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Study of the proton weak decay of $^{12}_{\Lambda}C_{g.s.}$ with FINUDA

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Abstract. The FINUDA experiment studies the Λ-Hypernuclei formation and decay using the reaction (K^-_{stop}, π^-) induced by the low-momentum K^- from the deacy of the ϕ meson produced at the (e^+, e^-) collider DAϕNE at the Laboratory Nazionali di Frascati of INFN. In this paper we present new data on the proton spectra following the weak decay of $^{12}_{\Lambda}$C.

PACS. 2 1.80.+a; Hypernuclei – 1 3.75.Ev Hyperon-nucleon interactions.

1 Introduction

FINUDA (FIsica NUcleare a DAΦNE) is a non focusing magnetic spectrometer devoted to hypernuclear physics. The aim of FINUDA is to study simultaneously the formation and decay of hypernuclei produced by the strangeness exchange reaction induced by the stopped K^- coming from the decay of the $\phi(1020)$ mesons produced at the DAΦNE ϕ-factory.

The FINUDA apparatus, described in detail in [1], [2], [4], [3] and [5] and references therein, consists of an inner section surrounding the interaction-target region, an external tracker, an outer scintillator array and a superconducting solenoid providing a magnetic field of 1.0 T. The whole tracking volume ($\sim$ 8 m^3) is immersed in a He atmosphere to minimize multiple Coulomb scattering. The geometry of the spectrometer, the position of the detectors and the value of the maximum magnetic field have been chosen in order to optimize the momentum resolution and acceptance for the prompt π^- from the hypernuclear formation reaction $K^-_{stop} + \, ^{A}Z \rightarrow \, ^{A}_{\Lambda}Z + \pi^-$. For such

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π^- (250-280 MeV/c), the design momentum resolution is $\Delta p/p = 3.5 \times 10^{-3}$ $(FWHM)$, corresponding to a resolution of 830 keV in the hypernuclear energy levels.

${}^{12}_{\Lambda}C$ spectroscopy

The first run of FINUDA started on Decembre 1^{st} 2003 and ended on March 24 2004. In this period the machine delivered an integrated luminosity of ~ 250 pb^{-1}, of which 190 pb^{-1} usefull for physics studies[6]. The analysis of the data started with a study of the excitation energy spectrum of ${}^{12}_{\Lambda}C$, trying to push at the best the instrumental resolution on the measurement of the π^- momenta. To that purpose the following requirements were adopted in order to optimize to signal to background ratio: 1) a negative track (negative pion candidate) connected to the K^- stopping point, 2) a track reconstructed by fitting 4 points measured by the spectrometer detectors, 3) a forward pion track, i.e. not crossing back the interaction/vertex region, 4) the pion momentum reconstructed and corrected for the energy loss in the crossed material, 5) quality cut on track fitting. The π^- momentum spectrum obtained under these conditions and corresponding to about half of the collected statistics is shown in fig.1a) taken from [7].

There is a physical background extending beyond the kinematical limit of the reaction $K^-_{stop} + {}^{12}C \rightarrow {}^{12}_{\Lambda}C + \pi^-$ (273 MeV/c) due to the $K^-NN \rightarrow \Sigma^-N$ reaction followed by $\Sigma^- \rightarrow n\pi^-$. This source of background, which is the only one affecting considerably the bound state region of ${}^{12}_{\Lambda}C$, was well reproduced, togheter with the other background sources affecting the lower momenta region, by a dedicated MonteCarlo simulation code inspired by the work of Tamura [8]. After subtraction of this background and conversion on a $-B_{\Lambda}$ scale, a nice excitation spectrum was obtained, with an energy resolution of 1.29 MeV FWHM. Furthermore, improvements in the reconstruction codes and on the relative alignement of the different sub-detectors led to a value of 1.1 MeV FWHM for a single target [9]. However, since the full statistics on ${}^{12}C$ has been collected using 3 carbon targets located in different places around the interaction/vertex region, a particular care is needed in order to correct the pion momenta for the DAΦNE beam boost [6]. This work in still in progress, and we present here the results of the analysis of the full statistics concerning the spectrum of protons emitted by the ${}^{12}_{\Lambda}C$ ground state weak decay.

We notice here that we may obtain from the same raw data quite different excitation spectra just by changing the selection criteria described above, by means of a less tight selection on the track fitting quality and by accepting in the data sample analized the tracks crossing back the interaction/vertex region. Fig.1b) shows the momentum spectrum of π^- from ${}^{12}C$ (three targets) obtained with more relaxed selection criteria. An increase of statistics of about a factor 6 is evident as well as the signal/background ratio worsening. The experimental situation is quite different from that ot the fixed target spectrometers [10] in which data at high resolution or at high statistics require different target thiknesses and dedicated runs.

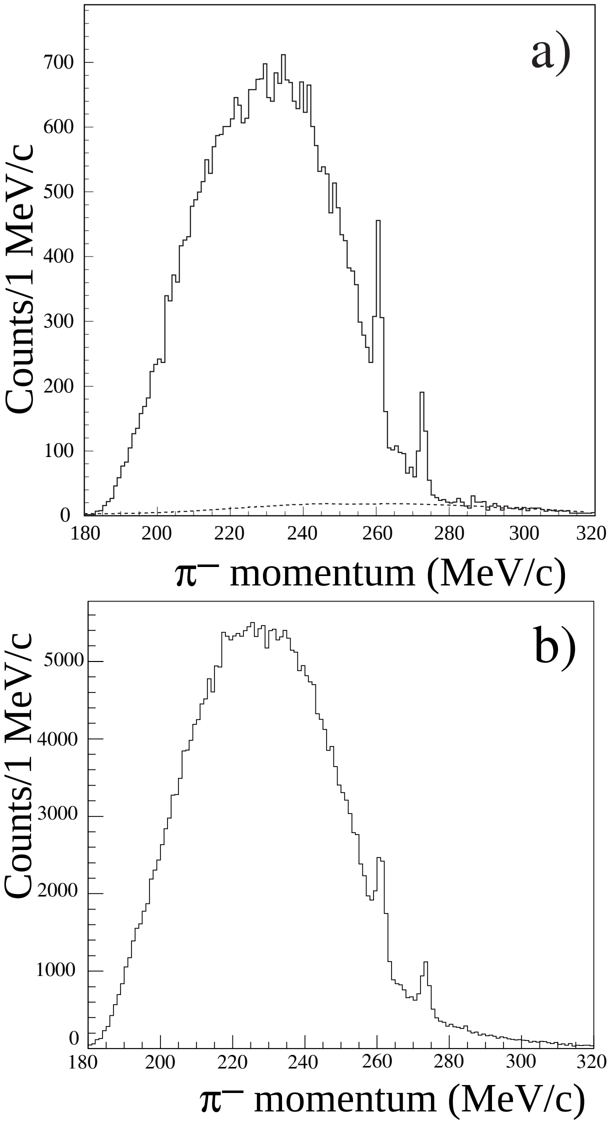

Fig. 1. a) Momentum spectrum of π^- from ${}^{12}C$ targets, obtained with the selection criteria optimized for high energy resolution hypernuclear spectroscopy. The dashed line represents the distribution from K^- absorption by two nucleons. From [7]. b) Momentum spectrum of π^- from ${}^{12}C$ targets obtained using more relaxed selection criteria with respect to the spectrum of fig.1a)

Proton spectra from ${}^{12}_{\Lambda}C$ ground state decay

Fig.2 shows the π^- spectrum of fig.1b) with the additional requirement of a proton in coincidence. We may notice that the statistics is of the same order of the spectrum at high resolution (fig.1a)) but with a worser signal/noise ratio. The dashed spectrum in fig.2 represents the π^- simulated spectrum from the reaction $K^-np \rightarrow \Sigma^-p$ followed by $\Sigma^- \rightarrow n\pi^-$ passed through the same selection criteria of the real data and normalized in area beyond 275 MeV/c.

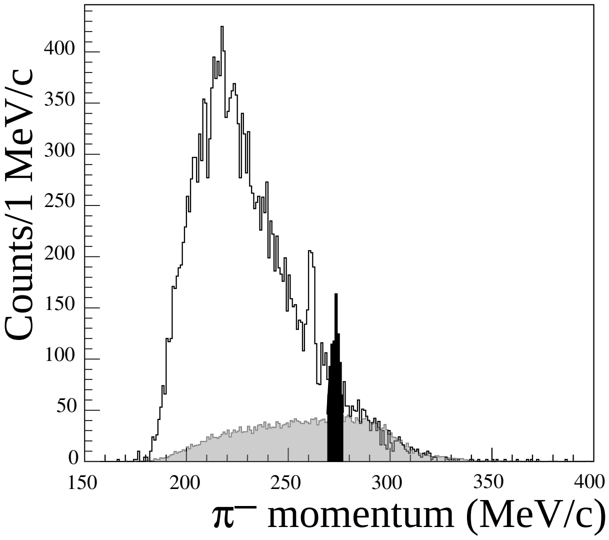

Fig. 2. Momentum spectrum of π^- of fig.1b) with the additional requirement of a proton in coincidence. The grey spectrum represents the π^- spectrum from K^- absorption by two nucleons. The black area of the peak at 273 MeV/c represents the ${}^{12}_{\Lambda}C$ ground state region.

Fig.3a) shows the proton energy spectrum (dots) emitted in coincidence with a π^- coming from the ${}^{12}_{\Lambda}C$ ground region (black area of fig.2). The squares represent the proton spectrum coming from the two nucleon absorbtion mechanism, evaluated by the MonteCarlo simulation program and corresponding to the interval 270-275 MeV/c in π^- momenta (black area of fig.2). Both hsitograms are acceptance corrected. We remark that the main feature of such a spectrum (a broad bump centered around 120 MeV) was already observed in another study of the proton spectra emitted following capture of the K^-[11]. Fig.3b) shows the difference between the two spectra in fig.3a). The errors are statistical only (data and MonteCarlo). We remark that in a simple, fully experimental approach of the background contribution done by subtracting the proton spectrum measured in correspondence to the sidebins (275-280 MeV/c) of the π^- spectrum, we obtained a spectrum fully compatible with that of fig.3b), even with large errors. The absolute branching ration Γ_p for the proton stimulated weak decay is found to be $(0.41 \pm 0.15) \times \Gamma_\Lambda$, for protons of energy larger than 20 MeV.

Discussion and conclusion

The proton spectrum of fig.3b) is the one naively expected from a simple $\Lambda n \rightarrow np$ weak decay reaction in nuclear matter. The bell shaped spectrum, centered around 80 MeV (Q-value of the weak decay reaction) is well explained by the Fermi momentum of the interacting baryons in the nucleus, giving a width of ~ 60 MeV. The low energy rise can be explained both by the Final State Interaction of the emitted protons, and by the two-nucleon induced mechanism $\Lambda(np) \rightarrow nnp$. As a matter of fact early theoretical calculations [12] predicted such a naive spectrum, however inconsistent with early emulsion experiments [13] or counter experiment having a quite large energy threshold for proton detection [14].

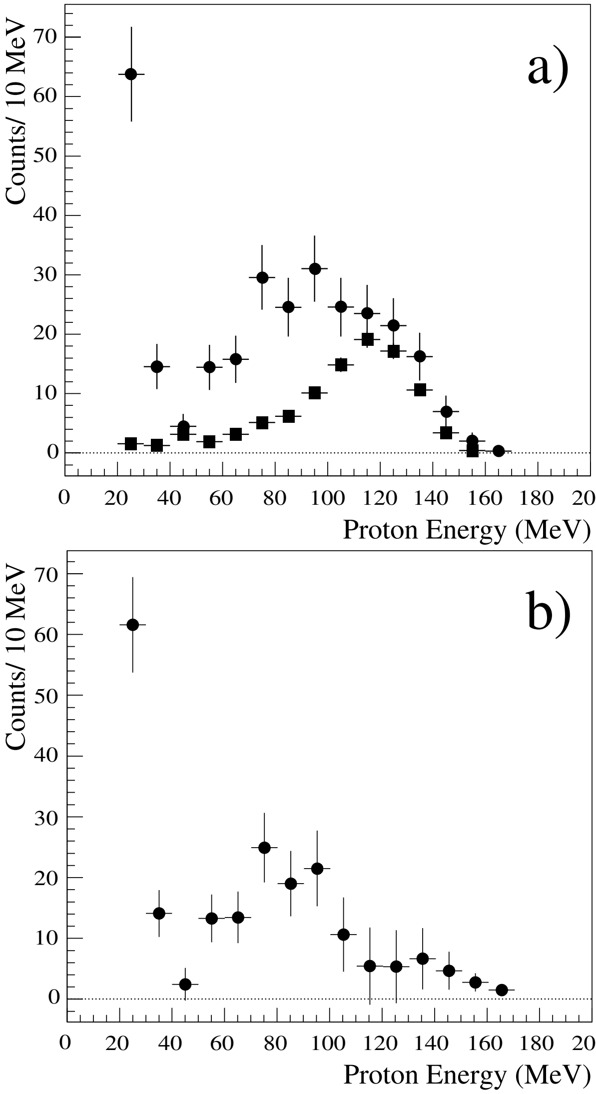

Fig. 3. a) Dots: energy spectrum of the protons emitted in coincidence with π^- in the ^{12}C ground state region. Squares: energy spectrum of the protons from the K^- absorption by two nucleons emitted in corrispondence of the shaded area of fig.2. b) difference between the two spectra of fig.3a)

In the following years a big effort was done, both on experimental side at KEK with the SKS spectrometer and on theory side, that partially shed light on several items. Quite recent reviews are due to Outa[15] and Alberico and Garbarino[16]. A high statistics proton spectrum measured from the ${}^{12}_{\Lambda}C$ ground state decay was recently published by Okada et al. [17]; their spectrum is quite flat and with an energy threshold of ~ 30 MeV and is quite inconsistent with the proton energy spectrum reported in this work. Fig.4 shows a comparison of the two spectra normalized in area beyond 35 MeV. A reduced χ^2 (χ^2/d.o.f) test applied to the compatibility of the two distribution gives a values of 5.0 corresponding to a confidence level (C.L.) lover than 10^{-7}. The same check done with the raw data spectrum of fig.3a) and the spectrum from SKS gives a χ^2/d.o.f. of 23.1, leading to an even bigger inconcistency netween the two set of data.

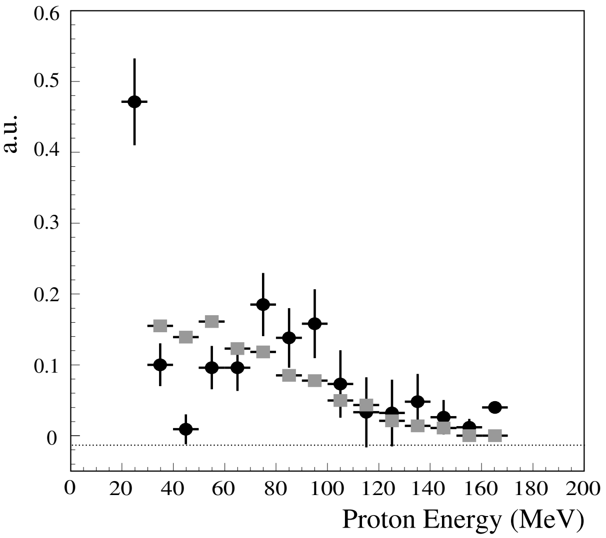

Fig. 4. Comparison between the present (dots) and KEK-SKS (gray squares) data. The two spectra were normalized in area beyond 30 MeV.

We may put forward the following comments on the above discrepancy. The FINUDA data are certainly superior concerning the quality of the experimental tools; the proton energy measured by the FINUDA magnetic spectrometer providing a resolution better than 1% FWHM is more precise than that obtained with a range telescope like in SKS. Furthermore the stopping target in FINUDA are very thin (less the 200 mg/cm^2) and introduce a lower proton energy threshold, ~ 20 MeV, which can be lowered to about 5 MeV with a different cryterium of track selection. On the contrary the nuclear target thikness used at SKS was quite high to increase the coincidence counting rate and then the raw data had to be corrected to take into account this effect. Furthermore we may notice that a recent theoretical work[18] found a strong disagreement between the proton spectra reported by SKS and the calculations that lead the authors to put forward the possibility of an under-extimation of the number of protons in experimental data.

In conclusion we may assert that further measurements on proton spectra and other hypernuclear weak decay observable are needed. At the moment FINUDA just started a long data taking period with the goal of collecting data with an integrated luminosity of about 1 fb^{-1}, corresponding to an increase of statistics of about a factor 10 with respect to the previous data taking. Further measurements are also foreseen with SKS in the next future at J-PARC[19].

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