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Latest results of stopped K^- physics with FINUDA

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The FINUDA experiment was operated at one of the two interaction points of the DAΦNE e^+e^- collider in LNF (Frascati-Italy). A rich program of studies of K^--induced interactions was performed stopping the low energy K^- from the $\Phi(1020)$ decay on a set of nuclear targets. A survey of the results achieved so far is given, with emphasis on the study of mesonic and non-mesonic weak decays of Λ-hypernuclei and on the search for bound kaonic nuclear aggregates.

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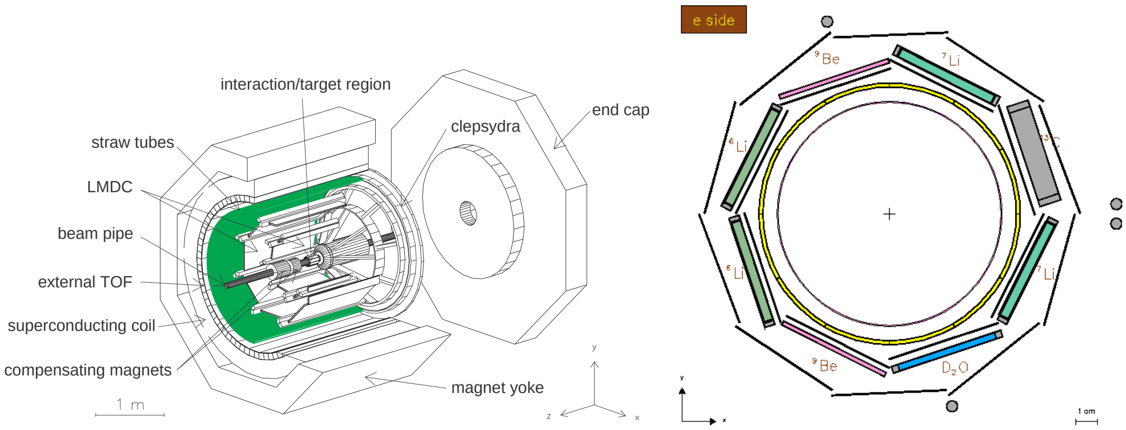

Figure 1: On the left the global view of the FINUDA apparatus and on the right the interaction-target region.

1. The FINUDA experiment

The FINUDA experiment was installed at one of the two interaction points of the DAΦNE e$^+e^-$ collider in LNF (Frascati-Italy). DAΦNE is a unique source of low energy negative kaons ($\sim 16\,MeV$) from the $\Phi(1020)$ decay ($\Phi \rightarrow K^-K^+$). The K^- can be tagged by detecting in coincidence the associated K^+ and in this way an efficient background rejection can be performed. These charged kaons slow down crossing the internal region of the FINUDA apparatus until they interact at rest in thin targets. The FINUDA apparatus in Fig.1, whose structure details can be found in Ref. [1], was a non-focalizing magnetic spectrometer within a superconducting solenoid, which provided a highly homogenous magnetic field of 1.0 T. The tracking volume ($\sim 8\,m^3$) was immersed in a He atmosphere to reduce multiple scattering, a crucial task to achieve the required momentum resolution. Its three main regions were:

- **Vertex:** the 500 μm Beryllium beam pipe, a segmented detector made of plastic scintillators (TOFINO), used to start the TOF system and discriminate kaons from MIPs at trigger level, a layer of 8 double-sided microstrip silicon detectors (ISIM) facing the targets (up to 8 different tiles). Targets' thickness (0.2-0.3 mg/cm^2) caused negligible energy degradation and was accurately chosen to stop the negative kaons close to their external surface to minimize momentum straggling of the emitted particles.

- **External Tracker:** a layer of 10 double-sided microstrip silicon detectors (OSIM) facing the external side of the targets, two arrays of Low Mass Drift Chambers (LMDC), filled with a He-iC_4H_{10} mixture and a system of longitudinal and stereo straw tubes (STB).

- **External Time-Of-Flight detector**: an array (TOFONE) of 72 slabs of plastic scintillator, 10 cm thick, for first level trigger purposes, TOF measurements and neutron detection with a 10 % efficiency.

The FINUDA main features were: 1) precise kaon vertex reconstruction; 2) Particle Identification (PID) using the information of the specific energy loss in ISIM, OSIM, the two layers of LMDC and TOF; 3) high momentum resolution of the tracking system ($\sim$ 0.6% FWHM for pions of $\sim$

270 MeV/c); 4) multiple targets; 5) large angular acceptance, $\sim 2\pi$ sr.
During the first FINUDA data taking period (from October 14^{th}, 2003 to March 22^{nd}, 2004) a maximum luminosity of $7 \cdot 10^{31}$ cm^{-2} s^{-1} was reached, with 100 bunches per ring. The average integrated luminosity per day was about 2 pb^{-1}, and a total integrated luminosity of 250 pb^{-1} was collected (190 pb^{-1} useful for physics analyses).
The second FINUDA data taking started on October, 2006 and ended on June, 2007. During the second data taking period an increased peak luminosity of $1.4 \cdot 10^{32}$ cm^{-2} s^{-1} was reached. The average integrated luminosity per day was about 7 pb^{-1} and a total integrated luminosity of 964 pb^{-1} was collected. The targets chosen in the first exploratory data-taking were ^{6}Li (two), ^{7}Li (one), ^{12}C (three), ^{27}Al and ^{51}V, while in the second run the set-up was made of ^{6}Li (two), ^{7}Li (two), ^{9}Be (two), ^{13}C and D_2O.

2. K^-_{stop} physics with FINUDA

The stopped K^- may be absorbed by one nucleon producing a pion and a slow hyperon. This is the basic mechanism of the hypernuclear formation via strangeness exchange reaction ($K^- + n \rightarrow \Lambda + \pi^-$). The K^- absorption may occur also on two or more nucleons without pion emission ($K^- + (2N) \rightarrow Y + N\,, K^- + (3N) \rightarrow Y + (NN)\,, K^- + (4N) \rightarrow Y + (NNN)$). These non mesonic channels can be exploited to search for kaon-nuclear clusters. The hyperon momentum in the multi-nucleon absorption reactions is rather large (>500MeV/c) in spite of its low momentum in the one nucleon absorption reaction.
In the following I will focus on two items of the kaon induced reactions: Λ hypernuclei weak decays and the study of multi-nucleon K^- absorption to search for antikaon-nuclear clusters.

2.1 Λ hypernuclei weak decays

A Λ hypernucleus may decay by emitting a nucleon and a pion (Mesonic channel, MWD) as it happens for the Λ hyperon in the free space ($\tau_\Lambda^{free} = \hbar / \Gamma_\Lambda^{free} = 2.632 \times 10^{-10}$ s) according to the processes: $\Lambda \rightarrow \pi^- p\,(B.R. = 63.9 \times 10^{-2}, \Gamma_{\pi^-})$ and $\Lambda \rightarrow \pi^0 n\,(B.R. = 35.8 \times 10^{-2}, \Gamma_{\pi^0})$ (not detectable by FINUDA). In the hypernuclei an alternative channel is opened due to the many-baryon weak interaction of the Λ with the nucleons: the Non Mesonic Weak Decay (NMWD). The NMWD mode is dominant in medium-heavy nuclei (A $\geq$12), where the mesonic decay is suppressed because of Pauli blocking. The NMWD can be induced by one or two nucleons: in the first case the hyperon interacts with a single nucleon ($\Lambda n \rightarrow nn$ (Γ_n) and $\Lambda p \rightarrow np$ (Γ_p)) in the second with a pair of correlated nucleons ($\Lambda NN \rightarrow nNN$ (Γ_2)). The total weak decay rate of a Λ–hypernucleus is $\Gamma_T = \Gamma_M + \Gamma_{NM}$, where Γ_M and Γ_{NM} are, respectively, the mesonic and non mesonic decay widths, which can be written as $\Gamma_M = \Gamma_{\pi^-} + \Gamma_{\pi^0}$, $\Gamma_{NM} = \Gamma_1 + \Gamma_2$ with $\Gamma_1 = \Gamma_n + \Gamma_p$. A systematic study of MWD [4] of p-shell Λ-hypernuclei was performed by the FINUDA experiment and, for the first time, a magnetic analysis of π^- spectra from MWD of $^7_\Lambda$Li, $^9_\Lambda$Be, $^{11}_\Lambda$B and $^{15}_\Lambda$N was made. The lower threshold for the detection momentum of these π^-'s is $\sim$ 80 MeV/ and their momentum resolution is $\Delta p/p \sim 6\%$ FWHM at 110 MeV/c. The data analysis required coincidence events of two negative pions from the K^- vertex reconstructed in the target, one of them giving the signature of the formation of the ground-state of an hypernucleus, while the second one, of low momentum ($\approx$ 100 MeV/c), was emitted in the decay.

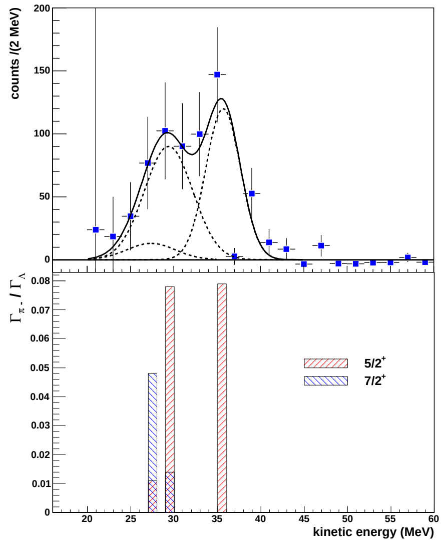

Figure 2: Upper figure: kinetic energy spectrum of MWD π^- after acceptance correction for ${}^{11}_{\Lambda}B$. The solid curve is a three Gaussian fit to the spectrum to compare with theoretical predictions in the lower part; dashed curves are the single components. Lower figure: mesonic decay strength functions calculated [2] for initial hypernuclear ground-state spin $5/2^+$[4].

MWD decay rates $\Gamma_{\pi^-}/\Gamma_\Lambda$ have been evaluated and compared to previous measurements and theoretical calculations. Decay rates were calculated, using known $\Gamma_{tot}/\Gamma_\Lambda$ values or relying on a linear fit to the known values of all measured Λ-hypernuclei in the mass range $A = (4 \div 12)$. The study of the pion spectra from MWD can be an indirect spectroscopic investigation tool providing information on the spin-parity of the hypernuclear ground state; this is based on a comparison between both MWD spectrum shape and the evaluated decay rate and the theoretical calculations. In this way the spin-parity assignment $J^\pi({}^{11}_{\Lambda}B_{g.s.}) = 5/2^+$, shown in in Fig. 2, was confirmed and a new assignment, $J^\pi({}^{15}_{\Lambda}N_{g.s.}) = 3/2^+$, was made.

Thanks to the large mass number range and to the low energy threshold (15 MeV) featured for the proton detection, FINUDA could give a precious contribution to the NMWD studies. The proton identification efficiency was about 90% while the proton energy resolution was $\Delta E/E \sim 2\%$ FWHM at 80 MeV.

The FINUDA experiment performed a complete analysis of the proton energy spectra emitted in the NMWD of ${}^{5}_{\Lambda}$He, ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be, ${}^{11}_{\Lambda}$B, ${}^{12}_{\Lambda}$C, ${}^{13}_{\Lambda}$C, ${}^{15}_{\Lambda}$N and ${}^{16}_{\Lambda}$O hypernuclei. The analysis method required a coincidence of a proton and a negative pion, which carried the information of the hypernuclear state and therefore it was selected in the momentum region corresponding to the Λ–hypernucleus formation. In the ${}^{12}_{\Lambda}$C case the momentum selection was extended to the whole Λ bound region for statistics reasons. The details of the interval choice are exhaustively described in Ref. [4, 5]. The main background source was the $K^-(np) \to \Sigma^- p$ absorption on two correlated nucleons, followed by the in–flight $\Sigma^- \to \pi^- n$ decay, The reaction was simulated, reconstructed with the same analysis program used for the real data and subtracted from the spectra. Among

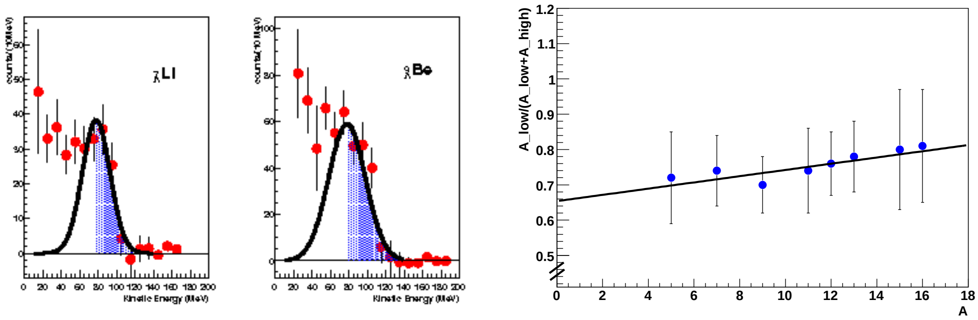

Figure 3: On the left two proton kinetic energy spectra from the NMWD of ${}^{7}_{\Lambda}$Li, ${}^{9}_{\Lambda}$Be. In the blue filled area the two–nucleon induced NMWD contribution is negligible; the last figure on the rigt shows the ratio $A_{\rm low}/(A_{\rm low}+A_{\rm high})$ as a function of the hypernuclear mass number [5].

the latest achievements by FINUDA on NMWD, let me focus on the Final State Interactions (FSI) and the two–nucleon induced NMWD contributions to the decay process. Each proton spectrum, background subtracted and acceptance corrected, was fitted by a Gaussian function from 80 MeV onwards. The spectrum was divided in two parts: an area below the mean value obtained by the gaussian fit, $\mathrm{A_{low}}$, and $\mathrm{A_{high}}$ above that value, as shown in Fig. 3 on the left for ${}^{7}_{\Lambda}Li$ and ${}^{9}_{\Lambda}$Be. The $\mathrm{A_{high}}$ area is fed mainly by the one-proton induced reaction, assuming the 2N-induced channel contribution in this region can be neglected as suggested by theoretical calculations. The $\mathrm{A_{low}}$ region is due to protons from both $\Lambda p \to np$ and 2N-induced decays. FSI also affects the proton spectra: $\mathrm{N_p^{FSI-low}}$ ($\mathrm{N_p^{FSI-high}}$) represents the difference between the number of protons detected in the region below (above) the peak of the spectrum and the (unknown) number of primary protons which originate from one– and two–nucleon induced weak decays. So one can write:

$$R \equiv \frac{A_{\rm low}}{A_{\rm low}+A_{\rm high}} = \frac{0.5N(\Lambda p \to np)+N(\Lambda np \to nnp)+N_p^{\rm FSI-low}}{N(\Lambda p \to np)+N(\Lambda np \to nnp)+N_p^{\rm FSI-low}+N_p^{\rm FSI-high}}\,. \tag{2.1}$$

where $\mathrm{N}(\Lambda\mathrm{p} \to \mathrm{np})$ is the total number of $\Lambda p \to np$ decays, assumed distributed half in $\mathrm{A_{low}}$ and half in $\mathrm{A_{high}}$, and $\mathrm{N}(\Lambda\mathrm{np} \to \mathrm{nnp})$ is the total number of $\Lambda np \to nnp$ decays. Due to FSI effects, both $\mathrm{A_{low}}$ and $\mathrm{A_{high}}$ are expected to be proportional to A, and the results of the fit of such a dependence induced to consider R as a simple linear function of A as shown in Fig. 3 . All the details of this analysis can be found in Ref. [5]. Assuming the $\Lambda np \to nnp$ process as the dominant in the 2N-induced NMWD channel and Γ_2/Γ_p independent from A, R(A) can be re-written as one:

$$R(A) = \frac{0.5+\dfrac{\Gamma_2}{\Gamma_p}}{1+\dfrac{\Gamma_2}{\Gamma_p}} + bA\,. \tag{2.2}$$

This equation can be solved for Γ_2/Γ_p considering each hypernucleus. From the weighted average of the solutions the experimental value Γ_2/Γ_p=0.43±0.25 is determined for the first time and the value $\Gamma_2/\Gamma_{\rm NMWD}$=0.24±0.10 for the two–nucleon stimulated decay rate to the total decay rate can also be extracted. This $\Gamma_2/\Gamma_{\rm NMWD}$ ratio is in agreement with both theoretical predictions [6] and the latest experimental results of Ref. [7, 8].

2.2 Search for Bound $\overline{K}$-Nuclear Clusters

In the hadronic physics field the existence of Bound $\overline{K}$-Nuclear Clusters is a controversial and interesting topic from both the theoretical and the experimental point of view. The existence of these aggregates (nucleons bound rather tightly by an anti-kaon) could have important implications expecially in the astrophysics field and in the understanding of the features of the strange nuclear matter.

The general understanding of the $\overline{K}N$ and $\overline{K}A$ interactions does not foresee the existence of detectable states, because their width (80-100 MeV) is forseen to largely exceed their separation [9][10], except maybe in heavy nuclei [11].

On the other hand the phenomenological approach developed by Akaishi and Yamazaki [12] claimed the existence, expecially in light nuclei, of strongly bound systems (DBKS)(up to 110 MeV), with a width as narrow as 20 MeV and therefore clearly detectable.

From the experimental point of view the observation have been very few until now. FINUDA can exploit both the analysis techniques used so far to identify DBKS, the invariant mass spectroscopy and the missing mass method, thanks to its large acceptance and to the completeness of the PID information provided.

To search for kaon-nuclear clusters their non-mesonic decay channels can be exploited: (Λp), (Λd), (Λt) distributions have been studied by FINUDA to investigate (K^-pp), (K^-ppn) and (K^-ppnn) systems. The main source of background is played by the multinucleon absorption reaction followed by FSI of the outgoing particles, increasing its relevance with the mass number. FINUDA could measure in coincidence high resolution momentum spectra for protons, Λ's, deuterons and tritons with a full topological event reconstruction. In the data from light targets (^{6}Li,^{7}Li,^{12}C) an enhancement was observed by FINUDA at about 2.25 GeV/c^2 in the (Λp) invariant mass spectrum for back-to-back pairs, as shown in Fig. 4. It could not be explained by the the simple K^- absorption mechanism in the Λp channel leaving the daughter nucleus in the ground state, which peakes at 2.34 GeV/c^2. The K^- absorption into $\Sigma^0 p$ and subsequent Σ^0 decay in $\Lambda\gamma$ cannot explain the signal, because the signature in this case would be much narrower and moreover the branching fractions of the two channels do not comply with the observed strength of the bump [13]. The Breit-Wigner fit of the observed bump leads to assign a binding energy of 115^{+6}_{-5}(stat)$^{+3}_{-4}$(syst) MeV and a width of 67^{+14}_{-11}(stat)$^{+2}_{-3}$(syst) MeV, with a production rate of the order of 0.1%/K^-_{stop}. Further details of the analysis can be found in Ref.[14].

For the (K^-ppn) system a mass of (3120-3152) MeV/c^2, corresponding to a binding energy of (170-190) MeV, and a width of (13-21) MeV are predicted by Ref.[12], depending on the isospin configuration. FINUDA studied the $^6\mathrm{L}i(K^-_{stop},\Lambda d)$ reaction and a strong (Λd) correlation was found. In the (Λd) invariant mass distribution, shown in Fig. 5 on the left, a bump can be observed at $\sim$ 3250 MeV/c^2 , fed by strongly back-to-back correlated (Λd) pairs, which is compatible with the existence of a (K^-ppn) system with a binding energy of about 60 MeV. The details of the analysis can be found in Ref.[15].

The clean Particle IDentification of tritons in FINUDA allows also the study of the (Λt) channel. Coincidence events with a triton, a pion and a proton were found and the (π^-p) invariant mass of

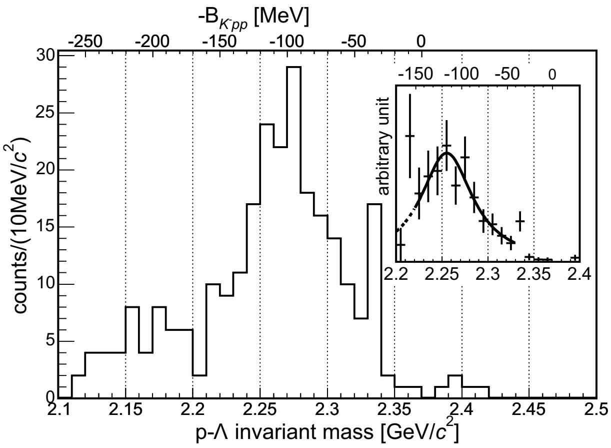

Figure 4: $\Lambda - p$ invariant mass distribution, acceptance-corrected, in light targets when $\Lambda - p$ pair is back-to-back correlated [14].

these events shows a narrow peak around the Λ mass value as shown in the Fig. 5 on the right, practically without background. (Λ t) pairs feature a strong back-to-back correlation and the momentum of both the particles is larger than 450 MeV/c. FINUDA could detect, overall, 40 (Λ t) events produced in light targets (^{6}Li,^{7}Li,^{9}Be); the capture rate of the K^- absorption reaction in the Λt channel could be measured for the first time: averaged on the three nuclei, a value of about $10^{-3}/K^-_{stop}$ was found of the same order of the other kaon absorption channels.

3. Conclusions

A total integrated luminosity of 1.2 fb^{-1} was collected by FINUDA in two differents data-takings. Thanks to its large acceptance and to the provided PID information FINUDA was able to explore a rich scientific program of K$^-$ stopped physics. Focussing on hypernuclear decays, the

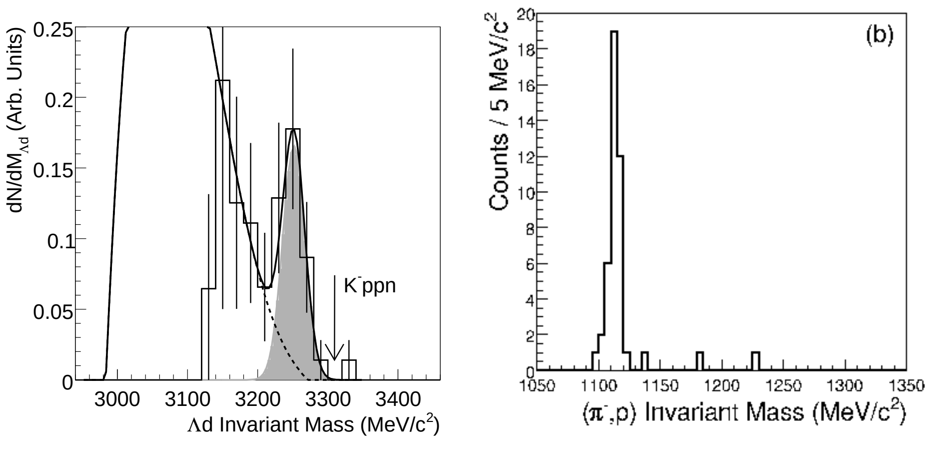

Figure 5: On the left $\Lambda - d$ invariant mass distribution from Ref. [15] and on the right ($\pi^- p$) invariant mass in coincidence events with a triton, a pion and a proton from Ref. [16]

first magnetic analysis of the MWD negative pions was performed for p-shell Λ-hypernuclei and the

MWD decay rates $\Gamma_{\pi^-}/\Gamma_\Lambda$ have been evaluated and compared to previous measurements and theoretical calculations. With these information FINUDA could suggest a new $J^\pi({}^{15}_{\Lambda}N_{g.s.}) = 3/2^+$ assignement and confirm $J^\pi({}^{11}_{\Lambda}B_{g.s.}) = 5/2^+$. On the Non Mesonic Weak Decay side FINUDA could study the proton kinetic energy spectra following the NMWD of Λ–hypernuclei in the $A = (5 \div 16)$ mass range. Thanks to this large systematics and the low kinetic energy threshold for proton detection a linear dependence of FSI on the hypernuclear mass number A was found. FINUDA made the first experimental determination of the ratio $\Gamma_2/\Gamma_p = (0.43 \pm 0.25)$ in a model-independent analysis.
Thanks to the FINUDA capabilities the K^- absorption processes on nuclei can also be investigated. The strong angular correlations found in (Λp), (Λd), (Λt) can suggest the existence of an intermediate strange state. The data analysis of the last run of the (Λp), (Λd) channels is underway and the larger statistics will allow to disentangle the contributions of the two channels in the different nuclei and shed light on the hot and controversial topic of the kaonic nuclear clusters existence.

References

[1] M. Agnello *et al.*, *Nucl. Phys.* **A754** (2005), 399c-409c; M. Agnello *et al.*, *Phys. Lett.* **B622** (2005), 35–44 ;

[2] A. Gal, *Nucl.Phys.* **A828** (2009), 72;

[3] T. Motoba, K. Itonaga, *Progr. Theor. Phys. Suppl.* **117** (1994), 477;

[4] M. Agnello *et al.*, *Phys. Lett.* **B681** (2009), 139–146;

[5] M. Agnello *et al.*,*Phys. Lett.* **B685** (2010), 247–252;

[6] A. Ramos, E. Oset and L.L. Salcedo, *Phys. Rev.* **C50** (1994), 2314; W. M. Alberico, A. De Pace, G. Garbarino and A. Ramos, *Phys. Rev.* **C61** (2000), 044314; G. Garbarino, A. Parreno and A. Ramos, *Phys. Rev. Lett.* **91** (2003), 112501; *Phys. Rev.* **C69** (2004), 054603; E. Bauer and F. Krmpotic, *Nucl. Phys.* **A739** (2004), 109; E. Bauer, G. Garbarino, A. Parreno and A. Ramos, arXiv:nucl-th/0602066v1;

[7] H. Bhang et al., *Eur. Phys. J.* **A33** (2007), 259;

[8] J.D. Parker et al., *Phys. Rev.* **C76** (2007), 035501;

[9] S. Hirenzaki*et al.*,*Phys. Rev.* **C61**(2000), 055205;

[10] A. Ramos, E. Oset,*Nucl.Phys.* **A671** (2000),153;

[11] J.Mares *et al.*,*Physics Letters* **B606**(2005), 295 ;

[12] Y.Akaishi, T. Yamazaki, *Phys. Rev.* **C65**(2002), 044005;
T. Yamazaki,Y.Akaishi, *Nucl.Phys.* **B535**(2002), 70; T. Akaishi *et al.*,*Physics Letters* **B613**(2005), 140 ; ;

[13] P.A. Katz *et al.*, *Phys. Rev.* **D1** (1970), 1267; C. Vander Velde-Wilcquet *et al.*, *Il Nuovo Cimento* **39A** (1977), 538;

[14] M. Agnello *et al.*, *Phys. Rev. Lett.* **94** (2005), 212303

[15] M. Agnello *et al.*, *Phys. Lett.* **B654** (2007), 80; M. Agnello *et al.*, *Eur. Phys. J.* **A33** (2007), 283;

[16] M. Agnello *et al.*, *Phys. Lett.* **B669** (2008), 229;