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PROSPECTS ON HYPERNUCLEAR PHYSICS

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Abstract

In spite of its age, hypernuclear physics is experiencing a renewed youth. Thanks to the high quality data coming form KEK, BNL and today also from LNF, some old standing problems are going to be solved. In this talk I present a review of the most recent results obtained in the last years and I'll show some prospects for the near future.

1 Hypernuclear physics: state of the art

Hypernuclear physics is an excellent environment to match nuclear and particle physics. The study of this field is extremely useful to make systematic studies in many sectors that cannot be addressed directly. Since 1953, when the first hypernucleus was observed into a stack of emulsions exposed to cosmic radiation [1], different experimental techniques have been used to explore this field.

The earliest studies were carried out with the emulsion technique by using the (K^-_{stop},π^-) reaction. Light hypernuclei (A<16) were produced and the binding energies of the ground states were measured. From these pioneering measurements the well depth of the Λ-nucleus potential was established to be about 1/2 of that of the nucleon.

In the seventies, a new series of experiments with counter detectors started at CERN and at BNL with the intention of evaluating the spin-orbit contributions of the Λ-N interaction [2, 3, 4]. The production reaction more used was (K^-,π^-) in flight. The energy resolution available in those experiments was actually quite poor ($\sim$ 5 MeV), therefore only qualitative speculations could be hold. Nevertheless, the non-observation of spin-orbit splitting of the energy levels seemed to indicate a contribution of the spin terms to the ΛN potential smaller than that of ordinary nuclei, which amount to 3-5 MeV.

In the eighties the (π^+,K^+) reaction was proposed [5] as a better tool to perform spectroscopic studies. Here the Λ hyperon is produced with a large momentum ($\sim$ 350 MeV/c) allowing to populate many excited hypernuclear levels. This new technique was intensively used both at BNL and at KEK. In the last years, at KEK, it has been performed on target materials from A=10÷208 a complete survey, by using this production reaction and the SKS spectrometer [6, 7]. This systematic study has pointed out the independence of the Λ binding energy from the atomic mass number, revealing the single-particle nature of the Λ-nucleus interaction. This has been the arrival point of hypernuclear spectroscopy up to the introduction of the Ge detectors γ-ray spectroscopy technique. The measurement of the energy of the γ-rays emitted in the transitions among the different hypernuclear levels has pin down the energy resolution from the MeV to the keV level, allowing to attack the long standing puzzle of the ΛN spin-orbit interaction. Firstly tried at KEK, this new experimental technique was then exported to BNL, reveling new subjects for hypernuclear physics like the Λ "*glue-like role*" [9] and the study of the meson properties modification in the nuclear medium [10].

For what concerns the production mechanisms, presently two new techniques are starting to demonstrate their good possibilities: photo-production, and the use of (K^-_{stop},π^-) reaction employing the low energy kaons arising from the ϕ-decay. Photo-production, in spite of its low cross-section, that nevertheless is fully compensated by the high intensity of the TJNAF electron beam, is characterized by a large momentum transfered to the Λ, and also by the possibility to induce spin-flip transitions. This allows to populate hypernuclear states with unnatural parity [11, 12]. On the other hand, the K^- of 127 MeV/c available at DAΦNE, the Frascati ϕ factory, may be stopped in very thin nuclear targets ($\sim$ mg/cm^2) reducing the energy degradation suffered by the pion emitted in the hypernucleus formation reaction. This feature, combined with the high momentum transfered to the Λ particle, is opening new possibilities for hypernuclear spectroscopy. The new production techniques, used in conjunction with modern spectrometers designed to achieve sub MeV energy resolutions, are producing a new high quality data set both for studying hypernuclear spectroscopy and hypernuclear decay modes. Figure 1 shows the preliminary ${}^{12}_{\Lambda}$C spectrum, obtained by the FINUDA Collaboration at DAΦNE [13], and the ${}^{12}_{\Lambda}$B one obtained with the photo-production technique [11].

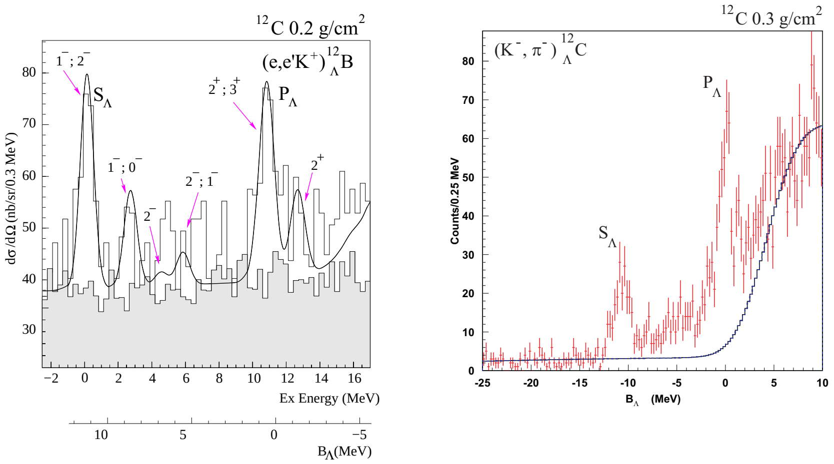

Figure 1: *Left: Spectrum of ${}^{12}_{\Lambda}B$ measured at JLAB (energy resolution 900 keV). Right: Spectrum of ${}^{12}_{\Lambda}C$ measured at DAΦNE (energy resolution 1.4 MeV).*

In the following sections I will review some of the most important results that are coming out from different experiments in this field.

2 Hypernuclear spectroscopy

The spectroscopic studies of hypernuclei are of paramount importance for constraining ΛN interaction models. In fact, direct measurements of hyperon-nucleon interaction [14, 15] are extremely difficult due to the low hyperon beam intensity and short lifetime ($c\tau \sim 10$ cm). Production and scattering in the same target is almost automatically required. Two classes of theoretical models of ΛN interaction are nowadays available: meson exchange models (where the exchange of one or sometimes two mesons is considered) [16], and quark-cluster models that introduce quark degrees of freedom to better describe short-range interaction [17]. To overcome the lack of scattering data both classes of models try to determine free parameters by fitting together NN and YN experimental data. Nevertheless, none of these theoretical approaches is completely satisfactory and discrepancies come out especially when the spin-terms of the interaction are considered. Since the quality of the YN scattering data cannot be improved, alternative information are extracted from hypernuclear spectroscopic studies. At present, experimental measurements of the spin-observable, performed mainly using Ge detectors, are the major source of data to discriminate among the different approaches.

The two-body ΛN effective interaction is normally expressed as the sum of five radial integrals associated with different contributions:

$$V_{\Lambda N}(r) = V_0(r) + V_\sigma(r)\vec{s}_{\mathcal{N}} \cdot \vec{s}_\Lambda + V_\Lambda(r)\vec{l}_{\Lambda N} \cdot \vec{s}_\Lambda + V_N(r)\vec{l}_{\Lambda N} \cdot \vec{s}_N + V_T(r)\mathbf{S_{12}} \quad (1)$$

where $\mathbf{S_{12}} = 3(\vec{\sigma}_N \cdot \vec{r})(\vec{\sigma}_\Lambda \cdot \vec{r} - \vec{\sigma}_N \cdot \vec{\sigma}_\Lambda)$

These five terms ($\bar{V},\ \Delta,\ S_\Lambda,\ S_N,\ T$) are taken to be constant throughout the shell. The average central interaction ($\bar{V}$) has been fixed to reproduce the measured Λ binding energies (B_Λ), and the spin dependent terms can be determined by observing γ ray transitions from p-shell hypernuclei. The spin-spin force (Δ), the Λ spin-orbit force (S_Λ), and the tensor force (T) are obtained from hypernuclear fine structure. The nucleon spin-orbit force (S_N) determines the difference between the nucleon excitation energy of the hypernucleus and its core nucleus.

Since 1998, when the Hyperball Ge-detector started its experimental activity, a big bulk of data have been collected on the energy of the gamma-ray transitions of many light hypernuclei both at KEK and at BNL.

The data collected up to now [18, 19, 20, 21] show the great potentialities of hypernuclear γ-spectroscopy, nevertheless, the contradictory results presently available do not allow to draw any firm conclusion. Probably, the picture will become more clear after the completion of the research program under way for the J-PARC future facility [22]. Furthermore, complementary information will come also form FINUDA2 [23] and from PANDA at GSI [24] where similar activities are foreseen.

2.1 ΛΛ-hypernuclei

The case of double Λ hypernuclei is quite peculiar: they were discovered in an emulsion experiment in 1963 [25], but after this first observation several counter experiment tried to detect them unsuccessfully. Finally, in the last years new experiments at KEK (E176 and E373) and at BNL (E906) have detected new events. The strong interest in this research is related to the fact that ΛΛ-hypernuclei could be the door to access the H-particle, a dybarionic S = -2 state (*uuddss*) [26] never seen up to now, and also because this is the unique possibility to get information on YY interaction. The new evidence of ${}^{6}_{\Lambda\Lambda}$He through the so called Nagara event [27] has provided an invaluable source of information on the strength of the ΛΛ interaction. Before this discovery, relying on the old measurements giving a value for $\Delta B_{\Lambda\Lambda} \sim 4.3$ MeV, it was believed that the ΛΛ force would be more attractive than the corresponding ΛN. Now it seems more reasonable that the ΛΛ interaction should be weakly attractive. In fact, the $\Delta B_{\Lambda\Lambda}$ value deduced from the Nagara event is 1.01 ± 0.20 MeV [28, 29].

Double Λ hypernuclei could be abundantly produced at the new facilities JPARC and PANDA allowing a systematic study of the binding energies of ground and excited states. Therefore, more information on the effective strength of YY interaction will come in the near future. Furthermore, the encouraging results obtained analyzing the γ-ray spectra of Λ-hypernuclei led to the proposal of the PANDA experiment of using the same technique for getting more information on ΛΛ interaction [24].

2.2 Neutron-rich hypernuclei

Nuclear matter with an extreme N/Z ratio is at present a hot topic of nuclear physics. It has been discovered that in such nuclear systems there is a so called "*halo phenomenon*": some of the nucleons extend far outside the region of the nuclear core. Following this line, Majiling [30)] stressed that Λ-hypernuclei may be even better candidates to have larger values of N/Z and halo phenomena thanks to the "glue-like role" of the Λ particle [9)]. The existence of neutron-rich hypernuclei, like ${}^{7}_{\Lambda}$H, with a value of N/Z = 5, and of halo hypernuclei like ${}^{7}_{\Lambda}$He and ${}^{9}_{\Lambda}$He, has been predicted by many theoreticians, but an experimental confirmation has not yet been found.

Present experiments, KEK E521 and FINUDA are looking for these systems, but up to now, only upper limits on the production rates have been given [31, 32, 33)]. Nevertheless, with the facilities foreseen for the future [22, 34)] it would be possible to study systematically the production of neutron rich hypernuclei, assessing their existence and determining their binding energies.

3 Hypernuclear decays

Hypernuclear decay studies may give access to experimental information not otherwise achievable, in particular non-mesonic decays (NMWD). They consist into a weak interaction of the Λ with a nucleon, producing in the final state a pair of nucleons: $\Lambda + n \rightarrow n + n + 176\text{MeV}; \Lambda + p \rightarrow p + n + 176\text{MeV}$. These processes $(\Gamma_n; \Gamma_p)$ are the only way to explore the four fermions, strangeness changing, baryon-baryon weak interaction. The ratio Γ_n/Γ_p is an important observable used to study the isospin contributions to the NMWD. During the last 40 years there has been a long standing puzzle concerning this ratio. In fact the experimental value (close to 1) was fairly in disagreement with the theoretical calculations, based on One Pion Exchange models (OPE), predicting a number close to zero. This large discrepancy stimulated many theoretical speculations while the experimental data still remain with large errors. Recently, the neutron and proton energy spectra from ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C have been measured with high statistics [35)]. The value obtained for the ratio Γ_n/Γ_p is ~ 0.5. This result rules out the theoretical calculations based on the OPE and supports recent speculations based on short-range interactions including also multi-nucleon induced processes, and large final state interaction effects [36, 37)]. Nevertheless, it remains unclear why the same calculations reproduce well hypernuclear total width. New data on different target materials are also coming out from the FINUDA experiment. Here again, protons and neutrons are both detected, and Γ_n and Γ_p are thus directly evaluated. Some preliminary results on this analysis are reported in these proceedings [38].

4 The FINUDA experiment at DAΦNE

KEK and BNL activities in the hypernuclear physics sector are no more going on. At present, the running hypernuclear factories are only DAΦNE at LNF and CEBAF at TJNAF. DAΦNE has a very wide and complete hypernuclear physics program that is carried out by the FINUDA international collaboration. FINUDA (FIsica NUcleare a DAΦNE) is the first hypernuclear physics experiment carried out at an e^+e^- collider. At DAΦNE Λ-hypernuclei are produced by means of the reaction: $K^-_{stop} + ^A Z \rightarrow ^A_\Lambda Z + \pi^-$ stopping the low energy negative kaons from the ϕ decay into a thin ($200 \div 300$ mg/cm^2) nuclear target. The positive kaons emitted on the other side are extremely useful to tag the reaction [39].

FINUDA is a non-focusing magnetic spectrometer designed to achieve a resolution Δp/p of 0.35% (*FWHM*) for the π^- emitted in hypernucleus formation. This translates into an energy resolution of 830 keV for the levels of the hypernucleus. Furthermore, it detects the charged particles and the neutrons emitted after the Λ decay, allowing to perform, at the same time, hypernuclear spectroscopy and studies on the hypernuclear decay modes. More details on the FINUDA detector could be find in ref. [40].

The first round of the FINUDA data taking has been performed from October 2003 up to March 2004. A first integrated luminosity of about 50 pb^{-1} has been collected both for machine and detector calibration purposes; further 200 pb^{-1} are being used for the scientific analyses. With the two ^{6}Li targets FINUDA may access light hypernuclear systems; $^6_\Lambda$Li is unstable for proton emission that makes it decaying into $^5_\Lambda$He + p or it may transform into $^4_\Lambda$He + p + n or into $^4_\Lambda$H + p + p via a Coulomb assisted mechanism. Furthermore, ^{6}Li data are used to look for neutron-rich hypernuclei. The ^{7}Li target has been chosen since $^7_\Lambda$Li is the most extensively studied hypernucleus with γ-ray spectroscopy: FINUDA intention is to provide the first data on its decay modes. Another aspect that may be addressed through the light targets data

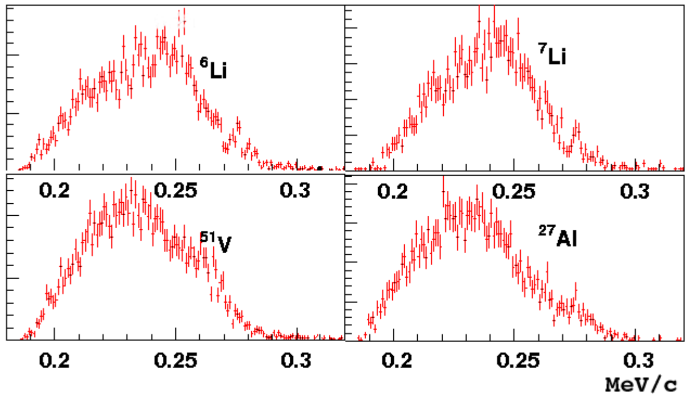

Figure 2: π^- *spectra measured by the FINUDA spectrometer on different nuclear targets.*

is the existence of the deeply-bound kaonic systems [41]. $^{12}_{\Lambda}$C is the best known hypernuclear system, therefore, the three targets of this material will help the calibration procedure of the apparatus and will provide enough statistics to perform non-mesonic decay studies. Finally, ^{27}Al, and ^{51}V are medium-heavy nuclei not well known. For $^{27}_{\Lambda}$Al there are old data taken using K$^-$ in flight and a very coarse energy resolution (6 MeV *FWHM*). The excitation spectrum of $^{51}_{\Lambda}$V has been measured at KEK [42] with an energy resolution of 1.65 MeV (*FWHM*). The peaks corresponding to p and d orbits show possible splitting that might be better resolved with the FINUDA higher resolution. Figure 4 shows the raw spectra of π^- coming out from different nuclear targets measured by the FINUDA spectrometer. Hypernuclear peaks are clearly visible in all the histograms.

5 Conclusions

Hypernuclear physics has achieved nowadays the status of a mature science. Thanks to excellent facilities, first class detectors, and optimum theoretical contribution we can expect in the next future new high quality results.

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