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HYPERNUCLEAR PHYSICS WITH FINUDA AT DAΦNE*

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The FINUDA detector has been installed at the (e^+, e^-) collider DAΦNE at Laboratori Nazionali di Frascati (Italy). The commissioning of the detector was started and will be immediately followed by a data taking run with targets of ^{6}Li, ^{7}Li, ^{12}C, ^{27}Al and ^{51}V. Hypernuclei of the same A as the target nuclei will be copiously produced by means of the strangeness exchange reaction by stopped K^-. The aim of the experiment is to measure simultaneously excitation energy spectra with a resolution better than 1 MeV, lifetime of the Λ in the different Hypernuclei, partial decay widths Γ_π, Γ_{np} and Γ_{nn} for mesonic and non-mesonic decays, in coincidence. Further information could be gained on neutron-rich Hypernuclei and rare two-body decays. Ideas for the continuation of the program, as well as possible extension to an improved machine (DAΦNE2) will be finally discussed.

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1. Introduction

Following the discovery of Hypernuclei by Danysz and Pniewski [1], of which we are celebrating here the 50$^{\text{th}}$ anniversary, experimental research on the field was carried out mostly with emulsion techniques up to mid sixties [2]. Afterwards, first generation measurements with electronics techniques were started and they were focused on some particular channels, relative to the formation or decay of Hypernuclei. Statistics was sometimes good, but the physical information was partial. However very interesting observations were done and they led to second generation experiments, carried out at BNL and KEK, in which coincidence measurements between formation and some decay channel were performed. FINUDA (acronym for FIsica

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NUcleare at DAΦNE) may be considered as a third generation experiment in which, thanks to the large angular coverage for detection of charged and neutral particles from the formation and decay of Hypernuclei, many observables (excitation energy spectra, lifetimes, partial decay widths for mesonic and non-mesonic (NM) decay), will be measured simultaneously, providing hopefully a bulk of data of unprecedented completeness, precision and cleanliness. Furthermore, spectra corresponding to different targets, will be measured simultaneously, avoiding possible systematic errors in comparing the properties of different Hypernuclei. Under this point of view, FINUDA is the modern electronic experiment approaching more closely the original visualizing technique by Danysz and Pniewski.

The detector was completed in 1998, but its installation into the machine was delayed by problems related to the operation of the superconducting coil in which the detector is immersed and mainly to unexpected difficulties encountered in the commissioning of the machine. Since 2000 the peak luminosity, $\mathcal{L}_{\rm peak}$, of the collider was increased from less than 10^{30} cm^{-2} s^{-1} to 7×10^{31} cm^{-2} s^{-1} at the end of 2002 and the quality of the colliding beams was greatly improved (strong reduction of the background).

From January 2003 the last operations necessary for the insertion of the detector in the interaction region were started, and took about four months. A particular care was devoted to the installation and calibration of the vertex/target assembly, described in Section 2. The roll-in of the detector into the collider was done on 28th April, 2003. Fig. 1, taken in June 2003, shows a picture of the DAΦNE hall, with FINUDA in place.

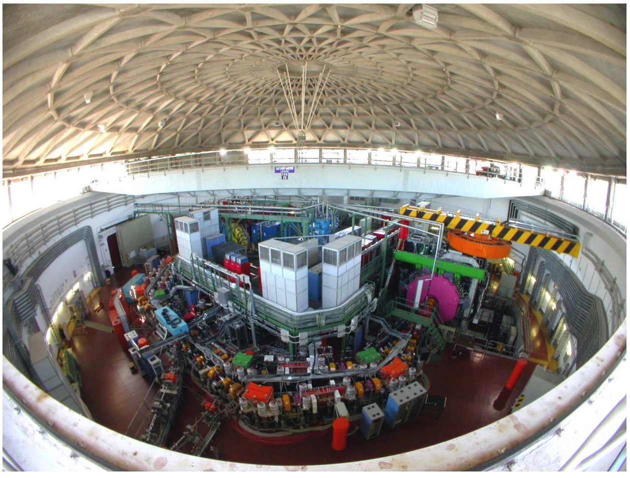

Fig. 1. Picture of the DAΦNE Hall, taken in June 2003. On the right the FINUDA detector is visible, waiting for beam.

Furthermore, the full detector was calibrated with cosmic rays during six weeks (three weeks with magnetic field off, three weeks with field on) in order to get the final calibrations concerning the efficiencies and the alignment of the different subdetectors which constitute the spectrometer. Engineering runs with DAΦNE starting commissioning (I remind that in the meantime many major improvements on the machine were done in order to increase $\mathcal{L}_{\rm peak}$) were scheduled from July 2003, but were unfortunately stopped due to shortages in the water supply necessary for the cooling of the different elements of the machine. The obvious reason for such a shortage was the anomalously hot and dry summer that affected all Europe. The machine operations were restarted at the end of August, and first collisions delivered at the half of October, just at the time in which this paper is being written.

2. The FINUDA detector at DAΦNE

The idea of performing an experiment on the production and decay of Hypernuclei, which is inherently a fixed target physics, at a collider seems not good at first sight. The main decay channel of the Φ-meson, produced at a rate of $\sim 4.4 \times 10^2$ s^{-1} at the luminosity $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}, is (K^+, K^-), $\sim$ 49%. Since the Φ-meson is produced at rest, DAΦNE is a source of $\sim 2.2 \times 10^2$ (K^+, K^-) pairs/s, which are collinear, background free, and, very important, of very low energy ($\sim$ 16 MeV). The low energy of the produced charged kaons is the key advantage for an experiment on Hypernuclei production and decay by means of strangeness-exchange reaction with K^- at rest:

$$K^-_{\rm stop} + ^A Z \rightarrow ^A_\Lambda Z + \pi^- \tag{1}$$

in which $^A Z$ indicates the nuclear target and $^A_\Lambda Z$ the produced Hypernucleus. The K^- can be stopped in very thin targets (a few hundreds of mg/cm^2), in contrast to what happens with the stopped K^- beams at hadron machines, where from 80% up to 90% of the incident K^- beam is lost in the degraders facing the stopping target. Furthermore, the cylindrical geometry of the interaction region at a collider allows the construction of cylindrical high resolution spectrometers with solid angles for detecting the π^- from (1) ($> 2\pi$ sr) very much bigger than those at fixed target machines ($\sim$ 100 msr). Last but not least, the use of thin targets introduces lower cuts on the measurement of the low energy charged particles (π^-, p, d) from the weak decay of the Hypernuclei produced by (1) and they are detected by the same arrays of detectors with large solid angles ($> 2\pi$ sr).

I put forward these considerations in 1991 [3] and a proposal was afterwards elaborated [4, 5] and soon accepted by the Scientific Committee of LNF.

Fig. 2 shows a sketch of the detector, immersed in a superconducting solenoid which provides a homogeneous magnetic field of 1.1 T inside a cylindrical volume of 146 cm radius and 211 cm length. (e^+, e^-) collide at the center of the magnet with an energy of 510 MeV each.

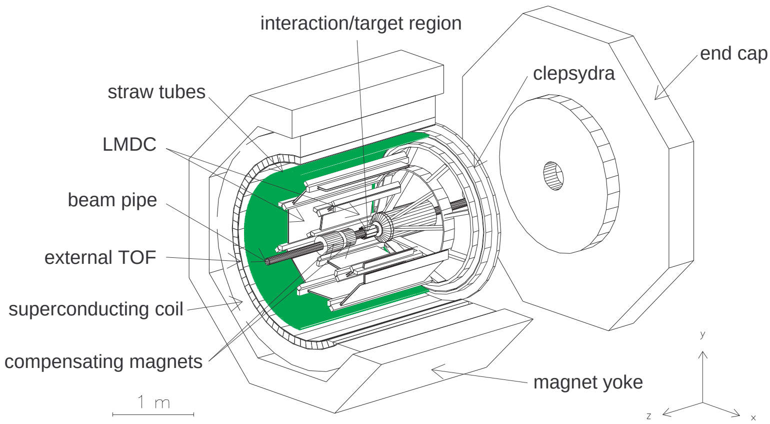

Fig. 2. Global view of the FINUDA detector with the superconducting solenoid and the iron yoke.

In the detector three main regions can be distinguished:

(i) the interaction/target region, sketched in Fig. 3. Here the highly ionizing (K^+, K^-) pairs are detected by a scintillator barrel (tofino) of 12 thin strips around the beam pipe, with a time resolution $\sigma \sim 250$ ps. The barrel is surrounded by an octagonal array of Si-μstrips (ISIM), with a spatial resolution $\sigma \sim 30\mu$m and energy resolution of 20% FWHM. A thin nuclear target module is positioned on the external side of each element of the octagon. The task of the μstrip detector is the reconstruction of the K^- interaction point in the nuclear target with an accuracy of ~ 250 μm.

(ii) the external tracking device, composed by four different position detectors immersed in a He atmosphere to reduce the effects of the multiple Coulomb scattering. Therefore four points are measured to reconstruct the tracks of particles crossing this region (*e.g.* the π^- of the Hypernucleus formation). The first element of the device is an array of 10 $Si-\mu$strips (OSIM), placed close to the target array. Then, two layers of planar low mass drift chambers, filled with a (70%He–30%C_4H$_{10}$) mixture, with a spatial resolution of $\sigma_{\rho,\phi} \sim 150$ μm. Finally, a straw tube detector, composed by three superlayers, giving a spatial resolution of $\sigma_{\rho,\phi} \sim 150$ μm and $\sigma_z \sim 500$ μm. In this volume the tracking of the p from NM decay can be done, with an acceptance of 30% and an energy resolution of 1.3 MeV at 80 MeV.

(iii) the external time of flight barrel, composed by 72 scintillator slabs, 10 cm thick, with time resolution of $\sim$ 500 ps FWHM. The neutrons from NM decays can be detected with an acceptance of 70% and with an efficiency of 10% and an energy resolution of 8 MeV at 80 MeV.

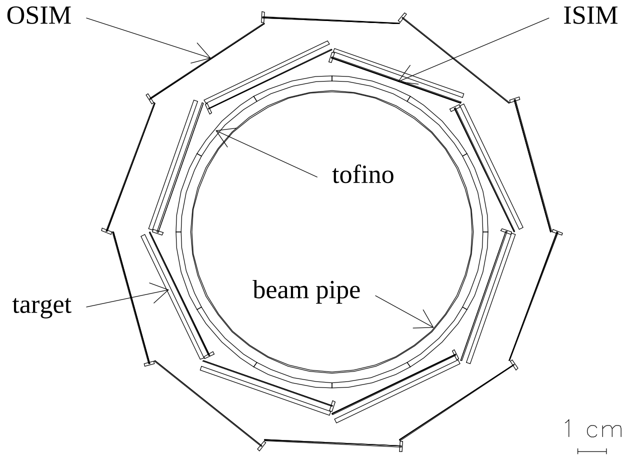

Fig. 3. Schematic view of the interaction/target region.

Concerning the production rate of Hypernuclei, it was found that for an hypernuclear final state produced at a rate of 10^{-3}/stopped K^-, which is typical for p-shell Hypernuclei, 80 events/hour were expected [10] at a luminosity $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1}. The detection rate for non-mesonic decays is, under the above conditions, 3 events/hour for the $(n,\ p)$ decay and 0.3 event/hour for the $(n,\ n)$ decay.

The lifetime of the Hypernuclei can also be directly measured with very good precision (better than 5 ps). More details on some of the above arguments may be found in [6–9].

3. The initial physics program of FINUDA

As can be seen from Fig. 3, eight different nuclear targets can be hosted near the interaction region. For the data taking run starting now the following series of target was chosen: two targets of ^{6}Li (isotopically enriched to 90%), one target of ^{7}Li (natural isotopic abundance), three of ^{12}C, one of ^{27}Al, one of ^{51}V. With an integrated luminosity $\mathcal{L}_{\rm int}$ of 250 pb^{-1}, which was allocated to the first data taking run (corresponding to about three months), I expect that the results described in the following will be obtained, for the different targets.

- ^{6}Li. The Hypernucleus $^6_\Lambda$Li, which is formed in reaction (1) is unstable for proton emission, and it decays in $\sim 10^{-22}$ s to $^5_\Lambda$He $+$ p. Thanks to the excellent momentum resolution, it will be possible to clearly identify the $^5_\Lambda$He production by simply looking at the end point of the momentum spectrum of π^- coming from (1) and by selecting the appropriate momentum range (see Fig. 4). A precise estimation of the expected rates for mesonic and NM decays of $^5_\Lambda$He was reported by [11], for a $\mathcal{L}_{\rm int}$ lower by more than a factor two. The number of events I expect may be deduced from the above evaluation. The partial decay widths for π^- decay, Γ_{π^-}, proton induced decay, Γ_p ($\Lambda + p \to n + p$), and neutron induced decay, Γ_n ($\Lambda + n \to n + n$), will be measured to a precision of the order of 10%.

I stress that all the above numbers are given for both nucleons measured in coincidence. A recent measurement was performed at KEK, with a total yield lower by a factor ~ 3 [12]. We may expect, with these yields, to observe also the $2\mathcal{N}$ decay width $\Gamma_{2\mathcal{N}}$ ($\Lambda + (\mathcal{N}+\mathcal{N}) \to \mathcal{N}+\mathcal{N}+n$) which was evaluated [13] to amount up to 15% of the total NM decay width $\Gamma_{nm} = \Gamma_p + \Gamma_n + \Gamma_{2\mathcal{N}}$. It is very important to ascertain experimentally the existence of this three-body channel in order to give a full pattern of the weak decay modes of Λ-Hypernuclei.

Hyperfragments $^4_\Lambda$He and $^4_\Lambda$H are abundantly produced through the Coulomb assisted mechanism on ^{6}Li, but they cannot be separated by windows on the π^- emission spectra (see Fig. 4). However, it would be conceivable to recognize the formation of $^4_\Lambda$He by detecting the two-body decays:

$$^4_\Lambda{\rm He} \to d + d\,, \qquad ^4_\Lambda{\rm He} \to p + {}^3{\rm H}\,. \tag{2}$$

These "rare" two body decays were never observed before, and could be detected in FINUDA even if their branching ratio would be as low as 10^{-3} [11].

A very interesting reaction which may occur when K^- are stopped in a ^{6}Li target is:

$$K^- + {}^6\,{\rm Li} \to {}^6_\Lambda{\rm H} + \pi^+ \tag{3}$$

since it is opening a window on the up to now unexplored field of neutron-rich Hypernuclei.

Nuclei at the most extreme N/Z ratio are found at small proton and neutron numbers. Among the bound nuclei ^{8}He has the largest N/Z value reached so far, $N/Z = 3$.

One of the most exciting recent discoveries in Nuclear Physics has been the observation of the *halo* phenomenon, *i.e.* that some of the nucleons

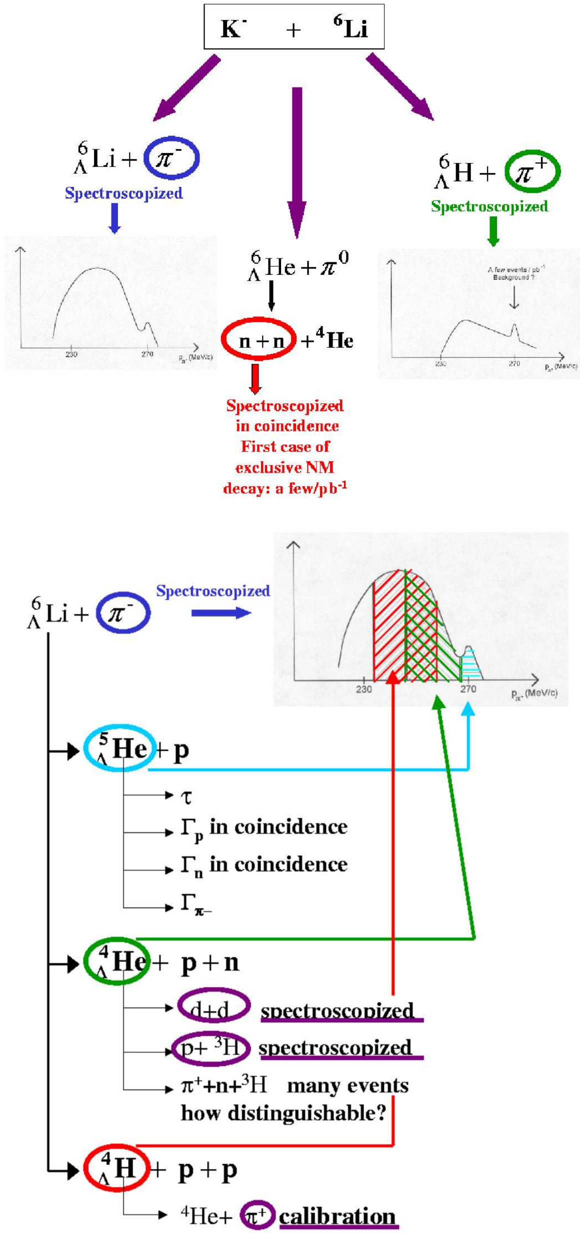

Fig. 4. Pictorial view of the manifold physical information that can be obtained from the $K^{-}+{}^{6}$Li reaction.

extend far outside the region of their nuclear core. In the archetype halo nucleus ^{11}Li, the two outermost neutrons occupy a volume almost comparable in size to that of the much heavier nucleus ^{208}Pb.

It was first stressed by Majiling [14] that Λ-Hypernuclei may be even better candidates for exhibiting larger values of N/Z and halo phenomena. The glue rôle of the Λ (compression of the nuclear core and the addition of the extra binding energy B_Λ) as well as the reliable picture in terms of single-particle states are the main arguments supporting such a prediction. Existence of Hypernuclei like $^7_\Lambda$H, with a value of $N/Z = 5$ (or $(\Lambda + N)/Z = 6$) and halo hypernuclei like $^7_\Lambda$He and $^9_\Lambda$He was predicted on the basis of calculations following simplified assumptions.

Unfortunately the production of neutron-rich Hypernuclei must proceed through two-step reactions occurring on two nucleons of the same nucleus (*e.g.* $K^- p \to \Lambda\pi^0, \pi^0 p \to n\pi^+$) with unavoidable low cross-sections or capture rates. Their experimental discovery has not yet been possible with the low intensity beams at present in use.

The reaction (3) is probably the best candidate for the observation of neutron-rich Hypernuclei (few nucleon system, no jump of the baryons between the different shells or sub-shells in the two-step mechanism that describes the reaction). I may expect a capture rate for (3) ranging between 10^{-4} and 10^{-5}. If so, it could be detected by FINUDA. See [15] for more details.

Finally, also the reaction/decay chain:

$$K^- + {}^6\,\text{Li} \to {}^6_\Lambda\,\text{He} + \pi^0\,, \qquad {}^6_\Lambda\text{He} \to {}^4\,\text{He} + n + n \tag{4}$$

could be observed by FINUDA, even though the π^0 is not detected. Due to the high nucleon emission threshold for ^{4}He (19.8 MeV) the measurement of both neutrons in coincidence, even if with a coarse resolution, will allow the unambiguous selection of the NM decay (4). It would be the first case for the observation of an exclusive NM decay. More details on this particular subject may be found in [16]. Fig. 4 summarizes pictorially the richness of Physics that may be obtained with reaction K^-+^6Li and the FINUDA detector.

- ^{7}Li. The low-lying excited states spectrum of $^7_\Lambda$Li is the most extensively studied with high-resolution γ spectroscopy [17]. With our experimental energy resolution we may expect to separate clearly the ground state doublet ($\vec{T} = 0,\ 1/2^+$ and $3/2^+$) from the ($\vec{T} = 0,\ 5/2^+$ and $7/2^+$) doublet at 2 MeV and from the ($\vec{T} = 1, 1/2^+$) state at 3.7 MeV. The statistics on this excitation spectrum will be large (some

10^4 events). Γ_n and Γ_p, never measured for this Hypernucleus, will be measured in coincidence, with a precision of $\sim 15\%$, and τ_Λ measured with a precision of 5 ps.

Observation of ${}^{7}_{\Lambda}$H through the reaction (K^-, π^+) would also be possible, provided that the capture rate is larger than 10^{-5}. The knowledge of all the above observables is of paramount importance to correct the results on ^{6}Li for the isotopic contamination ($\sim 10\%$).

- ^{12}C. ${}^{12}_{\Lambda}$C was the Hypernucleus more extensively studied up to now, at BNL and KEK [18]. For this reason it was decided to install three ^{12}C targets, in order to obtain calibration data, by comparing our results with the previous ones, and improve at the same time the precision on all the observables. The excitation energy spectrum will contain more than 10^5 events, distributed mainly in the ground state and in the well known excited state at 10 MeV, with three other peaks, corresponding to excited states (or groups of them) in between, corresponding presumably to excited states of the nuclear core ^{11}C [18]. Fig. 5 shows a Monte Carlo simulation of the spectrum expected with the design resolution of FINUDA and with a $\mathcal{L}_{\rm int}$ of 5 pb^{-1} [8]. It must be noticed that the above luminosity was that expected in 3 months of running of DAΦNE (year 2000). Today the same spectrum would be obtained in one day. With a 40 times larger statistics it is conceivable to observe ${}^{12}_{\Lambda}$C excited states produced at a rate of 10^{-5}/stopped K^- and even possible splittings of the main peaks. I remind that the best spectrum of ${}^{12}_{\Lambda}$C was measured with a 1.45 MeV resolution FWHM.

  I expect however more interesting results on the weak decays parameters Γ_n, Γ_p. The so-called Γ_n/Γ_p *puzzle* (strong discrepancy between the experimental ratio and that predicted by theoretical models) was recently partially solved by new measurements at KEK, not in coincidence, reported at this Conference by Bhang [19]. Preliminary results in coincidence [12] confirmed the results, but with poor statistics. Furthermore, both measurements are biased by a high detection threshold on the protons. I expect that FINUDA could give the definitive answer to this long-standing puzzle.

- ^{27}Al. Apart a very old measurement with the (K^-, π^-) reaction, performed for the first time with K^- in flight [20], no further data were produced on the ${}^{27}_{\Lambda}$Al Hypernucleus. A broad doubly bumped structure was observed, with the poor resolution of 6 MeV FWHM. I think that a detailed study of this Hypernucleus is important both from the spectroscopic side and from the weak decay one. Concerning the structure, ${}^{27}_{\Lambda}$Al is an Hypernucleus in which the nuclear core ^{26}Al has an equal number (5) of unpaired nucleons in the $1f_{7/2}$ shell. I may expect

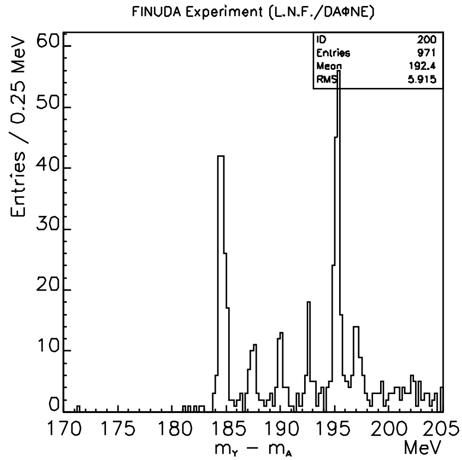

Fig. 5. Monte Carlo simulation of the ${}^{12}_{\Lambda}$C excitation spectrum expected from FINUDA with a $\mathcal{L}_{\rm int}$ of 5 pb^{-1}

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that interesting effects could appear with an excitation spectrum containing more than 10^4 events. Concerning the weak decay rate, it is essential to measure the capture rate to the ground state of ${}^{27}_{\Lambda}$Al, not known at present, in order to decide whether measurement of Γ_n and Γ_p in coincidence will be possible also for medium-large A targets.

- ^{51}V. The excitation spectrum of ${}^{51}_{\Lambda}$V was measured at KEK with (π^+, K^+) reaction with a resolution of 1.65 MeV, and peaks corresponding to the Λ in s-, p- and d-single particle orbits were already seen [18]. Furthermore, the peak due to the Λ in p- and d-orbits showed a possible splitting, that was tentatively attributed to a non-zero value of the Λ spin-orbit potential, in contrast to previous assumptions. The final resolution of FINUDA (0.7 MeV FWHM) as well as the good statistics that we expect to collect (about 2×10^4 events) would allow a confirmation of the previous observation. Furthermore, as for the case of ${}^{27}_{\Lambda}$Al, the measured capture rate for the ground state formation (never measured before) will indicate whether it will be possible to measure Γ_n and Γ_p in coincidence even for this Hypernucleus.

4. Continuation of the physics program beyond 2003

Similar beam allocation are expected, for at least the next three forthcoming years. It is likely that $\mathcal{L}_{\rm peak}$ will improve to 5×10^{32} cm^{-2} s^{-1} and $\mathcal{L}_{\rm int}$ / day to 10 pb^{-1}/day. I think that two options are open:

1. continue the survey on excitation energy spectra and weak decay parameters for targets of medium-large A. Targets, which are solid (or easily handled like H_2O) and naturally quite isotopically pure are: ^{9}Be, ^{16}O (water), ^{28}Si, ^{40}Ca, ^{65}Mn, ^{89}Y, ^{98}Nb, ^{133}Cs, ^{139}La, ^{165}Ho, ^{208}Pb, ^{209}Bi. Probably not all the above targets will be examined, but only a reasonable selection, following the results of the 2003 run, in particular for the ^{27}Al and ^{51}V targets;

2. a strong effort on some selected light targets, if new and interesting results will be obtained from the survey previously described. At present I think that, if neutron-rich Hypernuclei like $^{6}_{\Lambda}$H and $^{7}_{\Lambda}$H will be produced at good rates (some 10^{-5}/stopped K^-), an attempt to measure Γ_n and Γ_p could be worthwhile.

5. Hypernuclear Physics at DAΦNE2

Following the optimism on the present operation and reliability of the machine, an increase of $\mathcal{L}_{\rm peak}$ up to 10^{34} cm^{-2} s^{-1} seems within reach (DAΦNE2). Such an increase of two orders of magnitude will open at least two new options to FINUDA. The first one, that does not require any substantial modification of the present detector, apart the DAQ, is an effort of measuring $\Gamma_{2\mathcal{N}}$ to a precision better than 10% and to produce neutron-rich Hypernuclei. They could be produced at DAΦNE2 at a rate similar to that expected for "ordinary" hypernuclei at DAΦNE1. Then, not only their spectroscopy could be performed with good statistics, but also their NM decay in coincidence could be detected.

The second option would be that of starting high resolution γ-spectroscopy with Ge-detectors even in FINUDA. Technically it would mean to give up a portion ($\sim 25\%$) of the solid angle (at present $\sim 2\pi$ sr) used for π^- spectroscopy, and install an array of Ge-detectors, with a ($\varepsilon\ \Delta\omega$) factor of some 10^{-3} for 1 MeV photons. A raw estimate of the rate of production of de-excitation γ-rays in coincidence with the spectroscopized π^- is similar to that expected at J-PARC [21] under the same physical assumptions.

Finally, γ-spectroscopy by Ge-detectors of Hyperfragments produced from K^- capture seems very promising. The rates are even larger than those expected at J-PARC and the background conditions (no neutrons quite dangerous for the operation of intrinsic Ge-detectors) could be better.

6. Conclusions

The strong effort at DAΦNE on Hypernuclear Physics (about 40 physicians engaged, a detector costing more than 10 MEuros, one dedicated interaction region of the machine) and the ambitious research program of the

FINUDA detector starting up just in the 50th anniversary of the Hypernuclei's discovery, is the best tribute that can be offered to the two outstanding Polish physicists Danysz and Pniewski.

I am very grateful to Dr. E. Botta for her patient and precious help in writing this paper.

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