Vol. 38 (2007) *ACTA PHYSICA POLONICA B* No 9

AN OVERVIEW OF HYPERNUCLEAR WEAK DECAY*

G. Garbarino

Dipartimento di Fisica Teorica, Università di Torino and INFN
Sezione di Torino, 10125 Torino, Italy

(Received June 28, 2007)

A short review on hypernuclear weak decay is presented. Special regard is devoted to the recent progress concerning the determination of the Γ_n/Γ_p ratio and the asymmetry parameters.

PACS numbers: 21.80.+a, 13.30.Eg, 13.75.Ev, 25.40.–h

1. Introduction

Hypernuclear physics was born in 1952, when the first hypernucleus was observed through its decays [1]. We are honoured to recall that, since then, our late Euridice colleague and friend Dalitz gave important contributions to the development of this field [2]. At the end of the 50s [3], he performed the first calculation of the mesonic decay rates, an analysis that allowed to assign the ground state spin of s–shell hypernuclei. In the 60s, together with Block, Dalitz [4] developed a phenomenological model which is still in use today to analyse the possible violation of the $\Delta I = 1/2$ isospin rule in the non–mesonic decay. Since these pioneering studies, the field has been characterized by more and more new challenging questions and answers. The interest was further raised by the advances made in the last years.

The study of hypernuclear phenomena may help in understanding some important questions, related to:

1. The hyperon–nucleon and hyperon–hyperon strong and weak interactions;

2. The renormalization of hyperon and meson properties in the nuclear medium;

* Presented at The Final EURIDICE Meeting "Effective Theories of Colours and Flavours: from EURODAPHNE to EURIDICE", Kazimierz, Poland, 24–27 August, 2006.

3. The nuclear structure and the many–body nuclear dynamics;

4. The role played by quark degrees of freedom, flavour symmetry and chiral models in nuclear and hypernuclear phenomena.

In this contribution we deal with the weak decay of hypernuclei containing a Λ hyperon. In particular, we discuss recent indications for a solution of the long-standing puzzle on the ratio Γ_n/Γ_p and an open problem on the asymmetric decay of polarized hypernuclei. The need for new investigations to achieve a deeper understanding of the decay mechanisms is pointed out.

For comprehensive reviews on the subject we refer the reader to Refs. [5,6] and references therein.

2. Weak decay modes of Λ hypernuclei

A Λ hypernucleus decays by means of a strangeness–changing weak interaction via two different channels. The mesonic mode, $\Lambda \to \pi^- p$ and $\Lambda \to \pi^0 n$ with decay widths Γ_{π^-} and Γ_{π^0}, is the main decay channel of a Λ in free space. The experimental ratio for the free decay $\Gamma^{\rm free}_{\Lambda\to\pi^- p}/\Gamma^{\rm free}_{\Lambda\to\pi^0 n} \simeq 1.78$ is very close to 2 and thus strongly suggests the $\Delta I = 1/2$ rule on the isospin change. As for the decay of the Σ hyperon and for pionic kaon decays, this $\Delta I = 1/2$ rule is based on experimental observations but its dynamical origin is not yet convincingly understood on theoretical grounds.

The momentum of the final nucleon in the free mesonic decay is $\simeq$ 100 MeV. In nuclei the Λ mesonic decay is thus disfavoured by the Pauli principle, particularly in heavy systems. It is strictly forbidden in infinite nuclear matter, where the Fermi momentum is $k_{F^0} \simeq 270$ MeV, while in finite nuclei it can occur because of three important effects:

1. In nuclei the hyperon has a momentum distribution that allows larger momenta to be available to the final nucleon;

2. The final pion feels an attraction by the medium such that it has an energy smaller than the free one; due to energy conservation, the final nucleon again has more chance to come out above the Fermi surface;

3. At the nuclear surface the local Fermi momentum is considerably smaller than k_{F^0}, and the Pauli blocking is less effective in forbidding the decay.

Studies of the mesonic channel provides important information on the pion–nucleus optical potential since the mesonic widths turn out to be very sensitive to the pion self-energy in the medium.

If the pion emitted by the weak vertex is virtual, it is absorbed by the nuclear medium, resulting in one- and two-nucleon induced non-mesonic weak decays (NMWD): $\Lambda n \to nn$ (Γ_n), $\Lambda p \to np$ (Γ_p) and $\Lambda NN \to nNN$ (Γ_2).

This mode is only possible in nuclei and, nowadays, its systematic study is the only practical way to get phenomenological information on the hyperon–nucleon weak interaction. This is especially facilitated by the large momenta of the final nucleons in the NMWD ($p_N \simeq 420$ MeV for the one-nucleon induced channel). The NMWD is not forbidden by the Pauli principle but indeed dominates over the mesonic mode for all but the *s*-shell hypernuclei (see Fig. 1). Being characterized by a large momentum transfer, the NMWD channel is only slightly affected by the details of hypernuclear structure, thus providing useful information directly on the hadronic weak interaction.

The total decay rate of a Λ hypernucleus is $\Gamma_{\rm T} = \Gamma_{\rm M} + \Gamma_{\rm NM}$, with $\Gamma_{\rm M} = \Gamma_{\pi^-} + \Gamma_{\pi^0}$, $\Gamma_{\rm NM} = \Gamma_1 + \Gamma_2$ and $\Gamma_1 = \Gamma_n + \Gamma_p$. There is an anticorrelation between mesonic and non-mesonic channels such that $\Gamma_{\rm T}$ is quite stable from light to heavy hypernuclei. This behaviour, related to the saturation property of the $\Lambda N \to nN$ interaction in nuclei, is evident from Fig. 1.

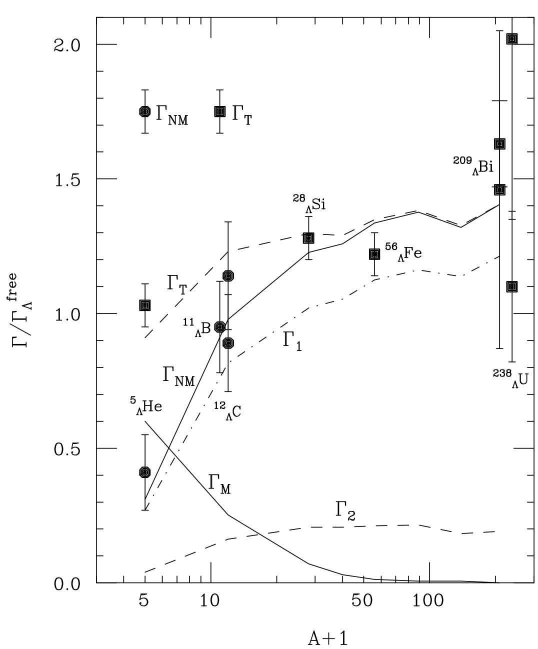

Fig. 1. Decay widths of a Λ in finite nuclei as a function of the nuclear mass number A (taken from Refs. [5, 7]).

3. The ratio Γ_n/Γ_p

For many years, the main challenge of hypernuclear decay studies has been to provide a theoretical explanation of the large experimental values of Γ_n/Γ_p [5, 6]. Until recently, the big uncertainties involved in the extraction of this ratio from data did not allow to reach any definitive conclusion. These "old" data were quite limited and not accurate due to the difficulty of detecting the products of the NMWD, especially the neutrons. However, thanks to recent theoretical and experimental progress, the Γ_n/Γ_p puzzle has been solved. In this Section we summarize these important developments.

The one-pion-exchange (OPE) approximation provides small ratios, typically around 0.1–0.2 for the best studied systems, ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$. This is mainly due to the particular form of the OPE potential, which has a strong tensor component requiring isospin 0 np pairs in the antisymmetric final state. On the contrary, the OPE model has been able to reproduce the NMWD rates measured for the mentioned hypernuclei [5, 6].

Other interaction mechanisms beyond the OPE might be responsible for the overestimation of Γ_p and the underestimation of Γ_n. Many attempts have been made to clarify the question. We recall the inclusion in the $\Lambda N \to nN$ transition potential of mesons heavier than the pion [8, 9], the implementation of interaction terms violating the $\Delta I = 1/2$ rule [10] and the description of the short range baryon–baryon interaction in terms of quarks [11], which automatically introduces $\Delta I = 3/2$ contributions.

A few calculations with transition potentials including heavy-meson-exchange and/or direct quark (DQ) contributions have recently improved the situation, without providing, nevertheless, a solution of the puzzle. In Table I we summarize the calculations that predicted ratios considerably enhanced with respect to the OPE values. Experimental data are given for comparison. Almost all calculations reproduce the observed NMWD widths, as one can see in Table II. Although no calculation is able to explain the "old" data on Γ_n/Γ_p of Refs. [12–15], extracted from single–nucleon measurements, some predictions are in agreement with the recent determinations of Refs. [16, 17] obtained by fitting the nucleon–nucleon coincidence data of Refs. [18–20].

We now discuss these recent achievements, which allowed to definitely solve the Γ_n/Γ_p puzzle. The authors of Refs. [16, 26] evaluated double-nucleon energy and angular correlations and analyzed the data obtained at KEK for ${}^{5}_{\Lambda}\mathrm{He}$ and ${}^{12}_{\Lambda}\mathrm{C}$ [18–20]. A one-meson-exchange (OME) model containing $\pi + \rho + K + K^{*} + \omega + \eta$ exchange was used for the $\Lambda N \to nN$ transition in a finite nucleus framework. The two-nucleon induced decay channel $\Lambda np \to nnp$ was taken into account via the polarization propagator method in the local density approximation [7], a model applied for the first

TABLE I

Theoretical and experimental determinations of the Γ_n/Γ_p ratio.

Ref. and Model	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C
Sasaki *et al.* [11]	0.70	
$\pi + K +$ DQ		
Jido *et al.* [21]		0.53
$\pi + K + 2\pi/\sigma + 2\pi + \omega$		
Parreño and Ramos [22]	$0.34 \div 0.46$	$0.29 \div 0.34$
$\pi + \rho + K + K^* + \omega + \eta$		
Itonaga *et al.* [23]	0.39	0.37
$\pi + 2\pi/\sigma + 2\pi/\rho + \omega$		
Barbero *et al.* [24]	0.24	0.21
$\pi + \rho + K + K^* + \omega + \eta$		
Bauer and Krmpotić [25]		0.29
$\pi + \rho + K + K^* + \omega + \eta$		
BNL [12]	0.93 ± 0.55	$1.33^{+1.12}_{-0.81}$
KEK [13]		$1.87^{+0.67}_{-1.16}$
KEK [14]	1.97 ± 0.67	
KEK–E307 [15]		0.87 ± 0.23
KEK–E462/E508	0.40 ± 0.11 $(1N)$	0.38 ± 0.14 $(1N)$
(analysis of Ref. [16])	0.27 ± 0.11 $(1N + 2N)$	0.29 ± 0.14 $(1N + 2N)$
KEK–E462/E508		0.37 ± 0.14 $(1N)$
(analysis of Ref. [17])		0.34 ± 0.15 $(1N + 2N)$

time to hypernuclear decay in Ref. [27]. The intranuclear cascade code of Ref. [28] was employed to simulate the nucleon propagation inside the residual nucleus. In Table III the ratio N_{nn}/N_{np} predicted by the OPE model and two different OME models of Refs. [16] for ${}^{5}_{\Lambda}$He and ${}^{12}_{\Lambda}$C is given for a nucleon energy threshold of 30 MeV and for the back-to-back kinematics, $\cos\theta_{NN} \leq -0.8$. The predictions for Γ_n/Γ_p are also quoted. The OME results well agree with the data, thus providing an indication for a ratio $\Gamma_n/\Gamma_p \simeq 0.3$ in both hypernuclei.

A weak-decay-model independent analysis of the KEK coincidence data of Table III has been performed in Ref. [16]. The results are given in Table I either by neglecting the two–nucleon stimulated decay channel $(1N)$ or by adopting $\Gamma_2/\Gamma_1 = 0.20$ for ${}^{5}_{\Lambda}$He and $\Gamma_2/\Gamma_1 = 0.25$ for ${}^{12}_{\Lambda}$C $(1N + 2N)$, as predicted in Ref. [7]. The Γ_n/Γ_p values determined in this way agree with the pure theoretical predictions of Refs. [21–25], but are substantially smaller than those previously determined from single–nucleon data [12–15] (see Table I). In our opinion, the results obtained via nucleon correlation analyses represents a strong evidence for a solution of the long-standing puzzle on the Γ_n/Γ_p ratio.

TABLE II

Theoretical and experimental determinations of the NMWD width Γ_{NM} (in units of $\Gamma_\Lambda^{\rm free}$). Only the one–nucleon induced decay channel has been taken into account in the theoretical evaluations.

Ref. and Model	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C
Sasaki *et al.* [11]	0.52	
$\pi + K +$ DQ		
Jido *et al.* [21]		0.77
$\pi + K + 2\pi/\sigma + 2\pi + \omega$		
Parreño and Ramos [22]	$0.32 \div 0.43$	$0.55 \div 0.73$
$\pi + \rho + K + K^* + \omega + \eta$		
Itonaga *et al.* [23]	0.42	1.06
$\pi + 2\pi/\sigma + 2\pi/\rho + \omega$		
Barbero *et al.* [24]	0.69	1.17
$\pi + \rho + K + K^* + \omega + \eta$		
Bauer and Krmpotić [25]		1.64
$\pi + \rho + K + K^* + \omega + \eta$		
BNL [12]	0.41 ± 0.14	1.14 ± 0.20
KEK [13]		0.89 ± 0.18
KEK [14]	0.50 ± 0.07	
KEK–E307 [15]		$0.828 \pm 0.056 \pm 0.066$
KEK–E462 [18]	0.424 ± 0.024	
KEK–E508 [18]		0.940 ± 0.035

TABLE III

Predictions of Refs. [16] for the ratio N_{nn}/N_{np} corresponding to an energy thresholds $T_N^{\rm th}$ of 30 MeV and to the back-to-back kinematics ($\cos\theta_{NN} \leq -0.8$). The data are from KEK–E462 and KEK–E508 [18–20].

	${}^{5}_{\Lambda}$He		${}^{12}_{\Lambda}$C	
	N_{nn}/N_{np}	Γ_n/Γ_p	N_{nn}/N_{np}	Γ_n/Γ_p
OPE	0.25	0.09	0.24	0.08
OMEa	0.51	0.34	0.39	0.29
OMEf	0.61	0.46	0.43	0.34
EXP	0.45 ± 0.11		0.40 ± 0.10	

This conclusion has been corroborated by a more recent study [17], analogous to the one of Ref. [16], but performed within a nuclear matter formalism adapted to finite nuclei via the local density approximation (see the results in Table I). At variance with Ref. [16], a microscopic model more in line with the approach of Ref. [29] has been used for the two-nucleon induced decays, also including the channels $\Lambda nn \to nnn$ and $\Lambda pp \to npp$ besides the standard mode $\Lambda np \to nnp$ of the previous phenomenological approach.

Forthcoming coincidence data from KEK, BNL [30], J–PARC [31] and FINUDA [32] could be directly compared with the results of Refs. [16,17,26]. This will permit to achieve better determinations of Γ_n/Γ_p and to establish the first constraints on Γ_2/Γ_1.

4. The asymmetry puzzle

Despite the recent progress discussed in the previous section, the reaction mechanism for the NMWD does not seem to be fully understood. Indeed, an intriguing problem, of more recent origin, is open: it concerns a strong disagreement between theory and experiment on the asymmetry of the angular emission of NMWD protons from polarized hypernuclei. This asymmetry is due to the interference between parity-violating and parity-conserving $\vec{\Lambda}p \to np$ transition amplitudes [33], while the rates Γ_n and Γ_p are dominated by parity-conserving amplitudes. The study of the asymmetric proton emission from polarized hypernuclei is thus supposed to provide new constraints on the dynamics of the NMWD.

The intensity of protons emitted in $\vec{\Lambda}p \to np$ decays along a direction forming an angle Θ with the polarization axis is given by [34]: $I(\Theta, J) = I_0(J)[1 + p_\Lambda(J)\, a_\Lambda \cos\Theta]$, where I_0 is the (isotropic) intensity for an unpolarized hypernucleus and J the hypernuclear spin. The shell model weak-coupling scheme allowed us to introduce, in this intensity, the polarization of the Λ spin, p_Λ, and the *intrinsic* Λ asymmetry parameter, a_Λ, which is expected to be a characteristic of the elementary reaction $\vec{\Lambda}p \to np$.

Nucleon final state interactions (FSI) acting after the NMWD modify the weak decay intensity $I(\Theta, J)$. Experimentally one has access to a proton intensity which is generally assumed to have the same Θ–dependence as $I(\Theta, J)$: $I^{\rm M}(\Theta, J) = I_0^{\rm M}(J)[1 + p_\Lambda(J)\, a_\Lambda^{\rm M}(J) \cos\Theta]$, $a_\Lambda^{\rm M}(J)$ being the *observable* asymmetry, which is expected to depend on the hypernucleus.

While theory predicts a negative a_Λ, with a moderate dependence on the hypernucleus, the measurements seem to favour positive or vanishing values for $a_\Lambda^{\rm M}({}^5_\Lambda\vec{\rm He})$ and negative or vanishing values for $a_\Lambda^{\rm M}({}^{12}_\Lambda\vec{\rm C})$. Theoretical (experimental) determinations of the intrinsic (observable) asymmetry are given in Table IV. Concerning this comparison between theory and experiment, it is important to stress that, while one predicts $a_\Lambda({}^5_\Lambda\vec{\rm He}) \simeq a_\Lambda({}^{12}_\Lambda\vec{\rm C})$, there is no known reason to expect this approximate equality to be valid for $a_\Lambda^{\rm M}$. Indeed, the relationship between I and $I^{\rm M}$ can be strongly affected by FSI of the emitted protons: this fact prevents a direct comparison between a_Λ and $a_\Lambda^{\rm M}$. To overcome this obstacle, an evaluation of the FSI effects on the NMWD of polarized hypernuclei has been recently performed [38] by adopting the same framework of Refs. [16, 26].

TABLE IV

Theoretical and experimental determinations of the asymmetry parameters (a_Λ and $a_\Lambda^{\rm M}$, respectively).

Ref. and Model	${}^{5}_{\Lambda}$He	${}^{12}_{\Lambda}$C
Sasaki *et al.* [11]		
$\pi + K + {\rm DQ}$	-0.68	
Parreño and Ramos [22]		
$\pi + \rho + K + K^* + \omega + \eta$	-0.68	-0.73
Itonaga *et al.* [35]		
$\pi + K + 2\pi/\sigma + 2\pi/\rho + \omega$	-0.33	
Barbero *et al.* [36]		
$\pi + \rho + K + K^* + \omega + \eta$	-0.54	-0.53
KEK–E462 [37]	$0.11 \pm 0.08 \pm 0.04$	
KEK–E508 [37]		$-0.20 \pm 0.26 \pm 0.04$

We summarize here some results of this investigation, which is the first one evaluating $a_\Lambda^{\rm M}$. In Table V we show OME predictions for the intrinsic and observable asymmetries. As a result of the nucleon rescattering in the nucleus, $|a_\Lambda| \gtrsim |a_\Lambda^{\rm M}|$ for any value of the proton kinetic energy threshold: when $T_p^{\rm th} = 0$, $a_\Lambda/a_\Lambda^{\rm M} \simeq 2$ for ${}^{5}_{\Lambda}\vec{\rm He}$ and $a_\Lambda/a_\Lambda^{\rm M} \simeq 4$ for ${}^{12}_{\Lambda}\vec{\rm C}$; $|a_\Lambda^{\rm M}|$ increases with $T_p^{\rm th}$ and $a_\Lambda/a_\Lambda^{\rm M} \simeq 1$ for $T_p^{\rm th} = 70$ MeV in both cases. Asymmetries $a_\Lambda^{\rm M}$ rather independent of the hypernucleus are obtained for $T_p^{\rm th} = 30$, 50 and 70 MeV. The data quoted in Table V refer to a $T_p^{\rm th}$ of about 30 MeV: the corresponding predictions of Ref. [38] agree with the ${}^{12}_{\Lambda}\vec{\rm C}$ datum but are inconsistent with the observation for ${}^{5}_{\Lambda}\vec{\rm He}$.

TABLE V

Results of Ref. [38] for the asymmetries a_Λ and $a_\Lambda^{\rm M}$ from [37].

	${}^{5}_{\Lambda}\vec{\rm He}$	${}^{12}_{\Lambda}\vec{\rm C}$
Without FSI	$a_\Lambda = -0.68$	$a_\Lambda = -0.73$
FSI and $T_p^{\rm th} = 0$	-0.30	-0.16
FSI and $T_p^{\rm th} = 30$ MeV	-0.46	-0.37
FSI and $T_p^{\rm th} = 50$ MeV	-0.52	-0.51
FSI and $T_p^{\rm th} = 70$ MeV	-0.55	-0.65
KEK–E462 [37]	$0.11 \pm 0.08 \pm 0.04$	
KEK–E508 [37]		$-0.20 \pm 0.26 \pm 0.04$

Recently, an effective field theory approach based on pion– and kaon–exchange and leading–order contact interactions has been applied to hypernuclear decay [39]. The coefficients of the considered four–fermion point interaction have been fitted to reproduce data on the NMWD widths of ${}^{5}_{\Lambda}$He, ${}^{11}_{\Lambda}$B and ${}^{12}_{\Lambda}$C. In this way, a dominating central, spin– and isospin–independent contact term has been predicted. It turned out to be particularly important to reproduce a small and positive value of the intrinsic asymmetry for ${}^{5}_{\Lambda}\vec{\mathrm{H}}$e, as indicated by the recent KEK experiments. In order to improve the comparison with the observed asymmetries in a calculation scheme based on meson–exchange, this result can be interpreted dynamically as the need for the introduction of a scalar–isoscalar meson–exchange.

Prompted by the work of Ref. [39], models based on OME and/or DQ mechanisms [40] have been supplemented with the exchange of the scalar–isoscalar σ–meson. Despite the rather phenomenological character of these works, they have clearly demonstrated the importance of σ–exchange in the NMWD. More detailed investigations are needed to establish the precise contribution of the scalar–isoscalar channel.

In conclusion, nucleon FSI turn out to be an important ingredient also when dealing with the NMWD of polarized hypernuclei, but they cannot explain the present asymmetry data. Further studies are required to clarify this issue. On the theoretical side, recent indications on the relevance of the scalar–isoscalar channel seem to suggest novel reaction mechanisms for the dynamics underlying the NMWD. New and/or improved experiments more clearly establishing the sign and magnitude of a_{Λ}^{M} for s- and p-shell hypernuclei are also necessary to guide the theoretical investigations.

Work supported by EURIDICE HPRN-CT-2002-00311 and INFN.

REFERENCES

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

[2] I.J.R. Aitchison, F.E. Close, A. Gal, D.J. Millener, *Nucl. Phys.* **A771**, 8 (2006).

[3] R.H. Dalitz, L. Liu, *Phys. Rev.* **116**, 1312 (1959).

[4] M.M. Block, R.H. Dalitz, *Phys. Rev. Lett.* **11**, 96 (1963).

[5] W.M. Alberico, G. Garbarino, *Phys. Rep.* **369**, 1 (2002); in *Hadron Physics*, eds T. Bressani, A. Filippi, U. Wiedner, IOS Press, Amsterdam 2005, p. 125; Proceedings of the *International School of Physics "Enrico Fermi"*, Course CLVIII, Varenna (Italy), June 22–July 2, 2004 [`nucl-th/0410059`].

[6] E. Oset, A. Ramos, *Prog. Part. Nucl. Phys.* **41**, 191 (1998).

[7] W.M. Alberico, A. De Pace, G. Garbarino, A. Ramos, *Phys. Rev.* **C61**, 044314 (2000).

[8] J.F. Dubach, G.B. Feldman, B.R. Holstein, *Ann. Phys.* **249**, 146 (1996).

[9] A. Parreño, A. Ramos, C. Bennhold, *Phys. Rev.* **C56**, 339 (1997).

[10] A. Parreño, A. Ramos, C. Bennhold, K. Maltman, *Phys. Lett.* **B435**, 1 (1998); W.M. Alberico, G. Garbarino, *Phys. Lett.* **B486**, 362 (2000).

[11] K. Sasaki, T. Inoue, M. Oka, *Nucl. Phys.* **A669**, 331 (2000); **A678**, 455(E) (2000); **A707**, 477 (2002).

[12] J.J. Szymanski *et al.*, *Phys. Rev.* **C43**, 849 (1991).

[13] H. Noumi *et al.*, *Phys. Rev.* **C52**, 2936 (1995).

[14] H. Noumi *et al.*, Proceedings of the *IV International Symposium on Weak and Electromagnetic Interactions in Nuclei*, eds H. Ejiri, T. Kishimoto, T. Sato, World Scientific, 1995, p. 550.

[15] Y. Sato *et al.*, *Phys. Rev.* **C71**, 025203 (2005).

[16] G. Garbarino, A. Parreño, A. Ramos, *Phys. Rev.* **C69**, 054603 (2004); W.M. Alberico, G. Garbarino, A. Parreño, A. Ramos, *DAPHNE2004: Physics at Meson Factories*, *Frascati Phys. Ser.* **36**, 249 (2005) [nucl-th/0407046].

[17] E. Bauer, G. Garbarino, A. Parreño, A. Ramos, nucl-th/0602066, submitted to *Phys. Rev.* **C**.

[18] H. Outa *et al.*, *Nucl. Phys.* **A54**, 157c (2005); H. Outa, in *Hadron Physics* (Ref. [5]) p. 219.

[19] B.H. Kang *et al.*, *Phys. Rev. Lett.* **96**, 062301 (2006).

[20] M.J. Kim *et al.*, *Phys. Lett.* **B641**, 28 (2006).

[21] D. Jido, E. Oset, J.E. Palomar, *Nucl. Phys.* **A694**, 525 (2001).

[22] A. Parreño, A. Ramos, *Phys. Rev.* **C65**, 015204 (2002).

[23] K. Itonaga, T. Ueda, T. Motoba, *Phys. Rev.* **C65**, 034617 (2002).

[24] C. Barbero, C. De Conti, A.P. Galeão, F. Krmpotić, *Nucl. Phys.* **A726**, 267 (2003).

[25] E. Bauer, F. Krmpotić, *Nucl. Phys.* **A717**, 217 (2003); **A739**, 109 (2004).

[26] G. Garbarino, A. Parreño, A. Ramos, *Phys. Rev. Lett.* **91**, 112501 (2003).

[27] E. Oset, L.L. Salcedo, *Nucl. Phys.* **A443**, 704 (1985).

[28] A. Ramos, M.J. Vicente-Vacas, E. Oset, *Phys. Rev.* **C55**, 735 (1997); **C66**, 039903(E) (2002).

[29] W.M. Alberico, A. De Pace, G. Garbarino, R. Cenni, *Nucl. Phys.* **A668**, 113 (2000).

[30] R.L. Gill, *Nucl. Phys.* **A691**, 180c (2001).

[31] T. Nagae, *Nucl. Phys.* **A754**, 443c (2005).

[32] M. Agnello *et al.*, *Nucl. Phys.* **A754**, 399c (2005).

[33] H. Bandō, T. Motoba, J. Žofka, *Int. J. Mod. Phys.* **A5**, 4021 (1990).

[34] A. Ramos, E. van Meijgaard, C. Bennhold, B.K. Jennings, *Nucl. Phys.* **A544**, 703 (1992).

[35] K. Itonaga, T. Motoba, T. Ueda, in *Electrophoto–production of Strangeness on Nucleons and Nuclei*, Sendai03, eds. K. Maeda, H. Tamura, S.N. Nakamura, O. Hashimoto, World Scientific, 2004, p. 397.

[36] C. Barbero, A.P. Galeão, F. Krmpotić, *Phys. Rev.* **C72**, 035210 (2005).

[37] T. Maruta *et al.*, *Nucl. Phys.* **A754**, 168c (2005).

[38] W.M. Alberico, G. Garbarino, A. Parreño, A. Ramos, *Phys. Rev. Lett.* **94**, 082501 (2005).

[39] A. Parreño, C. Bennhold, B.R. Holstein, *Phys. Rev.* **C70**, 051601(R) (2004).

[40] K. Sasaki, M. Izaki, M. Oka, *Phys. Rev.* **C71**, 035502 (2005); C. Barbero, A. Mariano, *Phys. Rev.* **C73**, 024309 (2006).