8]:

$$BR(K_S \to \pi^+\pi^-(\gamma))/BR(K_S \to \pi^0\pi^0) = 2.236 \pm 0.003_{\mathrm{stat}} \pm 0.015_{\mathrm{syst}}.$$

The selection of semileptonic $K_S \to \pi e \nu$ candidate events also starts from the sample tagged by the K_L interactions in the calorimeter: events are selected by requiring two tracks of opposite charge forming a vertex near the IR. A cut on the two tracks invariant mass is applied to reduce $K_S \to \pi^+\pi^-$ background. Semileptonic events are then identified on the

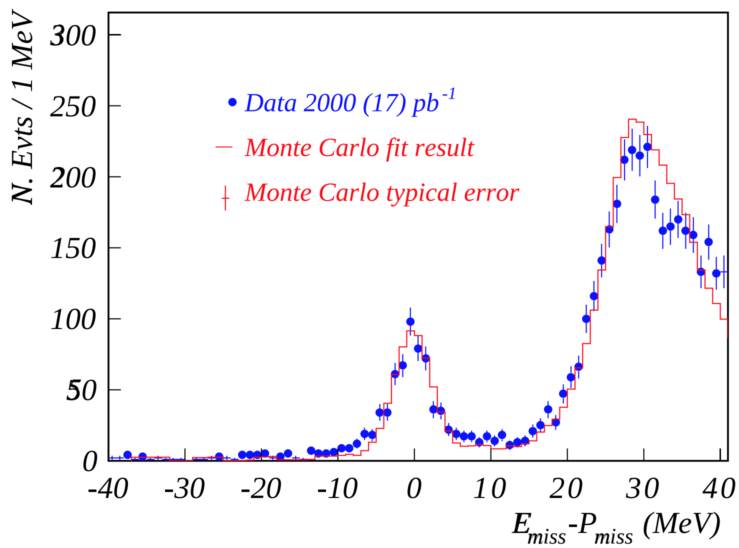

Fig. 1. K_S semileptonic decay: the experimental spectrum for $E_{miss} - p_{miss}$ shows a clear peak at zero, corresponding to $K_S \to \pi e \nu$ decays; a maximum likelihood fit with the Monte Carlo signal+background ($K_S \to \pi^+\pi^-$) shapes is superimposed.

basis of π/e assignment using the time-of-flight measurement for the two tracks. The K_L cluster gives an estimate of the K_S momentum, thus allowing the kinematic closure of the event. The difference between the missing energy and the missing momentum at the vertex is finally computed; such a difference should be zero for $K_S \to \pi e \nu$ decays. The $E_{miss} - p_{miss}$ spectrum is shown if Fig. 1, together with a fit to the sum of Monte Carlo simulations of the signal and $K_S \to \pi^+\pi^-$ background. The free parameters of the fit are the signal/background normalization and the signal yield, giving 627±30 events.

Correcting by all the selection and detection efficiencies, and normalizing to the number of observed $K_S \to \pi^+\pi^-$ events, the measured branching ratio is [9]:

$$BR(K_S \to \pi^\pm e^\mp \bar{\nu}(\nu)) = (6.91 \pm 0.34_{\rm stat} \pm 0.15_{\rm syst}) \cdot 10^{-4}$$

in agreement with the expected value $(6.70 \pm 0.07) \cdot 10^{-4}$ assuming the validity of $\Delta S = \Delta Q$ rule [6].

2.2. Results on ϕ radiative decays

The radiative decays of the ϕ meson offer a probe to study the nature of light scalar and pseudoscalar mesons.

In the pseudoscalar sector, the magnitude of the $\phi \to \eta'\gamma$ decay is sensitive to the $s\bar{s}$ and gluonium content of the η', while the ratio $BR(\phi \to$

$\eta'\gamma)/BR(\phi \to \eta\gamma)$ is related to the pseudoscalar mixing angle φ_P in the flavor basis [10].

$\phi \to \eta'\gamma$ events are selected using the decay chain $\eta' \to \eta\pi^+\pi^-$, $\eta \to \gamma\gamma$; the η from $\phi \to \eta\gamma$ is identified using the $\pi^+\pi^-\pi^0$ channel. In both cases the same final state $\pi^+\pi^-\gamma\gamma\gamma$ is observed, thus allowing the cancellation of many systematic effects in the measurement of the ratio of branching ratios. A good separation between the $\eta'\gamma$ and the dominant $\eta\gamma$ events is achieved by exploiting the fact that the radiative photon has much more energy in $\eta\gamma$ events ($\sim$ 360 MeV) than it has in $\eta'\gamma$ decays ($\sim$ 60 MeV). After having removed the $\eta\gamma$ sample, the $\pi\pi\gamma\gamma$ invariant mass distribution,

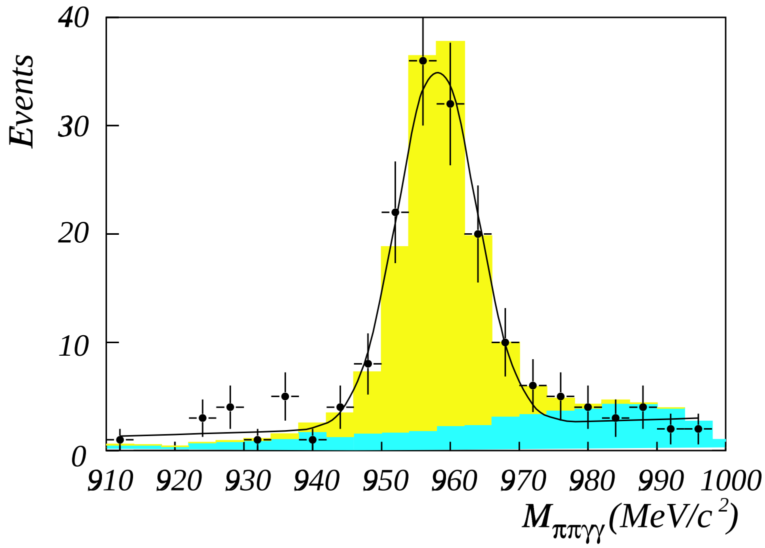

Fig. 2. $\phi \to \eta'\gamma$ decay: distribution of the $M_{\pi\pi\gamma\gamma}$ invariant mass, after removal of the $\eta\gamma$ identified events; the estimated residual background is also shown.

shown in Fig. 2, peaks at the η' mass value, with very low background: the number of signal events is $124 \pm 12_{\text{stat}} \pm 5_{\text{syst}}$. The ratio of branching ratio is then obtained by normalization to the $\eta\gamma$ observed events and by taking into account secondary BR's [6] and detection efficiencies [11]:

$$BR(\phi \to \eta'\gamma)/BR(\phi \to \eta\gamma) = (4.70 \pm 0.47_{\text{stat}} \pm 0.31_{\text{syst}}) \cdot 10^{-3}.$$

The corresponding value for the pseudoscalar mixing angle is $\varphi_P = (41.8^{+1.9}_{-1.6})^\circ$. Making use of the $\phi \to \eta\gamma$ branching ratio [6] we obtain:

$$BR(\phi \to \eta'\gamma) = (6.10 \pm 0.61_{\text{stat}} \pm 0.43_{\text{syst}}) \cdot 10^{-5},$$

which is the most precise determination to date. This results limits the gluonium content in the η' state to be less than 15%.

Turning to the scalar sector, the radiative decays $\phi \to a_0\gamma$, $\phi \to f_0\gamma$ are sensitive to the nature of the f_0 and a_0 mesons [12]. The three main hypotheses for these states are $q\bar{q}q\bar{q}$, $K\bar{K}$ molecules, or ordinary $q\bar{q}$. The various models can be disentangled by precise measurements of the ϕ radiative decay branching ratios and of the scalar meson mass spectra.

The $\phi \to f_0\gamma$ and $\phi \to a_0\gamma$ events are detected in KLOE by the decay chains $f_0 \to \pi^0\pi^0$ and $a_0 \to \eta\pi^0$ with $\eta \to \gamma\gamma$, both yielding a five photon final state. In the case of a_0, the secondary decay $\eta \to \pi^+\pi^-\pi^0$ has been also exploited, giving a final topology with two tracks and five photons.

The $M_{\pi^0\pi^0}$ and $M_{\eta\pi^0}$ spectra are reconstructed for selected events (see Fig. 3 for the $M_{\eta\pi^0}$ case). The observed distributions are used to evaluate

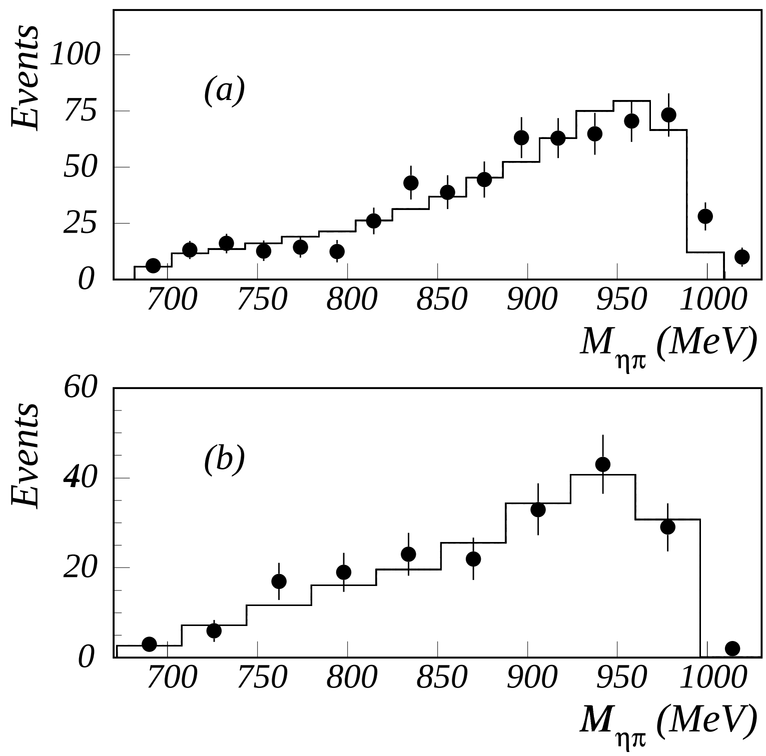

Fig. 3. $\phi \to \eta\pi^0\gamma$: $M_{\eta\pi}$ invariant mass distributions for two different samples: five photons sample (a), and five photons and two tracks sample (b), both for data (points) and Monte Carlo fit (histogram).

the branching ratios [14, 15], after having normalized the events to the ϕ production cross section, as measured in the $\phi \to \eta\gamma$ ($\eta \to \gamma\gamma$) three photon process:

$$BR(\phi \to \pi^0\pi^0\gamma) = (10.9 \pm 0.3_{\rm stat} \pm 0.5_{\rm syst}) \cdot 10^{-5}$$

$$BR(\phi \to \eta\pi^0\gamma, \eta \to \gamma\gamma) = (8.51 \pm 0.51_{\text{stat}} \pm 0.57_{\text{syst}}) \cdot 10^{-5}$$
$$BR(\phi \to \eta\pi^0\gamma, \eta \to \pi^+\pi^-\pi^0) = (7.96 \pm 0.60_{\text{stat}} \pm 0.40_{\text{syst}}) \cdot 10^{-5}$$

where the η decay BR's in the $\eta\pi^0\gamma$ final states have been scaled according to Ref. [6]. The above values include possible contributions from the resonant decay $\phi \to \rho\pi^0$, followed by $\rho \to \pi^0\gamma$ or $\rho \to \eta\gamma$. In order to extract the f_0 and a_0 parameters from the mass spectra, a fit has been performed on the $M(\pi^0\pi^0)$ and $M(\eta\pi^0)$ distributions respectively. The model spectrum is taken as the sum of $f_0\gamma$ ($a_0\gamma$), $\rho\pi$ and interference terms. For the scalar meson contribution the formulation of Ref. [12] is used, which is based on ϕ coupling to a charged kaon loop. The vector meson term is taken from VMD calculations [13]. As a result, the contribution from the $\rho\pi$ final state turns out to be negligible in both cases; moreover, a good fit to the $M(\pi^0\pi^0)$ spectrum can only be obtained including together with the f_0 a contribution from another light scalar meson (σ) and a strong negative interference term between the two. Branching ratios are finally obtained for the f_0 final state [14]:

$$BR(\phi \to f_0\gamma, f_0 \to \pi^0\pi^0) = (14.9 \pm 0.7) \cdot 10^{-5},$$

and for the a_0 final state [15]:

$$BR(\phi \to a_0\gamma, a_0 \to \eta\pi^0) = (7.4 \pm 0.7) \cdot 10^{-5}.$$

KLOE results on the scalar mesons, based on the 2000 data sample, are compatible with the four quarks model in the case of the f_0, while do not agree with the same model in the case of a_0 decay.

3. The DEAR experiment

The DEAR (DAΦNE Exotic Atom Research) experiment [16] aims at measuring X-rays from kaonic hydrogen and kaonic deuterium, using the "K^- beam" from the decay of ϕ's produced at DAΦNE, a cryogenic pressurized gaseous target and Charge-Coupled Devices (CCDs) as X-ray detectors. The physics goal is the determination of the isospin dependent kaon-nucleon scattering lengths through a 1% measurement of the K_α line shift in kaonic hydrogen, and a few percent measurement of its width. The first measurement of kaonic deuterium could also be made. The main advantages of the DEAR experimental approach are:

- the low momentum, monochromatic, high purity and intense kaon beam from DAΦNE;
- the resolution and, above all, the background rejection of CCDs;
- the use of a moderate-density target to reduce the Stark mixing.

In May 2001 the capability of creating and detecting exotic atoms has been tested, by measuring the X-ray spectrum of kaonic nitrogen. This measurement was performed with a cryogenic target (118 K) filled with nitrogen at 2 bar ($\rho \sim 4.5\rho_{NTP}$). As detector, 8 CCD-22's were used. A total integrated luminosity of 2 pb^{-1} was collected. The global fit [17] performed on the X-ray spectrum gave a poor statistical significance ($\sim 3\sigma$) on the two kaonic nitrogen lines measurable with DEAR (4.6 keV and 7.6 keV). The signal-to-noise ratio was as low as S/B = 1/50.

The test was repeated in April 2002 with an improved setup, equipped with 16 CCD-55's, with additional external and internal shieldings, which garantueed a higher efficiency ($\times 2$) and a lower background ($\times 0.3$). Further background reduction ($\times 0.3$) resulted from a new machine configuration, with additional scrapers and a new low-β optics for collisions in DEAR IR. Preliminary results based on 5 pb^{-1}, from a total sample of 20 pb^{-1} collected, gave a clear evidence for kaonic nitrogen lines (N(4.6 keV)$\sim$900, N(7.6 keV)$\sim$1500), with S/B $>$ 1/10.

Next stage of the experiment will be the X-ray spectrum measurement on kaonic hydrogen. From simulation, a 5-7% precision on KH K_α line is expected by integrating 50 pb^{-1} in the same experimental conditions (S/B $>$ 1/10). Such a measurement can be done before the next machine shutdown, scheduled for the end of 2002.

4. The FINUDA experiment

The FINUDA experiment [18] plans to study the physics of Λ-hypernuclei, by using the low energy (16 MeV) K^- beam from the decay of ϕ's produced at DAΦNE. The hypernuclei are formed through the reaction

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

The main advantage of using low energy kaons is the possibility to stop them using very thin targets. The prompt π^- is then minimally degraded, allowing a high resolution spettroscopy. Moreover, since the K^- are emitted isotropically all around the azimuth angle, and with a $\sin^2\theta$ distribution respect to the beam axis, high counting rates can be achieved by employing a cylindrical spectrometer with large geometrical acceptance.

The FINUDA spectrometer is equipped with a superconducting solenoid providing a 1.1 T field, with 2.7 m diameter and 2.4 m length. Starting from the beam pipe, we find a barrel of thin scintillator slabs, which is used to select the slow charged kaons by determining their energy loss and topology. Going outwards, there are two layers of Si microsptrip detectors with 20 μm resolution, both in z and ϕ coordinates. Charged kaons are stopped in a thin target located between the two Si layers, and consists of a cylindrical array of eight independent slabs. The inner Si microstrip layer will provide very accurate information on the impinging point of charged kaons on the target, while the outer detector will measure precisely the first point of the trajectory of the outgoing prompt π^- from hypernucleus formation. The tracking region is composed of two layers of planar, low-mass drift chambers and a multilayered, stereo array of long straw tubes. All detector is immersed in a helium atmosphere, in order to reduce the multiple scattering. The overall momentum resolution is 0.3% for 270 MeV/c pions, which allows them to achieve a 700 keV resolution on hypernuclei levels. All the sub-detectors, except the vertex region, have been instrumented and are presently under test with cosmic rays. During the winter shutdown the central region (beam pipe, inner TOF, μ-strips) will be installed, and the detector will be ready for data taking in the DEAR interaction region at the year 2003 machine restart.

The counting rate, due to the detector's large acceptance, allows to perform high quality spectroscopy studies by integrating 50 pb^{-1} on a set of ^{12}C, ^{27}Al, ^{58}V and ^{6}Li targets (with a production yield of $10^{-3}/K^-_{stop}$). Moreover, the study of the non-mesonic hypernuclear decay, both into the pn and nn channels, will be performed with 7% statistical accuracy by integrating 80 pb^{-1} and 290 pb^{-1} respectively. With the present DAΦNE performances, these physics goals can be accomplished with one year of data taking.

5. Conclusions and future perspectives

- DAΦNE performance has improved considerably during the first two years of data taking: delivered luminosity is now ~ 3 pb^{-1} per day in the KLOE IR, and ~ 1 pb^{-1} per day for DEAR. A big effort is under way in order to achieve a substantial background reduction. Major interventions are scheduled for the winter shutdown: FINUDA experiment roll-in; the installation of a new interaction region for collisions in KLOE, with the goal of reaching the design peak luminosity of 5×10^{32}cm^{-2}s^{-1}. This would allow us to perform CP and CPT studies starting from 2003-2004 data-taking periods.

- The KLOE detector is performing well and is completely understood. From the 2000 data sample (~ 23 pb^{-1}) results have been published on K_S decays and on ϕ radiative decays, which improve previous "PDG" values. Analysis on 2001 data sample (~ 180 pb^{-1}) is in progress.

- DEAR setup has been greatly improved, both from the detector's and from the machine's point of view. Preliminary results have been recently presented, showing a clear signature for the kaonic nitrogen X-ray lines. The collaboration aims at performing the measurement of the kaonic hydrogen K$_\alpha$ line with 5-7% precision by integrating a reasonable amount of luminosity (~ 50 pb^{-1}) before the end of 2002.

- FINUDA detector is ready for roll-in, which is scheduled for the end of the 2002.

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