The FINUDA physics program

M. Bertani

INFN, Laboratori Nazionali di Frascati,
P.O. Box 13, 00044 Frascati, Italy

for the FINUDA Collaboration

Abstract

FINUDA studies hypernuclear physics at DAΦNE, the e^+e^- ϕ-factory at the Laboratori Nazionali di Frascati. It will begin data taking by the end of 1999.

The main physics topics covered by FINUDA are reviewed and the expected physics performances foreseen by a complete Monte Carlo simulation are shown.

1 Introduction

An hypernucleus is a many-body system composed of conventional (non-strange) nucleons and one or more hyperons (Λ, Σ or Ξ). The presence of the strangeness degree of freedom in a hypernucleus adds a new dimension to the evolving picture of nuclear physics. In spite of the fact that hypernuclear physics dates back to the early 50's, our present knowledge is limited and cannot be compared with conventional nuclei (S=0). Nevertheless, it has already provided important information on nuclear structure and on $\Lambda - N$ interactions. To be more specific, in the following I shall refer to Λ-hypernuclei.

2 Hypernuclei production mechanisms

In this section the physical process commonly used to experimentally produce hypernuclei are briefly reviewed.

In the strangeness-exchange reaction with K^- beams in flight or stopped:

$$K^- + {}^AZ \rightarrow \ {}^A_\Lambda Z + \pi^- \tag{1}$$

$$K^-_{stop} + {}^AZ \rightarrow \ {}^A_\Lambda Z + \pi^- \tag{2}$$

Preprint submitted to Elsevier Preprint *11 May 1999*

$$K^-_{stop} + {}^AZ \rightarrow \; {}^A_\Lambda(Z-1) + \pi^o \tag{3}$$

a K^- transforms a struck neutron (proton) into a Λ with the emission of a π^- (π^o). In the associated production reaction with π^+ beams a $s\bar{s}$ pair is created inside the nucleus:

$$\pi^+ + {}^AZ \rightarrow \; {}^A_\Lambda Z + K^+ \tag{4}$$

In all the processes (eq. 1 $\div$ 4), the momentum of the outgoing π/K is directly related to the energy levels of the hypernucleus. In reaction (eq. 1) hypernuclei are produced in the ground state, while in (eq 2 $\div$ 4) the Λ is generated with high momentum, and several hypernuclear excited states are produced. Reactions (eq. 1, 2, 4) have efficiently been used at BNL and KEK (1; 2; 3; 4; 5), while an experiment at BNL (6) is under way which exploits reaction (eq. 3).

Finally at TJNAF (7) hypernuclei will be produced with the electro-production mechanism ($e^- + {}^AZ \rightarrow \; {}^A_\Lambda(Z-1) + e' + K^+$) which populates spin-flip hypernuclear states contrary to the meson-beam induced reactions. Such a mechanism has great importance for the determination of the spin-dependent part of the ΛN interaction.

2.1 The FINUDA way to hypernuclei

The main ϕ decay ($Br(\phi \rightarrow K^+K^-) = 49\%$) will provide the FINUDA experiment (8) with a unique K^- beam: monochromatic ($E_{kin} = 16$ MeV), slow (127 MeV/c), tagged by the collinear K^+, and background free. Very thin nuclear targets ($0.5\,\mathrm{g\,cm^{-2}}$) can be employed to stop the K^- with minimal straggling very near to the target surface and to produce hypernuclei via the process (eq. 2). This is the main advantage with respect to extracted beam-experiments where high energy K^- beams have to be degraded to rest with the use of a moderator in front of the target. Moreover, thick targets ($\sim$ several $\mathrm{g\,cm^{-2}}$) are used in order to obtain acceptable counting rates. As a consequence, the momentum resolution of the outgoing π^- is limited by the uncertainty in the stopping point and by energy straggling in crossing the thick target. On the contrary in FINUDA the π^- does not cross any significant amount of material and does not undergo any momentum degradation. This feature, together with the use of high momentum resolution spectrometer, will provide unprecedented momentum resolution: 0.3% FWHM on charged particles (p $\sim$ 200$\div$300 MeV/c), which means an energy resolution on hypernuclear levels better than 700 keV.

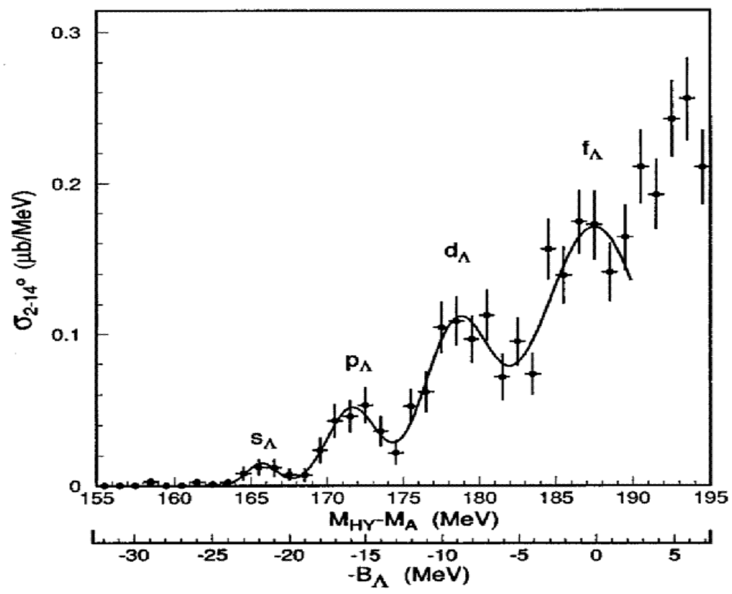

Fig. 1. ${}^{89}_{\Lambda}Y$ spectrum from KEK data (5).

3 The structure of hypernuclei

The Λ embedded in the nucleus is expected to behave as a distinguishable baryon, free to occupy orbits which are forbidden to a nucleon by the Pauli exclusion principle. At the quark level, the u and d quarks have to satisfy the Pauli principle, therefore only the s quark is free to occupy any orbit. The fundamental question whether the Pauli principle is valid at the baryon or at the quark level is very challenging (9).

Λ-hypernuclei provide a unique laboratory in which the properties of the ΛN interaction can be explored (10; 11). The ΛN system is expected to have a weaker potential than the NN system, and the spin-orbit potential in the hypernucleus is very weak. These features are substantially related to the zero isospin of the Λ which prevents the latter from exchanging an isovector meson (like π or ρ) with the nucleon, as in NN case, thus determining the lack of a strong tensor component in the interaction. The relative weakness of the ΛN interaction entails that the nuclear shell structure is not disrupted by the insertion of the Λ into a nucleus and that the mean field which binds the Λ is not as deep as the one which binds the nucleon. In this respect, hypernuclei provide one of the best examples of the validity of the shell model structure. A striking example is the excitation spectrum of the ${}^{89}_{\Lambda}Y$ shown in Fig. 1: it displays a pattern of the deep single particle levels never seen in ordinary nuclei. An improvement in energy resolution is essential for a better understanding of the nuclear structure: these data were taken with an energy resolution of about 2 MeV, FINUDA with 700 keV may reveal finer splittings in hypernuclear spectra.

4 Weak decay of hypernuclei and the $\Delta I = \frac{1}{2}$ rule

The decay of Λ-hypernuclei to non-strange nuclei occurs through the weak interaction which can exchange strangeness. The study of the weak decay of Λ-hypernuclei (12; 13; 14) aims to the understanding of the stability of the system and of the influence the nuclear medium have on the Λ decay and on the weak interaction it experiences. The two main mechanisms for the decay of a hypernucleus are:

(1) The mesonic decay

$$\Lambda \rightarrow p + \pi^- \quad , \quad \Lambda \rightarrow n + \pi^o \tag{5}$$

which is essentially the free decay of the Λ but now occurring in the nuclear medium. This decay mode obeys the so-called isospin rule $\Delta I = \frac{1}{2}$.

(2) When the Λ is embedded in medium-heavy ($A > 5$) nuclei, the mesonic decay is strongly suppressed (15) by phase-space reduction and by Pauli-blocking. The nuclear medium affects the weak decay of the Λ introducing a new, non-mesonic decay mode:

$$\Lambda + p \rightarrow p + n \quad , \quad \Lambda + n \rightarrow n + n \tag{6}$$

The $\Lambda N \rightarrow NN$ interaction resembles the weak NN interaction but with additional new physics (10): in $\Lambda N \rightarrow NN$ both parity-conserving and parity-violating partial rates can be measured (in NN weak interaction only the latter are measurable). The disadvantage is that, unlike the NN case, there is no data on the free $\Lambda N \rightarrow NN$ reaction and hypernuclei are the only source of information for this process.

Furthermore, there are indications (16) of a possible violation of the $\Delta I = \frac{1}{2}$ rule in the non-mesonic decay mode. The ratio (Γ_n/Γ_p) of the neutron over the proton induced decay rates (eq. 6) is sensitive to the isospin structure of the interaction and therefore to the question weather the rule is valid in non mesonic decays. Experimental data are scarce and affected by large errors (3; 4) and comparison with theory is extremely hard (17; 18).

The nuclear matter may also affect the Λ lifetime (τ_Λ). Again, experimental data available are affected by large errors, however they indicate a decrease of τ_Λ as a function of the mass number A.

The study of the weak decay of hypernuclei is one of the most important subjects that FINUDA will be able to investigate. FINUDA will measure the non mesonic decay observables ($\Gamma_\Lambda = 1/\tau_\Lambda$, Γ_n/Γ_p) in coincidence with hypernuclear ground state formation, within the same apparatus and with higher statistics than previous experiments.

5 FINUDA expected performances

The known hypernuclear levels for several hypernuclei and the background reactions have been simulated with the FINUDA Monte Carlo to test the physics performances of the apparatus. As an example, in Fig. 2 are shown the results of the simulation of the π^- spectrum for the $^{12}_{\Lambda}C$ hypernucleus. The main background source is the continuum π^- spectrum from K^- absorption in matter and from Λ and Σ decays (19). The known hypernuclear levels (5) at 261, 265, 270 and 273 MeV/c, corresponding to capture rates of 2×10^{-3}, 2×10^{-4}, 10^{-4} and 10^{-3} respectively, have been generated over the background (first picture). In the second picture the reconstructed spectrum is shown, where only the forward pions have been selected, *i.e.* those which are not crossing back the interaction/target region before entering the spectrometer. The cut at about 200 MeV/c is due to the magnetic acceptance of the spectrometer. The main source of background in the region of hypernuclear levels is due to the two-body Σ production and decay:

$$K^-(np) \rightarrow \Sigma^- p \quad , \qquad \Sigma^- \rightarrow n\pi^- \tag{7}$$

where π^- and p fake the final state from formation (eq. 2) and decay (eq. 6) in the signal. However in the background (eq. 7), π^- and p are correlated (almost back-to-back) while in the signal they are not. Therefore, by selecting events with a spectator proton in the final state and by cutting on the angular correlation (third picture) the background is greatly suppressed. In the last three pictures enlarged views of the reconstructed levels are shown: the reconstructed momentum is systematically lower by a 0.1% factor due to the correction to the momentum for the energy lost in crossing the target. The two peaks at 2×10^{-3} and 10^{-3} capture rates are clearly resolved with a resolution of $\sigma_p/p = 0.26\%\, fwhm$, while the peaks at 2×10^{-4} and 10^{-4} begin to be visible. This simulation corresponds to 7 hours data taking at a the initial luminosity of $L_{in} = 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The expected results on the non mesonic decays of Λ hypernuclei are also very encouraging. In one month of data taking at L_{in}, 1300 events for the (n,p) decay (eq. 6) and 300 events for the (n,n) decay will be collected, giving a statistical errors of about 3% and 6% on the partial widths Γ_p/Γ_Λ, Γ_n/Γ_Λ, thus allowing a more precise test of the $\Delta I = \frac{1}{2}$ rule.

The hypernucleus lifetime will be measured as the difference between the time of flight of the pion emitted in hypernucleus formation, and the time of flight of the proton emitted in the Λ non mesonic decay. In one week of data taking at L_{in} a statistical error of 2% will be obtained on τ_Λ, keeping the systematics under control.

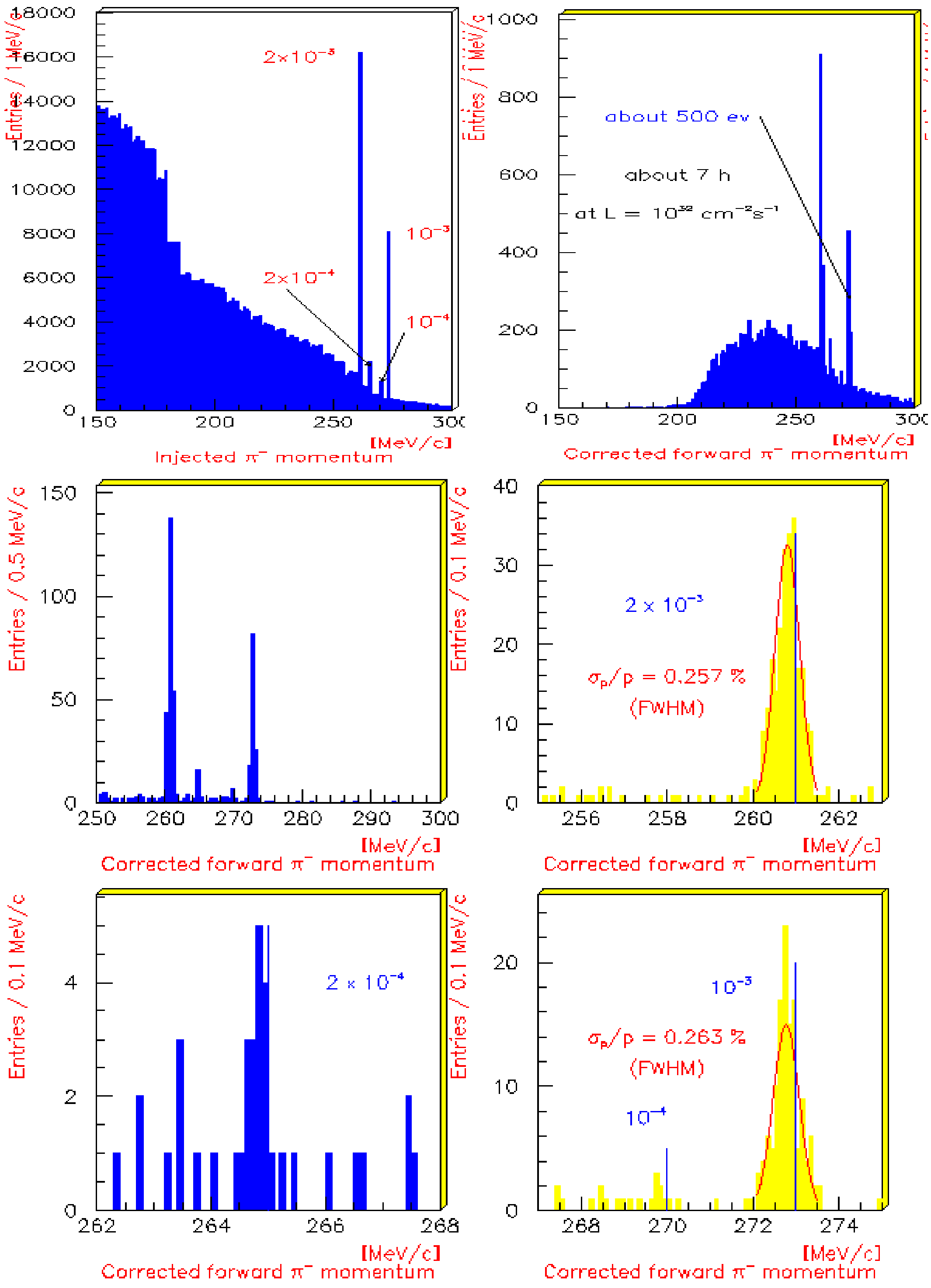

Fig. 2. From top to bottom, left to right: (i) Monte Carlo simulation of the π^- spectrum for ${}^{12}{}_{\Lambda}C$, with four hypernuclear levels; (ii) reconstructed π^- momentum distribution; (iii) with a detected proton in the final state and with a cut on π^- and p angular distribution. In the last three pictures enlarged views of the reconstructed levels are shown: the line above each peak corresponds to the injected momentum.

6 Conclusions

FINUDA will perform a physics program on hypernuclear spectroscopy and decay modes on several nuclear targets, thus enlarging the chart of known hypernuclei. The hypernuclear levels will be measured with the unprecedented energy resolution of 700 keV, the ratio Γ_n/Γ_p will be measured with 7% statistical error in one week of data taking, thus allowing a test of the $\Delta I = \frac{1}{2}$ rule. The completion of this program will represent a step forward in the understanding of the main hypernuclear open problems.

References

[1] H. Tamura *et al.* Nucl. Phys. A**479** (1988) 161c.
[2] P.H. Pile *et al.*, Phys. Rew. Lett **66** (1991) 2585.
[3] J.J. Szymansky *et al.*, Phys. Rev. C**43** (1991) 849.
[4] H. Noumi *et al.*, Phys. Rev. C**52** (1995) 2936.
[5] T. Hasegawa *et al.*, Phys. Rev. C**53** Vol.3 (1996) 1210.
[6] H.A. Thiessen, J.C. Peng *Investigation of Light Hypernuclei Using the* (K^-, π^o) *Reaction*, BNL-PROPOSAL-907 (1994).
[7] E.V. Hungerford, *Proc. LAMPF Workshop on* (π, K) *Physics* Los Alamos (1995);E. Cisbani *et al.* Nucl. Phys. A**623** 304c.
[8] The FINUDA Collaboration (M. Agnello *et al.*), *FINUDA Technical Report*, LNF-95/024(IR)(1995); S. Sarwar for the FINUDA Collaboration, these proceedings.
[9] E.V. Hungerford, L.C. Biedenharn, Phys. Lett. B**142** (1984) 232.
[10] B.F. Gibson, E.V.Hungerford III, Phys. Rep. **257** (1995) 349.
[11] A. Molinari, H. Feshbach, *Second DAΦNE Physics Handbook*, vol II, SIS-LNF (1995) 713.
[12] J. Cohen, Prog. Part. Nucl. Phys. **25** (1990) 139.
[13] B.R. Holstein, *Proc. Workshop on Physics and Detectors for DAΦNE '95*, Frascati Physics Series, Vol.IV (1995) 333.
[14] E. Oset and A. Ramos, Prog. Part. Nucl. Phys. **41** (1998) 191.
[15] W. Cheston, H. Primakoff, Phys. Rev. **92** (1953) 1537.
[16] R.A. Schumacher, Nucl. Phys. A**547** (1992) 143c.
[17] K. Itonaga, T. Ueda and T. Motoba, Nucl. Phys. A**585** (1995) 331c.
[18] A. Parreño, A. Ramos and C. Bennhold, Phys. Rev. C**56** (1997) 339; A. Parreño *et al.*, Phys. Lett. B**435** (1998) 1.
[19] H. Tamura *et al.*, Phys. Lett. B**160** (1985) 32.