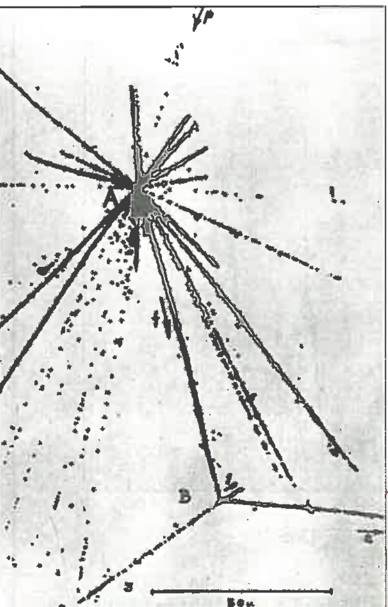
The physics of hypernuclei

Aldo Zenoni, Università di Brescia and INFN Sezione di Pavia, Brescia, Italy
Paola Gianotti, INFN Laboratori Nazionali di Frascati, Frascati, Italy

Hypernuclear physics was born 50 years ago, in 1953, when the Polish physicists M. Danysz and J. Pniewski [1] observed, in a stack of photographic emulsions exposed to cosmic rays at around 26 km above the ground, the event shown in Figure 1. A high energy proton, colliding with a nucleus of the emulsion, breaks it in several fragments forming a star. All the nuclear fragments stop in the emulsion after a short path, but one disintegrates, revealing the presence inside the fragment, stuck among the nucleons, of an unstable particle decaying weakly, the Λ hyperon. For this reason, this partic0ular nuclear fragment, and the others obtained afterwards in similar conditions, were called hyperfragments or hypernuclei.

The Λ hyperon is a baryon, like the nucleons (proton and neutron), with mass 1115.684 ± 0.006 MeV/c^2, 20% greater than the mass of the nucleon, zero charge and isospin I=0. It carries a new quantum number, not contained normally inside the nuclei, the strangeness $S = -1$. The Λ hyperon is unstable and decays with lifetime 263 ± 2 ps, typical of the weak interaction that doesn't conserve strangeness and makes a free Λ mainly disintegrate in a nucleon-pion system.

However, since strangeness is conserved in the strong interaction and the Λ particle is the lighter particle in the family of hyperons (baryons with strangeness), it can stay in contact with nucleons inside nuclei and form hypernuclei. The mere existence of hypernuclei is of great scientific interest; it gives indeed a new dimension to the traditional world of nuclei by revealing the existence of a new type of nuclear matter and generating new symmetries, new selection rules, etc. Hypernuclei represent the first kind of *flavoured* nuclei (with new quantum numbers), in direction of other exotic nuclear systems (charmed nuclei and so on).



◄ **Fig. 1:** The first hypernuclear event observed in a nuclear emulsion [1]. (A) indicates the star of the primary interaction of the high energy cosmic ray (p) colliding with a nucleus of the emulsion; (f) is the track of the produced hyperfragment; (B) is the vertex of the decay of the hyperfragment. The other non-strange nuclear fragments stop in the matter.

A hypernucleus is generally indicated with the symbol of the parent nucleus with the suffix Λ, indicating that a Λ particle has replaced a neutron. $^{12}_{\Lambda}C$ means a nuclear system composed of 6 protons, 5 neutrons and one Λ particle. Three events of double hypernuclei were observed, in which 2 nucleons are substituted by 2 Λ particles. One example is $^{6}_{\Lambda\Lambda}He$, a system composed of 2 protons, 2 neutrons and 2 Λ particles.

The concept of hypernuclei can be extended to nuclei where a nucleon is replaced by hyperons other than the Λ one. Experimental evidence was claimed of the existence of Σ-hypernuclei, in which a nucleon is replaced by a Σ hyperon. This is rather surprising since, in nuclear matter, the Σ can decay through a strong interaction process ($\Sigma + N \rightarrow \Lambda + N$) giving very large widths for the hypernuclear states, unless a strong suppression mechanism is at work. However, the experimental evidence of the existence of narrow Σ-hypernuclei is rather controversial and only the case of $^{4}_{\Sigma}He$ is considered unambiguous.

After the very first evidence of hyperfragments in cosmic ray interactions with nuclei, starting from the end of the Sixties, the installation of beams of K^- mesons at particle accelerators made it possible to study the formation of hypernuclei in the laboratory. Hypernuclei were produced copiously with little background, the required negative strangeness for Λ hyperon production being present in the beam. The typical reaction utilized was the "*strangeness exchange reaction*", where a neutron hit by a K^- is changed into a Λ hyperon emitting a π^- ($K^- + n \rightarrow \Lambda + \pi^-$). The experimental techniques used in these experiments were photographic emulsions and bubble chambers (filled with *He* or heavy liquids) exposed to K^- beams. These experiments mainly measured the hyperon binding energies, by means of the kinematical analysis of the disintegration star, and observed the principal decay modes of the hypernuclei.

Starting from the Seventies, the study of hypernuclei was continued with K^- beams by means of counter techniques with magnetic spectrometers and the introduction of new particle detectors (multiwire proportional chambers and drift chambers). The identification of well defined excited hypernuclear levels, by means of the kinematical analysis of the production reaction, was one of the most important results of a first series of experiments started at CERN and continued at Brookhaven (USA). The physical interpretation of these spectra was possible in terms of microscopic descriptions of the Λ-nucleus and Λ-nucleon potentials.

In the Eighties, a new technique for hypernucleus production was introduced at the Brookhaven laboratory, by means of intense beams of high energy π^+. With this technique the Λ hyperon is produced inside the nucleus by an "*associated production reaction*" ($\pi^+ + n \rightarrow \Lambda + K^+$). This reaction has a reduced cross section, compared to the "*strangeness exchange*" reaction, however this drawback is over compensated by the greater intensities of the π^+ beams. The technique was fully exploited at the KEK laboratory in Japan where, for more than ten years, a great wealth of excellent hypernuclear data were produced, concerning both spectroscopy and decay of hypernuclei.

The interest in these new data has triggered the attention of the nuclear physics community and, in the last few years, different laboratories around the world have started a hypernuclear physics program: COSY at Jülich in Germany, TJNAF at Newport News in USA, Nuclotron in Dubna (Russia). In particular, it is worth mentioning the Italian hypernuclear project, the FINUDA experiment (acronim of FIsica NUcleare a DAϕne) at the Laboratori Nazion-

features

ali di Frascati of INFN, which is going to start collecting data next year. The experiment, which has an ambitious physics program, has some special features compared to traditional hypernuclear physics experiments. In fact, interestingly enough, it will operate at a e^+e^- collider, rather than on an extracted beam. What follows will describe it in some detail.

Structure of Λ–hypernuclei

A Λ-hypernucleus ${}^{A}_{\Lambda}Z$ is a bound state of Z protons, (A-Z-1) neutrons and a Λ hyperon. The ground state of such a system is made by the (A-1) nucleons accommodated in the ground state of the nucleus ${}^{(A-1)}Z$ and the Λ hyperon in its lower energy state. The Λ hyperon, carrying the strangeness quantum number, is a distinguishable baryon and is not subject to the limitations imposed by the Pauli principle, therefore it can occupy all quantum states already filled up with nucleons. This feature makes the Λ hyperon, embedded in a hypernucleus, a unique means to explore nuclear structure.

The binding energy B_Λ of a Λ particle in the hypernucleus ${}^{A}_{\Lambda}Z$ in its ground state is defined as:

$$B_\Lambda = M_{core} + M_\Lambda - M_{hyp}$$

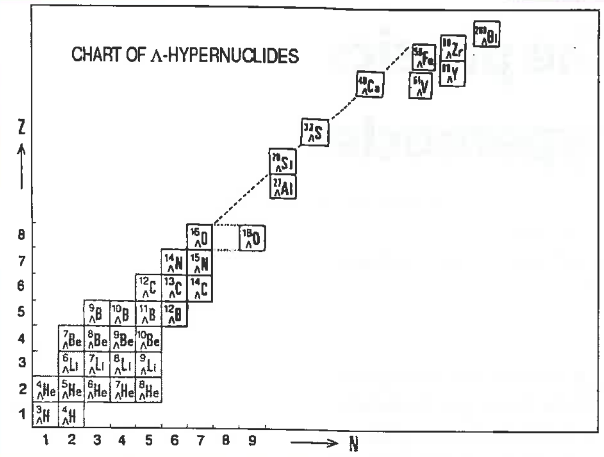
where M_{core} is the mass (in MeV/c^2) of the nucleus ${}^{(A-1)}Z$, M_Λ is the mass of the Λ particle and M_{hyp} the mass of the hypernucleus ${}^{A}_{\Lambda}Z$, experimentally measured. B_Λ varies linearly with A with a slope of about 1 MeV/(unit of A) and saturates at about 23 MeV for the heavy hypernuclei. This behavior suggests a simple model in which the Λ particle is confined in a potential well with a radius equal to the nuclear radius and a depth of 28 MeV, to be compared to the 55 MeV typical value of the nucleon potential well.

This is consistent with a Λ-nucleon interaction weaker than the nucleon-nucleon one. Indeed, in a meson exchange model of the interaction, the zero isospin of the Λ prevents the exchange of isovector mesons like the π or the ρ with a nucleon and determines the lack of strong tensor components in the interaction. The relative weakness of the Λ-nucleon interaction entails that the shell structure is not disrupted by the insertion of the Λ in the nucleus and the lack of Pauli effects allows all the nuclear single particle states to be populated by the Λ. In Figure 2, the so called "*Segrè table*" of the hypernuclei shows the 35 hypernuclei known at present.

Experiments of hypernucleus production by "*strangeness exchange*" and "*associated production*" processes can produce hypernuclei in which the Λ populates different single particle states. The latter technique is particularly suitable for populating low lying Λ states, thanks to the high recoil momentum transferred to the Λ particle in the reaction.

A beautiful representation of this process is given in Figure 3, where the excitation spectrum of ${}^{89}_{\Lambda}Y$, obtained by the "*associated production*" reaction ${}^{89}Y(\pi^+, K^+)\,{}^{89}_{\Lambda}Y$ at the KEK laboratory in Japan, is shown. The spectrum demonstrates how, starting from a neutron in the $g_{9/2}$ state, it is possible to accommodate a Λ particle in the hypernuclear states f, d, p and even in the ground state s.

These measurements constitute the spectacular confirmation, at a textbook level, of the validity of the independent particle model or shell model of the nucleus. In non-strange nuclei, the observation of single particle states is only possible for the states of the most external nucleon orbits. In fact, due to the Pauli principle and pairing interactions, deeply bound nucleon single particle states are so fragmented as to be essentially unobservable. The present experimental data on hypernuclear binding energies and detailed spectroscopic features are limited in quantity and

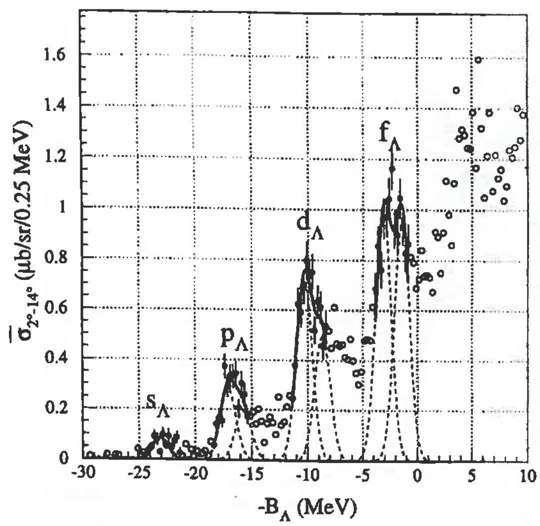


▲ **Fig. 2:** *"Segrè table"* of the 35 known Λ-hypernuclei. The hypernucleus is formed by Z protons, N neutrons and a Λ hyperon.

quality, due to the limited beam intensities available for hypernuclear studies from the existing facilities and the modest energy resolution of the present experiments. Nevertheless, the gross features of the data are reasonably well reproduced by effective one-body hyperon-nucleus interactions constructed on potential models of the hyperon-nucleon *YN* interaction.

The starting point of these models is a good *NN* interaction generated by the exchange of nonets of mesons, with SU(3)$_f$ constrainst for the coupling constants. Their predictions are fitted simultaneously to the abundant *NN* data and the very scarce *YN* free scattering data. However, until now, it has not been possible to obtain a reliable and unambiguous *YN* interaction model.

The improvement of the *YN* interaction models would need precise data on the free *YN* interaction, which are very difficult to



▲ **Fig. 3:** Hypernuclear mass spectrum of ${}^{89}_{\Lambda}Y$ obtained at KEK by the E369 experiment, with an energy resolution of 1.65 MeV. The bump structures correspond to the Λ major shells orbits (s, p, d, f) in the bound region. The widths of the bumps for the p-, d- and f-orbits are significantly wider than the experimental resolution and the peak for the f$_\Lambda$-orbit is split into two peaks.

obtain, due to low hyperon beam intensities and short lifetimes of the hyperons. In particular, production and scattering in the same target are almost automatically required. At present, the experimental data on ΛN and ΣN scattering consist of not more than 850 scattering events, in the momentum region from 200 to 1500 MeV/c. The low energy data, in particular, fail to adequately define even the relative sizes of the dominant s-wave spin-triplet and spin-singlet scattering lengths and effective ranges.

This is the reason why a systematic and detailed spectroscopic study of hypernuclei with high resolution experiments, with single and even multiple strangeness contents, would offer the possibility of increasing the experimental information on *YN* interaction and, for the first time, allow both the study the dynamics of systems carrying $SU(3)_f$ flavour symmetry, in the non-perturbative QCD sector, and the generalization of the baryon-baryon interaction to the full $SU(3)_f$ family, including hyperons [2].

The spin dependent parts of the *YN* interaction are of major interest, since they are intimately related to the modelling of the short-range part of the interaction. In particular, for the ΛN interaction, the spin-orbit interaction was found to be smaller than that for the nucleon, which amounts to 3-5 MeV. In fact, experiments based on the hypernucleus formation kinematics, with the best energy resolution on the nuclear levels achieved until now of 1.5 MeV, were not able to measure any spin-orbit splitting.

Calculations of the spin-orbit component of the ΛN interaction using meson exchange theories, lead to predictions of the spin orbit splitting, for the $5/2^+$-$3/2^+$ doublet in ${}^9_\Lambda Be$, of 80-160 keV, depending on the interaction used [3]. On the other hand, when a quark model based spin-orbit force is used, which naturally accounts for the short range part of the interaction, much smaller values of 30-40 keV are obtained. The two types of models, in fact, predict different features for the antisymmetric part of the spin-orbit force. However, it needs to be said that quark models have yet to provide an extensive and satisfactory description of the *YN* interaction.

Figure 4 reports a recent measurement of the splitting of the $5/2^+$-$3/2^+$ doublet in ${}^9_\Lambda Be$ by the BNL-AGS E930 experiment [4], measuring γ rays emitted in the nuclear transitions with the new germanium detector array Hyperball. This new technique allowed the energy resolution on low lying hypernuclear levels to be improved from a few MeV to a few keV, even if the count rate resulting is still quite low, ~200 γ's per month of data taking. The spacing of the two levels was measured to be 31 ± 2 keV, incompatible with the prediction of the meson exchange models.

At KEK the spin orbit splitting of the $3/2^-$–$1/2^-$ doublet in ${}^{13}_\Lambda C$ was measured, though with a coarse resolution on γ rays [5], and a doublet spacing of 152±54(*stat*)±36(*syst*)keV was determined. The splitting predicted for this transition by meson exchange models is 390-780 keV, depending on the interaction used, and 150-200 keV by quark based models [3].

Nevertheless, other recent spectroscopic data seem to suggest a larger spin-orbit level splitting on heavy hypernuclei, especially at large values of the Λ angular momentum. The spectrum reported in Figure 3 for ${}^{89}_\Lambda Y$ is an example; it shows a splitting of the f_Λ level and the width of the other levels broader than the instrumental energy resolution.

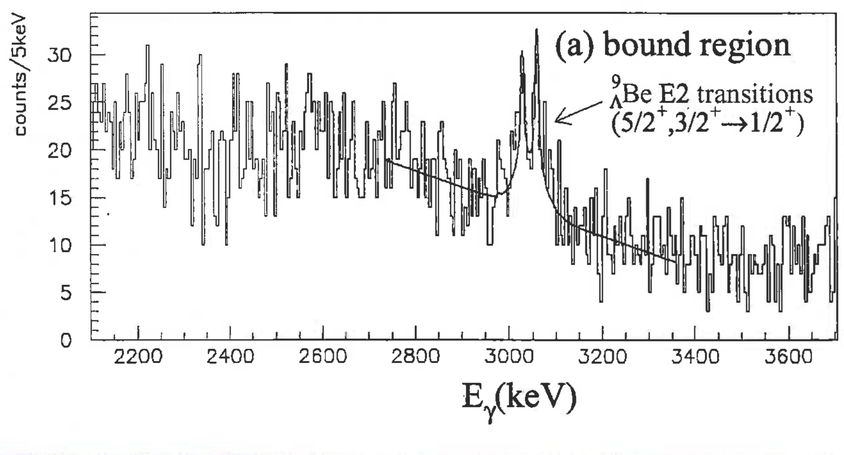
The meson exchange models constitute the best description available, at present, for the strong interaction at low energy. The question whether they should be modified with the inclusion of explicit quark effects remains open.

Decay of Λ-hypernuclei

In addition to information on nuclear structure and the *YN* interaction, hypernuclei may give access to experimental information not otherwise accessible by their decays, in particular the non-mesonic decay. Let us recall that a free Λ hyperon decays almost totally into a pion and a nucleon ($\Lambda \to p\pi^-(\approx 64\%)$, $\Lambda \to n\pi^0(36\%)$), with a release of kinetic energy of about 5 MeV to the nucleon, corresponding to a final momentum of about 100 MeV/c. The decay may occur, in principle, with isospin change $\Delta I = {}^1/_2$ or $\Delta I = {}^3/_2$. However, the experimental decay branching ratios of the Λ and other hyperons imply a dominance by a factor 20 of the $\Delta I = {}^1/_2$component over the $\Delta I = {}^3/_2$ one. The origin of this empirical rule is essentially not understood in a fundamental way.

The situation described above changes dramatically when the Λ is imbedded in the nuclear medium, since the nucleon of the mesonic decay is emitted with a momentum much less than the nucleon Fermi momentum $k_f \approx 280$ MeV/c . Thus, the pionic decay modes are severely inhibited by Pauli blocking of the final state nucleon in all but the lightest hypernuclei and new, non-mesonic decay modes of the hypernucleus are introduced, through the weak interaction of the Λ with the nucleons ($\Lambda + n \to n + n + 176$ MeV , $\Lambda + p \to n + p + 176$ MeV). This process is possible only in hypernuclei, thanks to the unique beam of Λ's, stable against the mesonic decay and strong interaction, which is available inside a hypernucleus.

The study of the non-mesonic weak decay is of fundamental importance, since it provides primary means of exploring the four fermion, strangeness changing, baryon-baryon weak inter-



◄ Fig. 4: γ-ray energy spectrum from the deexcitation of the ${}^9_\Lambda Be$ hypernucleus obtained at BNL [4]. The energy difference between the two E2 ($5/2^+$-$1/2^+$ and $3/2^+$-$1/2^+$) transitions gives information on the strength of the ΛN spin-orbit interaction. The small measured level splitting of 31 ± 2 keV is incompatible with predictions obtained from meson exchange models.

action $\Lambda N \rightarrow NN$. The non-mesonic process resembles the weak $\Delta S = 0$ nucleon-nucleon interaction, which has been studied experimentally in parity-violating NN scattering measurements. However, the $\Lambda N \rightarrow NN$ two body interaction mode offers more information, since it can explore both the parity-conserving and the parity-violating sectors of the $\Delta S = 1$ weak baryon-baryon interaction. In the weak NN system the strong force masks the signal of the weak parity-conserving part of the interaction.

In addition, the large momentum transfer in non-mesonic decay processes implies that they probe short distances and might, therefore, expose the role of explicit quark/gluon substructure of the baryons. Furthermore, the fundamental question as to whether the $\Delta I = 1/2$ rule, which governs pionic decay, applies to the non-mesonic weak decays may also be addressed.

One of the most important experimental observables of the non-mesonic decay of hypernuclei is the ratio of the neutron-induced ($\Lambda n \rightarrow nn$) over the proton-induced ($\Lambda p \rightarrow np$) decay rate Γ_{nn}/Γ_{np}, which is sensitive to the isospin structure of the interaction. In particular, it should be sensitive to the question of the validity of the $\Delta I = 1/2$ rule.

Notwithstanding the considerable physical interest, experimental data are scarce and affected by very large errors. This is mainly due to the tremendous difficulty in producing abundantly Λ hypernuclei in their ground state and detecting the products of their decay, in particular neutrons.

However, the comparison between the predictions of the theory and the scarce data available is particularly puzzling. In fact, whereas experimental data favour values of the ratio $\Gamma_{nn}/\Gamma_{np} = 1 - 2$ (although with errors of the order of 50%), the meson exchange models, involving one strong interaction vertex and a weak one, systematically underestimate the value of the experimental ratio [6]. In this type of models the $\Delta I = 1/2$ rule is generally enforced in the weak vertex.

Among the mechanisms explored to remedy the puzzle, direct quark model approaches have been adopted, in which the short range region is modelled by effective four quark vertices plus strong interaction corrections. These models are motivated by the large momentum transfer of the $\Lambda N \rightarrow NN$ reaction. The results of these calculations, which yield a large violation of the $\Delta I = 1/2$ rule, provide, on the contrary, significant larger values for the ratio Γ_{nn}/Γ_{np}. Could this be interpreted as a sign of explicit quark effects in nuclei or a consequence of a strong violation of the $\Delta I = 1/2$ rule? To answer these fundamental questions, a drastic improvement of the quality of the experimental data is certainly needed.

FINUDA: the Italian hypernuclear factory

The Italian National Institute for Nuclear Physics (INFN) has built, in its Frascati National Laboratory, a special accelerator, DAΦNE, dedicated to the copious production of $\phi(1020)$ particles, for the purpose of producing beams of extremely high intensity and precise energy for the study of the most rare subnuclear phenomena.

DAΦNE (Double Annular ring For Nice Experiments) [7] consists of two almost circular pipes, one for the electrons and the other for the positrons, that overlap in two straight sections where the beams collide head-on. The energy of each beam is set to 510 MeV in order to produce the $\phi(1020)$ particle in the collisions. This particle is unstable and decays, in a very short time, mostly into neutral and charged K mesons. A view of the DAΦNE hall can be seen in Figure 5.

Even though the main aim of the DAΦNE machine is the precision study of CP and CPT symmetries in the neutral kaon

▲ Fig. 5: A fish eye view of the DAΦNE hall at LNF (Frascati National Laboratory). The DAΦNE accelerator has a circumference of about 190 m and two interaction regions: IP1, on the right side of the picture, is presently occupied by the KLOE experiment devoted to CP violation studies; IP2, on the left, is the FINUDA interaction region. The FINUDA detector, the assembly with dark pink octagonal end-caps, will be moved onto the beam line next autumn.

system, K^- mesons can be used, as it has been seen before, to insert "strangeness" inside the nuclei and produce hypernuclei. FINUDA [8] is the experiment that, next year, will make the most of this facility and will try to shed new and brighter light on the world of hypernuclear physics.

Presently, DAΦNE is delivering something like 150 ϕ/s, half of which decay into a pair of opposite charged kaons with very low momentum, only 127 MeV/c. This low and almost monochromatic momentum value is a great advantage for hypernuclear studies, when comparing the main features of the different production techniques.

When K^- or π^+ beams are used for "*strangeness exchange*" or "*associate production*" reactions, thick targets of the order of some g/cm^2 must be employed to obtain sufficient event rates. Hence, the uncertainty regarding the point of interaction and the energy straggling of the emitted particles limit the resolution achievable on the hypernuclear levels. The same problem occurs in experiments using K^- at rest at proton machines. Here, intense fluxes of kaons are emitted from an external production target, but the distance between the kaon source and the experimental area must be of some tens of meters, due to radiation safety requirement. Therefore, kaons with momentum lower than 400-450 MeV/c cannot survive such a path in a number suitable to give a beam.

Consequently, experiments with stopped K^- must be performed using beams of 500-600 MeV/c, degraded in momentum with a moderator placed just before the production target. This introduces a great uncertainty on the interaction point that can negate any excellent capability of measuring the momenta of the emitted particles. On the contrary, the low momentum of DAΦNE kaons, allowing them to be stopped simply in 0.1 g/cm^2 of carbon, permits the accuracy achievable on the energy levels of the produced hypernuclei to be improved up to 750 keV. In addition, the large acceptance of the apparatus, typical of a collider experiment, allows for high acquisition rates of the order of 80 event/hour, for a typical hypernuclear level, at the design luminosity of the machine.

The FINUDA apparatus (Figure 6) is not only optimised to perform high resolution hypernuclear spectroscopy, but also to

▲ **Fig. 6:** A group of FINUDA collaborators is proudly depicted in front of the experimental apparatus. The leftmost lady squatting down is one of the authors.

study the hypernuclear decay processes. Charged particles, emitted following hypernucleus production or decay, are tracked into the FINUDA cylindrical magnetic volume (1 m radius, 2 m length) by means of four different sub-detectors, each one optimized for a different task: silicon microstrips detect with high accuracy the hypernucleus formation point; drift chambers and straw tubes reconstruct charged particle trajectories; plastic scintillators, detectors with nanosecond time response, are used to select hypernuclear events among other kaon-nucleus interactions and to detect neutrons produced by the hypernuclear decay.

The magnetic field of 1.10 Tesla, produced by a superconducting solenoid, is essential to bend charged particles allowing for a precise evaluation of their momentum. Each element of the FINUDA detector is a small masterpiece of mechanics and electronics. Since particles involved are of low energy, in order to perturb their properties as little as possible, only light materials have been employed in the construction. For the same reason the whole detector atmosphere is filled with Helium gas. In fact, if air is left in the detector, the momentum resolution $\Delta p / p$ would be worsened from 0.3% to 1.5%.

For more then 5 years, the design, assembling and installation of the FINUDA detector has involved some 50 physicists, mainly Italians, together with dozens of highly professional engineers and technicians. After such a long training period, all is now ready for the power-up.

References

[1] M. Danysz and J. Pniewski, *J. Phil. Mag.* **44** (1953), 348

[2] B.F. Gibson and E.V. Hungerford III, *Phys. Rep.* **257** (1995) 349

[3] E. Hiyama et al., *Phys. Rev. Lett.* 85 (2000) 270

[4] H. Akikawa et al., *Nucl. Phys.* **A691** (2001) 134

[5] S. Ajimura et al., *Phys. Rev. Lett.* 86 (2001) 4255

[6] W.M. Alberico and G. Gabarino, *Lanl nucl-th/0112036*, 2001 (To be published on Phys. Rep. 2002)

[7] M. Preger for the DAFNE Team: "Status of DAFNE", presented at HEACC2001 - 18th International Conference on High Energy Accelerators, 26-30 March 2001, Tsukuba, Japan.

[8] P. Gianotti, *Nucl. Phys.* **A691** (2001) 483c

features