FORMATION OF $\Sigma\pi$ PAIRS IN NUCLEAR CAPTURES OF K^- MESONS*

Raffaele Del Grande[a,b], Kristian Piscicchia[c,a]
Sławomir Wycech[d]

[a]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[b]Università degli Studi di Roma Tor Vergata, Rome, Italy
[c]CENTRO FERMI — Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Rome, Italy
[d]National Centre for Nuclear Studies, Warszawa, Poland

(Received September 21, 2017)

The capture of K^- mesons on nucleons bound in nuclei offers a chance to study the $\Sigma\pi$ pairs below the kinematic threshold of the $\bar{K}N$ systems. Various hyperon–pion charged combination are presently under investigation by AMADEUS. These data allow to test both isospin 0 and 1 amplitudes giving the possibility to detect the structure of resonant $\Lambda(1405)$ state. Contrasted against similar electro-production data, they allow to detect changes of $\Lambda(1405)$ in nuclear media. Expected spectra and their uncertainties are calculated.

DOI:10.5506/APhysPolB.48.1881

1. Introduction

The emission of hyperon and meson pairs $\Sigma^{\pm}\pi^{\mp}$ following the K^-p capture in nuclei was studied in nuclear emulsion and in bubble chambers. For example, see Refs. [1–8]. In particular, the research in Ref. [3] concentrated on measurements of total $\mathrm{P}_{\Sigma\pi}$ momenta and invariant masses $M_{\Sigma\pi}$. Such experiments allow one to test the invariant mass of the K^-p pair in the subthreshold region. One purpose of the research is to learn the structure of $\Lambda(1405)$ resonance located below the $\bar{K}N$ threshold. Properties of the latter may be detected with a simultaneous measurement of: $M_{\Sigma\pi}$, $P_{\Sigma\pi}$ and the ratio of two formation rates $\sigma(\Sigma^+,\pi^-)/\sigma(\Sigma^-,\pi^+) = R_{\pm}(M_{\Sigma\pi})$. This ratio depends strongly on the invariant mass shapes and reflects an interference of the resonant isospin-zero amplitude with an isospin-one background. Recent

* Presented at the 2nd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics, Kraków, Poland, June 3–11, 2017.

experiments by the FINUDA Collaboration allowed more precise measurements of both the meson and the hyperon momenta in a series of light nuclei [9]. Unfortunately, the quantity which is of easiest use for theoretical analysis, the invariant mass distribution, has not been measured. AMADEUS is investigating the reactions

$$K^{-\,12}\mathrm{C} \to (\Sigma^+\pi^-)/\left(\Sigma^0\pi^0\right)^{11}\mathrm{B}\,, \tag{1}$$

see Refs. [10–12]. The experimental investigation of negative kaons absorption on ^{12}C (and similar studies on ^{4}He) makes an extension of the former results, offering better precision and higher statistics. The nuclear absorptions described in equation (1) are due to basic transitions on protons and are described by the following combinations of two isospin $I = 0, 1$ transition amplitudes T_0 and T_1:

$$T\left(K^- p \to \Sigma^\pm\pi^\mp\right) = \frac{1}{\sqrt{6}}T_0 \pm \frac{1}{2}T_1\,; \qquad T\left(K^- p \to \Sigma^0\pi^0\right) = -\frac{1}{\sqrt{6}}T_0\,. \tag{2}$$

The invariant mass distribution has, in the leading approximation, the simple structure

$$P^p\left(M_{\Sigma\pi}\right)\,\mathrm{d}\rho = |T\left(M_{\Sigma\pi}\right)|^2 |F^p(P_{\Sigma\pi})|^2\,\mathrm{d}\rho\,, \tag{3}$$

where "all" the nuclear physics is contained in a form-factor F^p, determined by the initial state of nucleon and meson and by the final-state interactions of the hyperon. One does not determine the absolute normalization. The phase space element $\mathrm{d}\rho$ makes a fairly trivial factor in the atomic capture, but becomes a bit more involved for the in-flight captures.

A parallel experimental study of the K^- capture on neutrons could also be very useful because the T_1 amplitude can be directly obtained

$$T\left(K^- n \to \Sigma^-\pi^0\right) = \frac{1}{\sqrt{2}}T_1\,; \qquad T\left(K^- n \to \Sigma^0\pi^-\right) = -\frac{1}{\sqrt{2}}T_1\,. \tag{4}$$

This could be done in the context of AMADEUS. The related invariant mass distribution can be written, similar to (3), as

$$P^n(M_{\Sigma\pi})\,\mathrm{d}\rho = |T(M_{\Sigma\pi})|^2 |F^n(P_{\Sigma\pi})|^2\,\mathrm{d}\rho\,, \tag{5}$$

where F^n is now the form-factor for the K^-n interactions. Assuming that $|F^n| \simeq |F^p|$, the nuclear physics can be disentangled and the ratio

$$R(p/n) = \frac{P^p(M_{\Sigma\pi})}{P^n(M_{\Sigma\pi})} \tag{6}$$

allows one to directly study the ratio between T_0 and T_1. The main complication in such analysis comes from the $I = 1$ $\Sigma(1385)$ resonance formation in the P-wave K^-n interaction. Indeed, while in S-wave the T_1 can be considered approximately constant, the P-wave K^-n interaction is affected by the resonance formation. However, the $\Sigma(1385)$ is fortunately very weakly coupled to the $\Sigma\pi$ decay channel. This analysis is also complicated by the final-state absorption of the hyperon, which will be discussed in Section 3.

The ratio $R_\pm(M_{\Sigma\pi}) = P^p(M_{\Sigma^+\pi^-})/P^p(M_{\Sigma^-\pi^+})$ was studied in the thesis by Keane [13] and was analysed in Ref. [14] where also the data are reported. These, not very precise, data give a ratio which indicates an anomaly 35 MeV below the K^-p threshold which was discussed in terms of Dalitz [15] suggestion of a sizable three quark component in $\Lambda(1405)$. Recent electro-production experiments on proton indicate $R_\pm(M_{\Sigma\pi})$ to be a fairly smooth function of the energy [16]. Thus, the anomaly in question is apparently related to the presence of the nucleus. A second anomaly can be found in the data published by FINUDA [9], where a strong enhancement of events close to the Σ^+ formation threshold, that is for low Σ^+ energies, can be observed for K^- captures at-rest on ^{6}Li target. A Monte Carlo interpretation in terms of energy loss of the Σ^+ in the target seems to miss an accurate description of the measured P_{Σ^+} momentum spectra. In Ref. [12], AMADEUS also reported a low-momentum peak structure in P_{Σ^+} momentum distribution in a sample of $\Sigma^+\pi^-$ pairs produced in K^- ^{12}C absorptions. The low-energy Σ^+ events amount to some percent of the total sample. The solid target is much thiner in this case, so again energy loss seems not the only satisfying explanation. Moreover, the low-momentum structure is not observed in [12] when the K^- is absorbed on a solid ^{9}Be target. These findings are interpreted in Ref. [17] as formation of a Gamov state in the Σ^+-residual nucleus system. It would be of interest to learn if a relation among the two anomalies holds. In this note, we present the "gross structure" of the spectra. In particular, we present technical description of the distributions $P^p(M_{\Sigma\pi})$, while the hyperon momentum distribution $P(P_\Sigma)$ is presented in a parallel work [17].

2. Emission probabilities

The $\bar{K}N$ forces are known to be very short, we then use the transition operator of zero range. This assumption allows to write the capture amplitude A as follows:

$$A = \int \mathrm{d}\boldsymbol{r}\ \Phi^*_\Sigma(r)\Phi^*_\pi(r)T(K^-p \to \Sigma\pi)\Phi_p(r)\ \Phi_K(r) \sim T(M_{\Sigma\pi})\ F^p(P_{\Sigma\pi})\,, \tag{7}$$

where F^p is the form-factor introduced in (3) and defined as

$$F^p(P_{\Sigma\pi}) = \int \mathrm{d}\boldsymbol{r}\; \Phi_{\Sigma}^*(r)\Phi_{\pi}^*(r)\; \Phi_p(r)\; \Phi_K(r)\,. \tag{8}$$

Definition (8) requires the knowledge of the initial wave function of the proton $\Phi_p(r)$ (taken from Ref. [18]) and kaon Φ_K (calculated with K-nucleus optical potential). Due to peripherality of the absorption, it occurs essentially on the P-wave nucleons. As the absolute rate is not measured, the overlap of initial and final nuclei is not relevant in the determination of the spectra. The wave function of the kaon depends on the atomic quantum numbers n and l of the orbital from which the K^- is captured. For captures in-flight, Φ_K is close to a plane wave, and the initial state is known. The X-ray transitions in carbon terminate at the $l = 1$ state but $l = 2$ is apparently the dominant angular momentum at the capture. The absolute rate of radial $l = 3 \to l = 2$ transition is 0.36(6), while the rate of subsequent radial transition is only 0.028(8) [19]. The distribution in terms of main quantum numbers is not known but is not relevant as the absolute capture rates are not measured. With the nuclear oscillator model of parameter α and pure Coulomb atoms, one obtains

$$\left\langle |F^p(P_{\Sigma\pi})|^2 \right\rangle \;\sim\; \frac{P_{\Sigma\pi}^2}{\alpha^2}\, e^{-\frac{P_{\Sigma\pi}^2}{\alpha^2}} \left[8\left(\frac{5}{2} - \frac{P_{\Sigma\pi}^2}{2\alpha^2}\right)^2 + \frac{3P_{\Sigma\pi}^4}{\alpha^4} \right], \tag{9}$$

where the form-factor is averaged over the atomic and nuclear magnetic orientation and summed over protons. The phase space $\mathrm{d}\rho$ in Eq. (3) is given by

$$\mathrm{d}\rho = \rho\; \mathrm{d}M_{\Sigma\pi} = P_{\Sigma\pi}\sqrt{E_0 - M_\Sigma - M_\pi + \frac{P_{\Sigma\pi}^2}{2(M_\Sigma + M_\pi)}}\; \mathrm{d}M_{\Sigma\pi}\,,$$

where $E_0 = M_p + M_K - E_p^{\text{binding}}$, E_p^{binding} is the binding energy of the absorbing proton (and kaon), for relativistic corrections, we refer to [20]. The final probability distribution function is

$$P(M_{\Sigma\pi})\mathrm{d}M_{\Sigma\pi} = |T(M_{\Sigma\pi})|^2 \left\langle |F^p(P_{\Sigma\pi})|^2 \right\rangle\; \rho\; \mathrm{d}M_{\Sigma\pi}\,. \tag{10}$$

It turns out that valence protons contribute 90% of the rate and this simplifies the relation of the invariant mass to the momentum $(M_{\Sigma\pi})^2 = E_0^2 - P_{\Sigma\pi}^2$ as the E_p^{binding} differs strongly in $2p$ where $E^{\text{binding}} = 16$ MeV and $1s$ nucleon orbital, where $E^{\text{separation}} \simeq 30$–50 MeV. In the atomic capture, the kinematic limit on the achievable invariant mass is 1416 MeV. For in-flight captures, the upper limit is pushed up of ~ 14 MeV by the kinetic energy of the kaon, for kaon momenta of ~ 120 MeV.

Figure 1 displays profiles of the $\Sigma^+\pi^-$ invariant mass spectrum including effects of resonant K^-p interactions. Final-state interactions have not been calculated. The shapes are obtained from the probability distribution function in Eq. (10), using $|T(M_{\Sigma\pi})|^2 = 1$ in the non-resonant reaction, while a Breit–Wigner shape is used for $|T(M_{\Sigma\pi})|^2$ in the resonant reaction. The difficulty of extraction of the resonance is essentially due to the sharp cut at 1416 MeV due to phases space limitations. However, the profiles are distinctive enough to allow checks of $T(M_{\Sigma\pi})$.

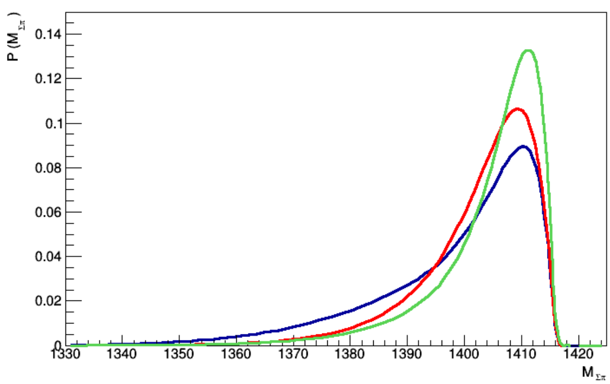

Fig. 1. (Colour on-line) Invariant mass distribution of $\Sigma^+\pi^-$ pairs following K^- capture from atomic $l = 2$ state in carbon. Final-state interactions have not been calculated. The curves test the dependence of the spectrum on the position of a 40 MeV wide resonance centred at $E_{\rm r} = 1405$ MeV (grey/red curve), $E_{\rm r} = 1420$ MeV (light grey/green curve). The non-resonant shape (black/blue curve) is obtained using $|T(M_{\Sigma\pi})|^2 = 1$. The area of the three curves is normalized to unity.

3. Higher order effects

Several corrections should be kept under control when experimental results are analysed:

(1) *Initial-state meson interactions.* In atomic capture, the correction due to the initial interaction of the meson is easy to introduce since the optical potential is known from X-ray data [21]. Moreover, it is the same for all $\Sigma\pi$ pairs and drops out when studying the ratios of emission rates. For captures in-flight, the analysis is more difficult because information is available from only an early scattering experiment on a

^{4}He target [22]. In addition, such an experiment does not agree with the atomic data. This may be due to the rapid change of the resonant $\bar{K}N$ amplitude, or to the poor energy resolution and then to the low quality of the data. Such discrepancy might be solved by the in-flight experiment on carbon and, preferably, on helium targets.

(2) *The final hyperon absorptive interactions.* This correction is more difficult to implement as it depends on the final charged channel. In particular, it is known from emulsion works that absorption of the final state Σ^+ differs from the absorption of the final state Σ^- [3, 14]. It is due to the Coulomb interaction and to differences in poorly known optical potentials for these hyperons. Both affect the low-energy part of the hyperon momentum spectra. Part of the difference is also related to the effect of the Gamov state, which is discussed in Ref. [17]. The description of such differences is rather involved and not very reliable [14]. The help from experiment is needed as the emulsion work provides total absorption rates and no related energy dependence. The best way forward for this experiment is to extract the difference from the hyperon momentum spectra.

(3) *Subtler effects related to the nuclear structure.* These effects are given by the fact that, in reaction (1), the final ^{11}B is a third body spectator. So far, we included the related energy recoil. Other changes would be to replace the coordinate $\boldsymbol{r}$ by a pair of Jacobi coordinates as done in the parallel calculation [17]. That part is simple in an oscillator model of the nucleus [18].

REFERENCES

[1] A. Barbaro-Galtieri *et al.*, *Phys. Lett. A* **5**, 63 (1963).

[2] P.J. Carlson *et al.*, *Nucl. Phys.* **74**, 642 (1965).

[3] E.H.S. Burhop, *High Energy Physics*, Vol. 3, Acad. Press, New York 1967.

[4] Proceedings of the International Conference on Hypernuclear Physics, Argonne National Laboratory, May 5–7, 1969.

[5] P.A. Katz *et al.*, *Phys. Rev. D* **1**, 1267 (1970).

[6] K. Brunnel *et al.*, *Phys. Rev. D* **2**, 98 (1970).

[7] D. Riley *et al.*, *Phys. Rev. D* **11**, 3065 (1975).

[8] C. Vander Velde-Wilquet *et al.*, *Nuovo Cim. A* **39**, 538 (1977).

[9] M. Agnello *et al.*, *Phys. Lett. B* **704**, 474 (2011).

[10] K. Piscicchia *et al.*, *PoS* **Bormio 2013**, 034 (2013).

[11] C. Curceanu *et al.*, *Acta Phys. Pol. B* **46**, 203 (2015).

[12] K. Piscicchia *et al.*, *EPJ Web Conf.* **137**, 09005 (2017).

[13] D.F. Keane, Thesis, University College Belfield, Dublin, 1981.

[14] L.R. Staronski, S. Wycech, *J. Phys. G* **13**, 1361 (1987).

[15] R.H. Dalitz, J.G. McGinley, in: *Low and Intermediate Energy Kaon–Nucleon Physics*, Proceedings of the Workshop held at the Institute of Physics of the University of Rome, March 24–28, 1980, (Eds.) E. Ferrari, G. Violini, p. 381.

[16] K. Moriya *et al.*, *Phys. Rev. C* **87**, 035206 (2013).

[17] S. Wycech, K. Piscicchia, *Acta. Phys. Pol.* **48**, 1861 (2017), this issue.

[18] T. Neff, H. Feldmeier, *Nucl. Phys. A* **738**, 357 (2004).

[19] H. Poth, *Compilation of Hadronic Atom Data*, Fachinformationszentrum Energie, Physik, Mathematik GmbH, Karlsruhe 1979.

[20] K. Piscicchia, S. Wycech, C. Curceanu, *Nucl. Phys. A* **954**, 75 (2016).

[21] E. Friedman, A. Gal, *Phys. Rep.* **452**, 89 (2002).

[22] P.O. Mazur *et al.*, *Phys. Rev. D* **1**, 20 (1970).