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Non-Mesonic Decay of Hypernuclei and the ΔI=1/2 Rule

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The decay of Λ-hypernuclei ($^{A}_{\Lambda}$X) is driven by the weak interaction and the two main mechanisms are:

i) the mesonic decay, namely $\Lambda \rightarrow \mathcal{N} + \pi$, which is just the free decay of the Λ but now occurring in the nuclear medium

ii) the non-mesonic (NM) decay, usually described as the result of the weak reaction $\Lambda + \mathcal{N} \rightarrow \mathcal{N} + \mathcal{N}$ which is only possible in a nucleus and is related to $\mathcal{N}\mathcal{N}$ parity non-conserving weak interactions

A quite recent and complete review on the subject is due to Cohen [1].

The branching ratios (BR) for the two branches of Λ decay in free space, $\Lambda \rightarrow p + \pi^-$ (64 %) and $\Lambda \rightarrow n + \pi^0$ (36 %) are, within 5 %, in agreement with the isospin rule $\Delta \mathbf{I} = 1/2$, as it can be readily checked by an elementary Clebsch-Gordan analysis. Such a phenomenological rule has never been explained on sound theoretical grounds. However the weak decay of the free Λ is strongly hindered when the Λ is embedded in nuclear matter, in the ground state of an hypernucleus (I remind that, due to different lifetimes for Λ weak decay and strong or e.m. decay of excited states of hypernuclei, the decay of hyperfragments occurs practically always from the ground state). The binding energy B_Λ of the Λ-hyperon in the ground state increases linearly with A, reaching the saturation value of 25 MeV for heavy hypernuclei, and the phase space for the mesonic decay is greatly reduced. The outgoing nucleon from the mesonic decay has a very low momentum (< 100

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MeV$/c$), quite less than the Fermi momentum of a nucleon in a nucleus (~ 270 MeV$/c$), and the process is substantially Pauli-blocked.

In all but the lightest hypernuclei the primary decay channel would then be the NM one, for which the energy release is approximately 176 MeV, corresponding to a momentum of each final nucleon of ~ 417 MeV$/c$. The NM mode has a much larger phase space and the final nucleons are not Pauli-blocked.

A measurement of the relative BRs for the two channels:

$$\Lambda + p \rightarrow n + p \tag{1}$$

$$\Lambda + n \rightarrow n + n \tag{2}$$

could provide information about the structure of the weak Hamiltonian, in particular on the relative importance of the $\Delta\mathbf{I}$=1/2 and $\Delta\mathbf{I}$=3/2 amplitudes that can contribute to the process.

Notwithstanding the considerable interest of this subject, experimental data are scarce and not precise, due to the difficulty of producing abundantly Λ-hypernuclei in their ground states and detecting their decay, in particular the NM one (2). However some recent data and analyses showed interesting new features: Schumacher [2], by analyzing the data on NM decay for the light hypernuclei ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He and ${}^{5}_{\Lambda}$He suggested that a violation of the $\Delta\mathbf{I}$=1/2 rule could be present. At the 1.6 σ level the data were not consistent with pure $\Delta\mathbf{I}$=1/2 hypothesis and suggested that the $\Delta\mathbf{I}$=3/2 amplitude could be comparable or even larger that the $\Delta\mathbf{I}$=1/2 piece.

In the near future an answer to this challenging question could be given by the FINUDA spectrometer [3], one of the two experiments approved for running at DAΦNE, the Frascati ϕ-Factory that will be commissioned next year. The production reaction of hypernuclei will be the (K^-_{stop},π^-) one and the "battle horse" of the apparatus will be just the study of NM decays, that will profit at best from the cleanliness of the K^- source [4] and the transparent structure of the detector [5], whose solid angle is larger than 2π sr. I remind the most important features of FINUDA [6]: about 75 hypernuclear states/hour for a production rate of 10^{-3} $K^-_{stopped}$, about 6 NM decays (1)/hour and about 1 NM decay (2)/hour at the initial luminosity of DAΦNE of 10^{32} cm^{-2} s^{-1}. These numbers are between one and two orders of magnitude larger than those of current or planned experiments at existing machines, and a further order of magnitude will be gained at the design luminosity of DAΦNE of 10^{33} cm^{-2} s^{-1}.

The energy of the hypernuclear final states produced in the reaction:

$$K^-_{stop} + {}^{\mathrm{A}}X \rightarrow {}^{\mathrm{A}}_{\Lambda}X + \pi^- \tag{3}$$

will be measured with a resolution of 0.6 MeV FWHM by means of the fine spectroscopy (Δp/p = 0.3 % FWHM) of the π^-, whereas the energy of the products from the NM decay of ${}^{\mathrm{A}}_{\Lambda}$ X:

$${}^{\mathrm{A}}_{\Lambda}X \rightarrow {}^{\mathrm{A}-2}(X-1) + n + p \tag{4}$$

$${}^{\mathrm{A}}_{\Lambda}X \rightarrow {}^{\mathrm{A}-2}X + n + n \tag{5}$$

will be measured with a precision of 1.3 MeV for the protons, about 10 MeV for the neutrons. These resolution will not allow, in general, the identification of the final nuclear states $^{A-2}$(X-1) and $^{A-2}$X in (4) and (5). In these inclusive measurements an averaging over the final states of the weak decays $\Lambda + \mathcal{N} \rightarrow \mathcal{N} + \mathcal{N}$ will be inherently present, and a possible violation of the $\Delta\mathbf{I}$ =1/2 rule could be inferred only by a systematic study of the ratio of the BR*s* for (1) and (2) as a function of the mass number.

I remind that in the simplified hypothesis of final total isospin 1, this ratio must be 1/2 for a pure $\Delta\mathbf{I}$=1/2 interaction.

However, for a ^{6}Li stopping target, the above resolutions may allow an exclusive measurement, in which also the final state of the residual nucleus is determined. Let me consider the following chains of production and decay processes for a ^{6}Li target:

$$K^- + {}^6\mathrm{Li} \rightarrow \pi^- + \boxed{{}^6_\Lambda\mathrm{Li}} \rightarrow p + \boxed{{}^5_\Lambda\mathrm{He}} \rightarrow {}^3\mathrm{H} + n + p \tag{6}$$

$$K^- + {}^6\mathrm{Li} \rightarrow \pi^0 + \boxed{{}^6_\Lambda\mathrm{He}} \rightarrow {}^4\mathrm{He} + n + n \tag{7}$$

where the squares contain the hypernucleus undergoing the following decay. In process (7) π^0 is not spectroscopized, even nor detected, and there are two neutrons in the final state. However, if I consider that the weak decay of an hypernucleus always occurs from the ground state, and that the slowing down time ($\sim 10^{-13}$ s) of $^6_\Lambda$He in the target following its production is much lower than the Λ lifetime (2.63×10^{-10} s), the detection of the two neutrons in coincidence with a total missing mass resolution of $\sim$ 14 MeV allows to isolate the final state of ^{4}He, which has a high threshold for particle emission (19.8 MeV) and no low-lying excited states. The shell model picture of $^6_\Lambda$He is two neutrons, two protons and the Λ in the $1s_{\frac{1}{2}}$ shell and one neutron in the $1p_{\frac{3}{2}}$ shell. If the residual nucleus is ^{4}He (two protons and two neutrons in the $1s_{\frac{1}{2}}$ shell) the NM exclusive decay is the result of a weak interaction among a Λ in an $1s_{\frac{1}{2}}$ state and a neutron in a $1p_{\frac{3}{2}}$ state.

To my knowledge, there are no theoretical calculations for exclusive NM decays. A guess on the relative weight of the exclusive process over the total NM decay rate can be inferred by analogy with some similar nuclear processes.
(π^-, $2n$) [7] or (π^+, $2p$) [8] reactions on nuclei are quite similar concerning the energy released to a nucleon pair: 140 MeV plus the π kinetic energy compared to 176 MeV for NM decays. For a ^{6}Li target, the residual nucleus distribution in (π, $2\mathcal{N}$) reactions is quite interesting: ^{4}He in the ground state is produced with a relative frequency of $\sim$ 30 %, for the remaining $\sim$ 70 % being produced in the continuum. These fractions may be taken into account for evaluating the relative BR*s* for the exclusive process (7). (π, $2\mathcal{N}$) reactions in ^{6}Li producing ^{4}He in the ground state involve the proton and the neutron of ^{6}Li in the $1p_{\frac{3}{2}}$ shell, whereas processes with ^{4}He unbound involve a proton and a neutron of $1s_{\frac{1}{2}}$ and $1p_{\frac{3}{2}}$ shells, like in the case of NM decays (7) with ^{4}He in the ground state.

Information on the exclusive process (7) will be unique and could lead to relevant constraints on the $\Delta\mathbf{I}$ = 1/2 rule, by a proper handling of the nuclear wave functions involved. However, also the continuum part of the missing mass spectrum of the two neutrons emitted in (7), leading to ^{4}He unbound states, is of great importance, since it is linked to the weak interaction of a Λ and a neutron both in the $1s_{\frac{1}{2}}$ state. Similar information on the weak interaction of a Λ and a proton in the $1s_{\frac{1}{2}}$ state could be obtained by a study of process (6) in which ${}^{6}_{\Lambda}$Li is unstable for proton emission. The total missing mass resolution for this channel could be better than 10 MeV, not enough for a clean separation of the exclusive channel with ^{3}H in the final state. However, if the collected statistics will be sufficient, unfolding techniques and angular correlation constraints might allow a quite precise determination also for this exclusive channel.

With the expected counting rates of NM decays in FINUDA, and considering that for process (7) the coincidence with a π^- is not required, I expect about 3 NM decays (6) and (7)/hour. Br*s* (6) and (7) could then be measured to a precision of $\sim 5\%$ in a reasonable time. At the same level of precision I expect the knowledge of absolute efficiencies of detection and acceptances, as well as the corrections for nuclear structure effects, quite known for the simple light nuclei involved. Deviation of the ratio of BR*s* for (6) and (7) from the value 1/2, expected by the pure $\Delta\mathbf{I} = 1/2$ rule, would be an indication of challenging new physics.

References

[1] J. Cohen, *Progr. Part. Nucl. Phys.* Vol. **25** (Pergamon Press, 1990) 139

[2] R. A. Schumacher, *Nucl. Phys.* **A547** (1992) 143c

[3] The FINUDA Collaboration, M. Agnello *et al.*, INFN Rep. LNF-93/021(IR) (1993)

[4] T. Bressani, in *Common Problems and Ideas of Modern Physics* (World Scientific, Singapore, 1992), p. 211

[5] T. Bressani, in *Common Problems and Trends of Modern Physics* (World Scientific, Singapore, 1992), p. 241

[6] The FINUDA Collaboration, M. Agnello *et al.*, FINUDA Technical Report, to appear as INFN LNF Report.

[7] F. Calligaris *et al.*, *Nucl. Phys.* **A126** (1969) 209

[8] T. Bressani *et al.*, *Nucl. Phys.* **B9** (1969) 427