HIGH-RESOLUTION SPECTROSCOPY OF HYPERNUCLEI WITH γ-RAY DETECTORS AT DAΦNE2

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Abstract

The study of hypernuclei production and of their decay modes represents a way to address several fundamental questions in modern physics. Recently the introduction of γ-ray detectors determined a significative breakthrough in the field. Hence high-resolution spectroscopy, based on this technique, represents the new frontier for hypernuclear physics. In this paper I will discuss the opportunity to carry on an experimental program with the modified FINUDA apparatus (FINUDA2) and by exploiting the improved performances, in terms of luminosity, of the proposed upgrade of the DAΦNE collider (DAΦNE2).

INTRODUCTION

Hypernuclear physics born exactly 50 years ago, when M. Danysz and J. Pniewski identified the first hypernucleus in an emulsion stack [1]. At that time it was really difficult to define the domain of this new research field: it was something of "strange", in between (traditional) nuclear and particle physics. Afterwards a hypernucleus was considered like an ordinary nucleus with a tracer. As a matter of fact a Λ particle embedded in a nucleus is stable against mesonic decay and strong interaction: hence it will survive for a while, maintaining its own identity among other nucleons. In addition it can deeply penetrate inside the nucleus since the Pauli principle is not effective. Today strangeness nuclear physics is considered an extension of the traditional one, obtained by adding a third dimension, the strangeness, to the well known chart of ordinary nuclei (see Fig. 1).

High-resolution γ-ray spectroscopy based on germanium (Ge) detectors represents one of the most powerful means of investigation in nuclear physics: the introduction of this technique determined a significative progress in the knowledge of the nuclear structure. Recently it has been experimentally proved that also strangeness nuclear physics can benefit of the same advantages: the energy resolution on hypernuclear levels has been in fact dramatically reduced from 1–2 MeV (FWHM) to few keV (FWHM) [2, 3, 4]. Thanks to this improvement it is possible to pursue the study of different physics topics that can be classified in three main categories:

1. low energy hyperon-nucleon interaction
2. impurity nuclear physics
3. medium effect on baryons

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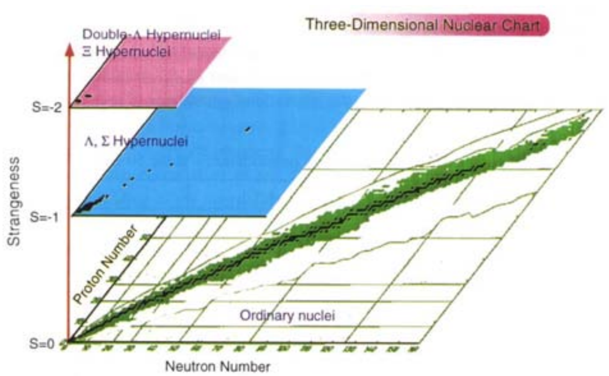

Figure 1: Three-dimensional chart of nuclear systems. At present about 35 S = -1 hypernuclei have been unambiguously identified, while only few S = -2 hypersystems have been produced.

Fig. 2 summarize the subjects on which hypernuclear physics spans: on one hand the hypernucleus spectroscopy is the only practical way to get information about the hyperon-nucleon ($Y\mathcal{N}$) interaction at low energy; on the other hand the study of hypernucleus decay modes represents the only opportunity to investigate the four-baryon, strangeness changing, $\Lambda\mathcal{N} \rightarrow \mathcal{N}\mathcal{N}$ weak vertex; in such reactions the large momentum transfer allows to probe the short range part of the interaction: this way the role of eventual explicit quark-gluon substructures can be put in evidence; another interesting subject that can investigated is that of the neutron-rich nuclei, produced thanks the "glue role" of the Λ particle: probably this is the most interesting effect of what today is called impurity nuclear physics; finally it is also possible to look at the other side of the coin, by studying how the nuclear medium could affect the properties of the embedded hyperon.

In the next Section I will concentrate on the arguments that can be addressed by means of high-resolution γ-ray spectroscopy of Λ-hypernuclei.

PHYSICS MOTIVATIONS

Hyperon-nucleon interaction

A central point of a high-resolution γ-ray spectroscopy program is the study of the $Y\mathcal{N}$ interaction. Direct measurements in $Y\mathcal{N}$ scattering experiments are in fact very hard, due to the difficulty in producing and managing hyperon beams of suitable intensity, and become practically impossible at low energy.

As usual the knowledge of the energy level spectrum

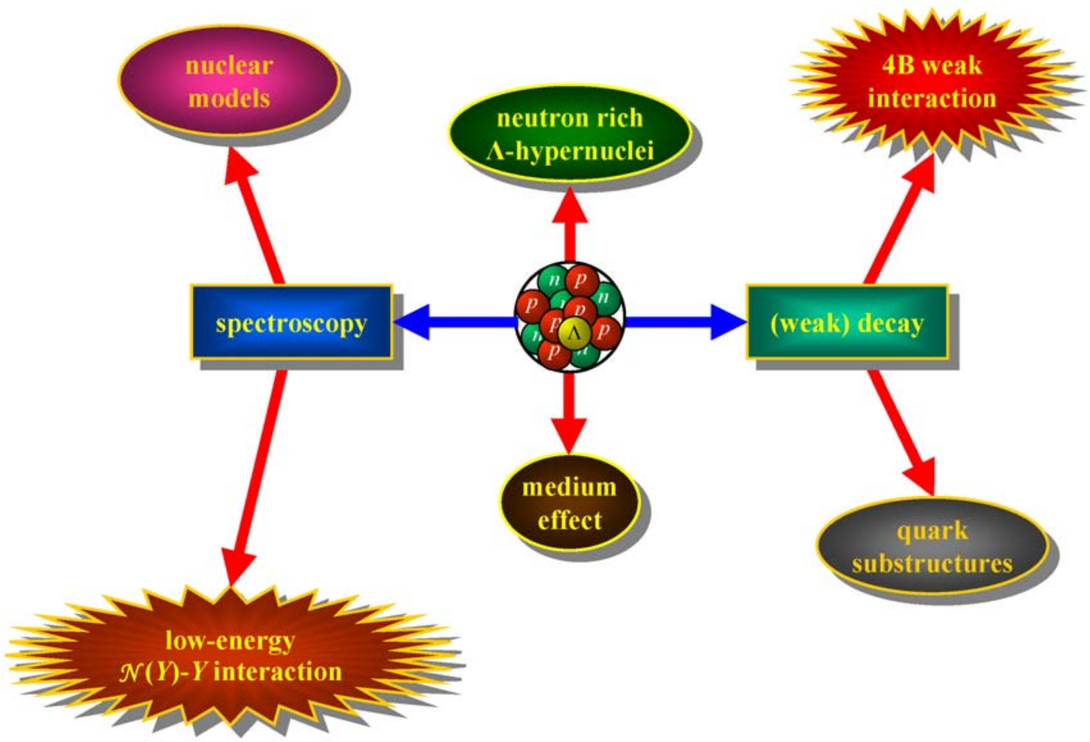

Figure 2: Block diagram of the physics information that may be get from the study of hypernucleus production and decay (adapted from Ref. [5]).

provides information about the interaction potential, in particular on the strength of the spin dependent terms. In addition the measurement of the angular distributions and of the polarization of the observed γ-ray transitions allows the spin-parity assignment for each produced state.

When the structure of the considered hypernuclear system is relatively simple, like in the case of light Λ-hypernuclei, it can be described in the frame of the shell model. In this case the $Y\mathcal{N}$ interaction can be expressed by the following equation:

$$\begin{aligned} V_{\Lambda\mathcal{N}}(r) &= V_0(r) \\ &+ V_\sigma(r)\vec{s}_\mathcal{N}\cdot\vec{s}_\Lambda \\ &+ V_\Lambda(r)\vec{l}_{\Lambda\mathcal{N}}\cdot\vec{s}_\Lambda \\ &+ V_\mathcal{N}(r)\vec{l}_{\Lambda\mathcal{N}}\cdot\vec{s}_\mathcal{N} \\ &+ V_T(r)[3(\vec{\sigma}_\mathcal{N}\cdot\vec{r})(\vec{\sigma}_\Lambda\cdot\vec{r}-\vec{\sigma}_\mathcal{N}\cdot\vec{\sigma}_\Lambda)] \end{aligned} \tag{1}$$

Under these simplifying assumptions, each of the five terms in Eq. (1) corresponds to a radial integral [6, 7], that can be phenomenologically determined from the low-lying level structure of several *p*-shell hypernuclei. The knowledge of these features of the $Y\mathcal{N}$ interaction allows to improve the models describing the baryon-baryon interaction and to discriminate between the ones based on the meson exchange pictures and those including quark-gluon degrees of freedom: the aim is to make a step towards an unified understanding of the baryon-baryon interaction.

However the measured energy level spectra can not be completely reproduced in terms of a simplified two-body effective interaction. It is now clear that a so called three-body force, due to intermediate Σ states, comes into play (see Fig. 3).

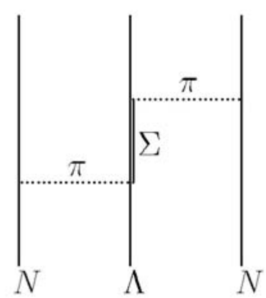

Figure 3: Diagram for the $\Lambda\mathcal{N}\mathcal{N}$ three-body force due to intermediate Σ states, introduced by $\Lambda\mathcal{N}-\Sigma\mathcal{N}$ couplings (from Ref. [8]).

Since the mass difference between Σ and Λ particles is smaller than in the case of Δ and $\mathcal{N}$, the three-body force is expected to be stronger than the analogous interaction involving intermediate Δ states in ordinary nuclei. Moreover, since the $\Lambda\mathcal{N}\mathcal{N}$ interaction is mediated by two-pion exchange, while the one-pion exchange is forbidden by isospin conservation, the $\Lambda\mathcal{N}\mathcal{N}$ force is expected to be larger than the $\Lambda\mathcal{N}$ one. It is then straightforward to conclude that the study of the three-body force, as well as of the two-body one, is fundamental in understanding the structure of hypernuclei.

Another important effect that can be investigated is a possible charge symmetry breaking. The Λ particle has both isospin and charge equal zero; then, if the charge symmetry holds exactly, the strength of the Λp and of the Λn interactions should be exactly the same. However it is well known that the measured Λ binding energies for the ${}^{4}_{\Lambda}H$ and the ${}^{4}_{\Lambda}He$ systems, the lightest pair of mirror hypernuclei, exhibit a significative difference. In other words this means that the Λp interaction is more attractive than the Λn one. At present there is no explanation for such an effect, although different mechanism, like the $\Lambda\Sigma^0$ mixing or the $\Lambda\mathcal{N} - \Sigma\mathcal{N}$ coupling, are taken into account to explain it.

Finally the determination of the strength of the spin-dependent terms of $\Lambda\mathcal{N}$ interaction could allow to solve the puzzle of the odd-state interaction. It is well known that the potential between the Λ and the residual core nucleus is governed by both even-state (S-wave) and odd-state (P-wave) interactions [9]. What is still unclear is the relative contribution of odd- and even-state forces. Moreover different models by Nijmegen and Jülich Groups that succeed in reproducing the main features of the 30 *MeV* $\Lambda\mathcal{N}$ central potential well, predict different behavior for the odd-state force: while the oldest ND model describes an attractive odd-state interaction, the NSC97f model assumes for it a repulsive character. However this assumption is in contrast with the experimental data on ${}^{13}_{\Lambda}C$ [10], despite of the fact that this latter model is able to successfully reproduce several hypernuclear data.

Impurity nuclear physics

Independently from the production method (strangeness exchange induced by both in-flight and stopped K^-, associated production exploiting π^+ beams or electro-production) a hypernucleus can be considered the outcome of a genetic engineering manipulation applied to the nuclear physics domain. The final result of each of the above mentioned reactions is indeed to put an explicit content of strangeness inside an ordinary nucleus.

As recalled in the Introduction, a strange particle is free from the Pauli effect and can then deeply explore the nuclear matter. The introduction of one (or two) hyperon(s) in a nucleus may give origin to various modifications of the nuclear structure, like changes of the size and of the shape, changes of the cluster structure, manifestation of new symmetries, changes of collective motions, etc..

The way to put in evidence such effects is an accurate study of the energy level spectrum of Λ-hypernuclei and a precise measurement of the $B(E2)$ probability by means of the recently introduced Doppler-shift attenuation method. This innovative technique has been made possible thanks to the use of high-resolution Ge detectors and it allowed to infer a spectacular ($\sim$ 20%) ${}^{6}Li$ nuclear core shrinkage due to the addition of a Λ particle in the $0s$ orbit [4]. Such a nuclear structure modification may appear in various hypernuclei [11], but even more drastic changes are expected when a Λ particle is implanted into neutron-rich systems having neutron skins or halos [12].

Medium effect

The relative stability of a hyperon embedded in a nucleus offers the opportunity to investigate possible modifications of its single-particle properties due to the nuclear medium. In particular if the mass (or the size) of a baryon in a nucleus is affected by a partial restoration of the chiral symmetry, its magnetic moment may be changed. The Λ particle represents the best probe to check this effect.

Direct measurement of the magnetic moment for a Λ embedded in nuclear matter is extremely difficult because of its short lifetime for spin precession. Then the new idea is to derive the Λ g-factor in a nucleus from the probability of the spin-flip transition between hypernuclear spin-doublets states (see Fig. 4).

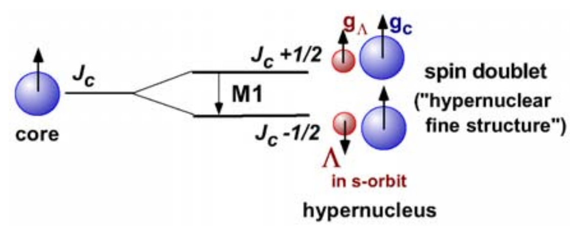

Figure 4: Spin doublet and spin-flip $M1$ transition in a hypernucleus. When a Λ particle is coupled to the core nucleus with spin J_c, the level is split into a doublet ($J_c + \frac{1}{2}, J_c - \frac{1}{2}$). The spin flip of the Λ gives origin to the $M1$ transition from the upper to the lower state in the doublet and its probability $B(M1)$ is proportional to $(g_c - g_\Lambda)^2$, where g_c and g_Λ denote g-factors of the core nucleus and a Λ particle inside a nucleus (from Ref. [8]).

In the weak coupling limit between a Λ and a core nucleus, the $B(M1)$ can be expressed as [6]

$$
\begin{aligned}
B(M1) &\propto |<\phi_{lo}|\mu^z|\phi_{up}>|^2 \\
&= |<\phi_{lo}|g_N J_N^z + g_\Lambda J_\Lambda^z|\phi_{up}>|^2 \\
&\propto (g_N - g_\Lambda)^2
\end{aligned}
\qquad (2)
$$

where g_N and g_Λ denote effective g-factors of the core nucleus and of the Λ, J_N^Z and J_Λ^Z denote their spin operators and the space components of the wavefunctions of the lower and upper states of the doublet ($\phi_{lo},\ \phi_{up}$) are assumed to be identical.

Transition probabilities such $B(M1)$ can be derived from lifetime of excited states, using again the Doppler-shift attenuation method or a new technique called "γ-weak coincidence method" [13], depending on the range of lifetime to be measured (see Fig. 5).

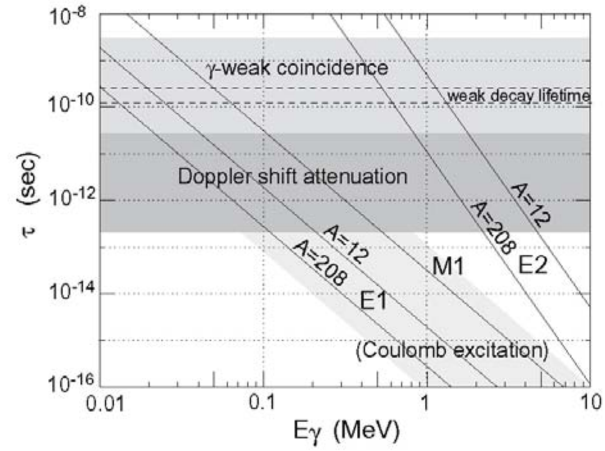

Figure 5: Lifetime ranges to which the Doppler-shift attenuation method and the γ-weak coincidence method can be applied for transition probability measurements of hypernuclei, shown together with the $E1/M1/E2$ lifetimes for Weisskopf unit as a function of transition energy. (from Ref. [13]).

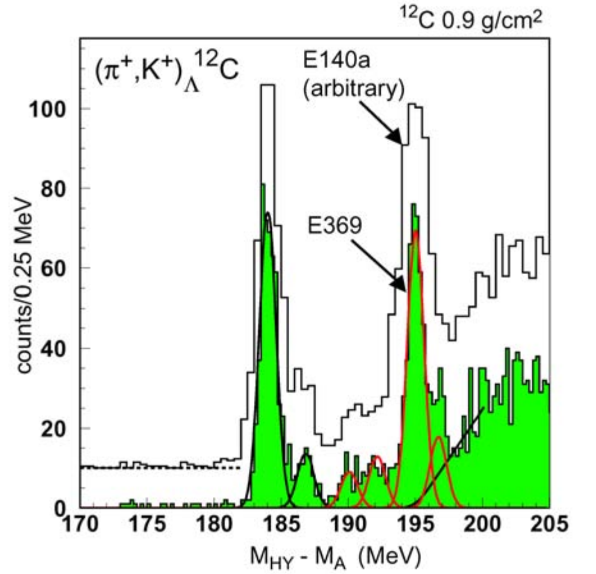

Figure 6: Hypernuclear mass spectrum of $^{12}_{\Lambda}C$ obtained with an energy resolution of 1.45 MeV (FWHM). A previous spectrum measured with a resolution of 1.9 MeV (FWHM) is superimposed with an arbitrary scale and an offset for comparison (from Ref. [14]).

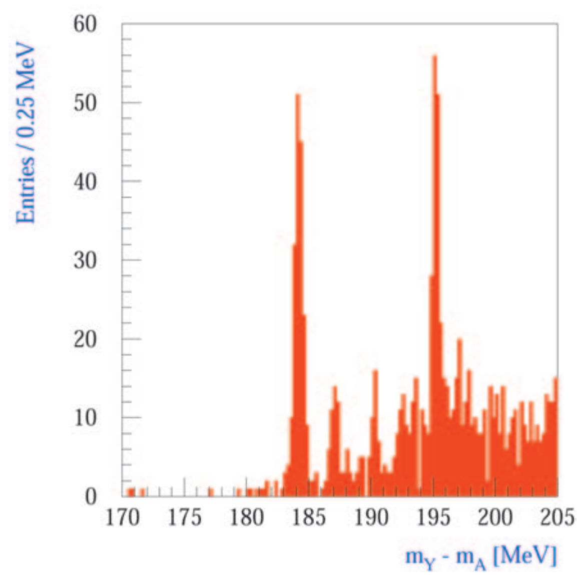

Figure 7: Simulated excitation spectrum for $^{12}_{\Lambda}C$ as seen from the FINUDA spectrometer in the hypothesis of an energy resolution of 750 keV. The spectrum corresponds to an integrated luminosity of 5 pb^{-1}.

EXPERIMENTAL SITUATION

The status of the art

In the last decade the progress in the field of the hypernuclear physics has been essentially determined by the improved energy resolution of the spectrometers. Fig. 6 shows clearly that a relative small improvement of the apparatus performances allowed to go beyond a gross description of the features of the spectrum and to start to resolve the fine structure between the two main peaks.

The FINUDA apparatus [15] was proposed to carry on a systematic scan of hypernuclear properties as a function of the mass number A, by exploiting the reaction

$$K^-_{stop} + {}^{A}Z \rightarrow {}^{A}_{\Lambda}Z + \pi^- . \quad (3)$$

By taking advantage of the fact that the extremely low-energy K^- ($\sim$ 16 MeV), produced in ϕ decay, can be stopped in very thin targets (0.1 – 0.3 g/cm^2)[1], the FINUDA spectrometer has been carefully designed in order to push the resolution on the momentum of π^- from Eq. (3) down to a 0.3% level (FWHM); this value translates in a nominal energy resolution of $\sim$ 750 keV, about a factor two better than the limit for magnetic spectrometer at present on the floor. Fig. 7 shows how the same spectrum of Fig. 6 would appear thanks to the expected performance of the FINUDA apparatus.

One step beyond

Notwithstanding this evident progress, the investigation of the physics arguments discussed in the previous Section definitely requires a further improvement of instrumental performances that can be only achieved thanks to the excellent properties of Ge detectors.

Most likely, FINUDA will be then the last apparatus for hypernuclear physics based exclusively on the magnetic analysis of the physical events. However it would be really misleading to think that this kind of "traditional" ap-

[1] It is worthwhile to note that a typical value for target thickness used in other experiments is $\sim 1\ g/cm^2$, as one can see from the indication in the upper-right corner of Fig. 6.

proach will be completely ruled out by the introduction of γ-ray spectroscopy techniques. It must be recalled, for instance, that for heavy hypernuclei the high-excitation region of the spectrum can not be explored with γ-ray spectroscopy; hence missing-mass spectroscopy remains a good tool for hypernuclear studies.

It is then straightforward to conclude that a clever combination of magnetic and γ-ray spectrometers represents the optimal solution for the next generation experiments.

Future perspectives

Thanks to the modularity of the FINUDA apparatus, it has been possible to envisage a detector upgrade in order to extend its activity beyond the completion of its original physics program. The idea is that of removing a couple of drift chambers both from the inner and the outer arrays. With a reduction of the present solid angle covered by the spectrometer ($\sim 3\pi\ sr$) of only $\sim 28\%$, such a modification provides room to install a couple of VEGA γ-ray detectors [16] inside the FINUDA magnet coil and directly looking at the nuclear targets. This segmented clover Ge detector has been developed at GSI and represents the most technologically advanced device available at present. Fig. 8 sketches how the nicknamed FINUDA2 apparatus will look like.

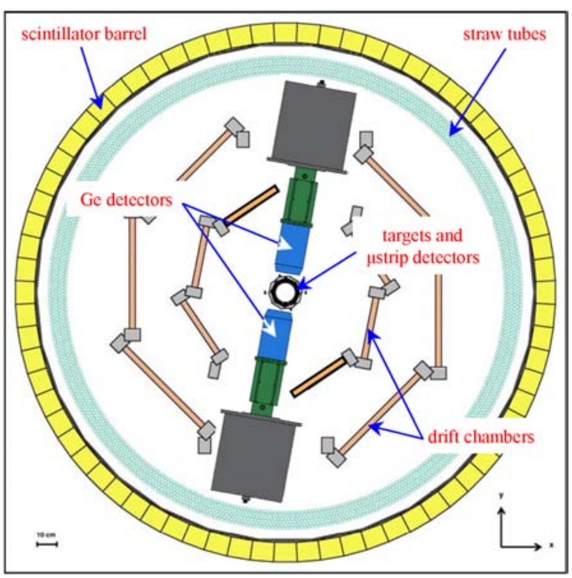

Figure 8: Frontal cross section of the modified FINUDA apparatus: four drift chambers have been removed in order to insert a couple of segmented Ge detectors.

Like the arab phoenix, the renewed FINUDA2 apparatus will then resume its activity with a physics program centered on γ-ray hypernuclear spectroscopy, but still maintaining the unique capability to detect with the same apparatus and in coincidence the prompt π^- from the hypernucleus formation reaction (3) as well as its decay products.

The main interest of the new physics program will be focussed on the γ-ray spectroscopy of a wide range of both light and medium-heavy hypernuclei, provided that the corresponding chemical element can be machined in solid slices[2].

At the actual DAΦNE luminosity, progressively approaching to $10^{32}\ cm^{-2}s^{-1}$, the expected counting rates will range from $\sim$ 1000 $event/day$ down to some $event/day$, depending on the selected γ-transition. Of course the scenario will be more attractive when it will be possible to exploit the new potentialities, in terms of luminosity, of DAΦNE2 [17]. It must be in fact recalled that the major drawback of Ge detectors is their low efficiency: the feasibility of the FINUDA2 experiments will crucially depend on the brilliance of the ϕ source.

By simply extrapolating the Monte Carlo calculations for the FINUDA apparatus in present configuration, at a luminosity of $10^{34}\ cm^{-2}s^{-1}$ one can expects to observe the formation of $\sim\ 1.6 \times 10^4\ {}^{12}_{\Lambda}C$ hypernuclei per hour in their ground state. By taking into account the following factors

• machine duty cycle:	75%
• reduced spectrometer acceptance:	72%
• Ge detector acceptance:	$\sim$ 30%
• Ge detector efficiency:	$\sim$ 30%

one finally gets $\sim\ 1.87 \times 10^4\ event/day$. By integrating this number over a typical data-taking period of 5 days one can expect to collect $\sim\ 9.33 \times 10^4$ events; this number is very close to the one foreseen for a proposed experiment [8] at the recently approved japanese facility J-PARC [18]: on the same target and in the same amount of time the authors think to observe 11.2×10^4 events.

A very promising way to overcome the limitation imposed by the availability of solid targets is represented by the study of hyperfragments, that is of hypernuclei with a mass number lower than the production target one. It is in fact well known that reaction induced by stopped K^- are the most efficient way to produce several species of hypernuclei, including proton- or neutron-rich ones, although the background level is generally high.

Therefore the production of hyperfragments further extends the possibility of hypernuclear γ-ray measurements. In addition, while medium- to high-resolution spectrometer is mandatory for direct reaction based experiments in order to identify produced bound states of a hypernucleus, poor or even no information at all on the outgoing π^- are required to detect γ-rays from hyperfragments. The identification of the created hypersystem will rely on $\gamma-\gamma$ coincidence measurements as well as on target dependence of γ-ray yields.

This fact allows to consider a spectrum of different experimental solutions: one can think of using FINUDA2 with a reduced or even without magnetic field; as an alternative it is conceivable to use the KLOE apparatus [19], provided that there is enough room between the drift chamber and the DAΦNE2 beam pipe to install a Ge detector

[2]The FINUDA/FINUDA2 arrangement is such that only solid targets are allowed to be installed around the DAΦNE collider beam pipe.

Table 1: Comparison between the expected hyperfragment "daily" yields at DAΦNE2 and at the J-PARC K1.1 line. (For the latter case numbers are taken from Ref. [8].)

	DAΦNE2	**J-PARC**
produced Φ	2.85×10^9	
produced K^-	1.40×10^9	6.67×10^8
K^- stopping efficiency	0.9	0.2
stopped K^-	1.26×10^9	1.33×10^8
hyperfragment formation probability	0.1	0.1
produced hyperfragments	1.26×10^8	1.33×10^7

array and a time-of-flight system; finally it is possible to design a dedicated apparatus, without magnet. The last two options could represent the final solution if DAΦNE2 will have only one interaction point.

Table 1 reports a comparison between the expected hyperfragments yields at DAΦNE2 and at J-PARC. Even if the number of daily delivered K^- is practical the same in both cases, the final expected yields are significantly different. This is due to the fact that the FINUDA2 target arrangement is such that the nearly totality of K^- from ϕ decay is stopped in very thin targets; on the contrary for the experiment foreseen at J-PARC the authors assume a K^- stopping efficiency of only 20% [8].

Besides these very encouraging perspectives, it is worthwhile to underline once more the important advantage due to the unique opportunity of working with low-energy K^-: they can be stopped in a very small amount of material, without any degraders. This way it is possible to greatly reduce the hadronic background, which represents the major concern for the Ge detectors safety due to the hazard of radiation damages. As a matter of fact the huge hadronic background inherent to the high-energy secondary meson beams was the main problem that in the past prevented the use of γ-ray detectors in hypernuclear physics.

CONCLUSIONS

After 50 years since the discovery of hypernuclei, the strangeness nuclear physics is a research field very active and still with a great discovery potential. Besides the interesting and, to some extent, surprising experimental results, this statement is supported by the fact that the number of experimental physicists involved is growing and that this endeavor is supported by a significative theoretical effort, well tuned on experimental data; in addition a good number of dedicated beams and of more and more sophisticated spectrometers is, or will be, available; finally hypernuclear physics appears among the main items of physics program of several future facilities.

This could be also the case of DAΦNE2: at a luminosity of $\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$ it will be possible to carry out an intensive and an exhaustive hypernuclear γ-ray spectroscopy program with the upgraded FINUDA spectrometer. The evaluated rates are such that the measurements turn out to be comparable, or even competitive, with those expected at the J-PARC facility.

REFERENCES

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

[2] H. Tamura, *Nucl. Phys.* **A 639** (1998) 83c.

[3] H. Tamura *et al.*, *Phys. Rev. Lett.* **84** (2000) 5963.

[4] K. Tanida *et al.*, *Phys. Rev. Lett.* **86** (2001) 1982.

[5] T. Bressani, *Proc. of the International School of Physics "Enrico Fermi"*, Course CLIII, A. Molinari, L. Riccati, W.M. Alberico and M. Morando (Eds.) (2003) SIF - Bologna, Italy.

[6] R.H. Dalitz and A. Gal, *Ann. Phys.* **116** (1978) 167;
R.H. Dalitz and A. Gal, *J. Phys.* G 6 (1978) 889.

[7] D.J. Millener *et al.*, *Phys. Rev.* **C 31** (1985) 499.

[8] J-PARC Strangeness Nuclear Physics Group, Letter of Intent for "New Generation Spectroscopy of Hadron Many-Body Systems with Strangeness S = -2 and -1" (2002) 1.

[9] Y. Yamamoto *et al.*, *Nucl. Phys.* **A 691** (2001) 432c.

[10] D.J. Millener, *Nucl. Phys.* **A 691** (2001) 93c.

[11] H. Tamura, *Eur. Phys. J.* **A 13** (2002) 181.

[12] V. Paticchio, *these proceedings*.

[13] H. Tamura, *Nucl. Phys.* **A 691** (2001) 86c.

[14] T. Nagae, *Nucl. Phys.* **A 691** (2001) 76c.

[15] The FINUDA Collaboration, "FINUDA: a detector for nuclear physics at DAΦNE", LNF-93/021 (1993) 1;
The FINUDA Collaboration, FINUDA technical report, LNF-95/024 (1995) 1.

[16] J. Gerl *et al.*, "VEGA: a proposal for Versatile and efficient GAmma-detectors", GSI Report (1998) 1.

[17] C. Biscari, *these proceedings*.

[18] The Joint Project team of JAERI and KEK, Proposal for High-Intensity Proton Accelerator, KEK Report 99-4 (1999) 1.

[19] The KLOE Collaboration, "KLOE: a general purpose detector for DAΦNE", LNF-92/019 (1992) 1.