Study of some two-body non-mesonic decays of $^4\Lambda\text{He}$ and $^5\Lambda\text{He}$

FINUDA Collaboration

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Abstract

The Non-Mesonic (NM) decay of $^4\Lambda$He and $^5\Lambda$He in two-body channels has been studied with the FINUDA apparatus. Two-body NM decays of hypernuclei are rare and the existing observations and theoretical calculations are scarce and dated. The $^4\Lambda$He $\rightarrow$ $d + d$, $p + t$ decay channels simultaneously observed by FINUDA on several nuclei are compared: the $pt$ channel is dominant. The decay yields for the two decay channels are assessed for the first time: they are $(1.37 \pm 0.37) \times 10^{-5}/K_{stop}$ and $(7.2 \pm 2.7) \times 10^{-5}/K_{stop}$, respectively. Due to the capability of FINUDA of identifying $^5\Lambda$He hypernuclei, a few $^5\Lambda$He $\rightarrow$ $d + t$ decay events have also been observed. The branching ratio for this decay channel has been measured for the first time: $(3.0 \pm 2.3) \times 10^{-3}$.

Key words: Light Hypernuclei; Non Mesonic Weak Decay

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1 Introduction

Two weak decay modes of $\Lambda$ Hypernuclei are known, mesonic and Non-Mesonic (NM). The latter gives a unique tool to study the baryon-baryon weak interactions. Relatively little information about NM decays can be inferred by alternative processes, such as nucleon scattering experiments or parity violating nuclear transitions.

The NM decay mode, in which two or more nucleons are emitted after a $\Lambda$-$A$ multibaryon weak interaction in a nuclear medium, is dominant for medium-heavy nuclei. It is characterized by a large momentum transfer; in fact, the emitted nucleons have a momentum in the range 400–600 MeV/$c$ and can escape the nucleus. In light hypernuclei the NM decay can also lead to final states composed by two bodies only:

$$^4\Lambda\text{He} \rightarrow d + d$$  \hspace{1cm} (1)

$$^4\Lambda\text{He} \rightarrow p + t$$  \hspace{1cm} (2)
Some of these reactions can be interpreted as two-nucleon induced decays. FINUDA recently determined the two-nucleon induced NM decay to be about 1/4 of the total NM, for \( p \)-shell hypernuclei \([1]\). In addition, a suppressed branching ratio for the two-body NM channels is expected because of the large momentum transfer and of the possible two-step mechanisms involved.

Theoretical predictions are scarce due to the very limited available data set. The only existing calculation for the two body \( ^4\Lambda\text{He} \) decay rates was performed in 1966 by Rayet \([2]\), and was based on a phenomenological non-relativistic matrix elements evaluation for the \( \Lambda N \to N + N \) interaction. Branching ratios of 0.015 for (1) and (2) and of 0.03 for (3) were predicted, with a spread within a 1.5 factor due to the dependence of the model on the nuclear density and on the \( \Lambda \) compression effect.

These evaluations are in rough agreement with the existing experimental observations, which are scarce and dated. They all belong to bubble chamber and emulsion experiments \([3,4,5]\). The full present database consists of a few \( ^4\Lambda\text{He} \to n + ^3\text{He} \) events \([3,4]\), whose rate is 8–14% of all the \( ^4\Lambda\text{He} \) NM decays, and one \( ^4\Lambda\text{He} \to d + d \) event \([4]\). No \( ^4\Lambda\text{He} \to p + t \) decays were observed. Keyes \textit{et al.} \([5]\), in a liquid Helium bubble chamber experiment, report 1.8% as upper limit for the reactions (1) and (2), to be compared to the \( \pi^- \) mesonic decay of \( ^4\Lambda\text{He} \). For the \( ^5\Lambda\text{He} \to d + t \) decay only one event was ever observed \([3]\), and just one theoretical evaluation for the expected decay rates of \( ^5\Lambda\text{He} \) exists \([6]\).

In this Letter the rates of the decay modes (1) and (2) for \( ^4\Lambda\text{He} \) hyperfragments and (4) for \( ^5\Lambda\text{He} \) are presented. The data were collected by the FINUDA spectrometer operating at the DAΦNE \( \phi \)-factory, Laboratori Nazionali di Frascati (LNF), Italy. FINUDA is a magnetic spectrometer designed for the study of hypernuclei production and decay being induced by stopped negative kaons on targets of different composition. The apparatus features a large geometrical acceptance (\( \sim 2\pi \) sr) and an outstanding particle identification capability for charged hadrons (98\% and 94\% for protons and deuterons, respectively), integrated over the full momentum range for their detection: (180–800) MeV/c for protons, (300–800) MeV/c for deuterons). Also thanks to the apparatus transparency an excellent momentum resolution is achieved, up to \( \Delta p/p \sim 0.6\% \) for the negative pions, of about 270 MeV/c, used in meson spectroscopy studies. FINUDA cannot give any information about reaction (3), since 507 MeV/c \( ^3\text{He} \) nuclei cannot be detected by the apparatus.

The (1), (2) and (4) two-body NM decays of Hyperhelium isotopes present a clear back-to-back topology for the reconstructed tracks. Such a feature, along with the PID information provided by the apparatus, makes the full

\[
^4\Lambda\text{He} \to n + ^3\text{He} \quad (3)
\]

\[
^5\Lambda\text{He} \to d + t. \quad (4)
\]
reconstruction of the hypernuclear decay products feasible.

The signature of two-body $^4_\Lambda\text{He}$ decays is particularly clean. For reaction (1), it consists of two 571.8 MeV/c monochromatic back-to-back deuterons, for reaction (2), the two hadrons $(p, t)$ are back-to-back emitted with a momentum of 508 MeV/c.

FINUDA can directly identify $^5_\Lambda\text{He}$ hypernuclei and indirectly detect $^4_\Lambda\text{He}$ hyperfragments. The identification of the $^5_\Lambda\text{He}$ hypernucleus is performed by measuring negative pions from the $K^-{^6}\text{Li} \rightarrow {^6}\text{Li} + \pi^-$ and $K^-{^7}\text{Li} \rightarrow {^7}\text{Li}^* + \pi^-$ reactions. The unstable hypernuclei decay strongly to $^5_\Lambda\text{He}$ according to the reactions $^6\text{Li} \rightarrow ^5_\Lambda\text{He} + p$ and $^7\text{Li}^* \rightarrow ^5_\Lambda\text{He} + d$. In these reactions, the proton and the deuteron momentum is below 100 MeV/c, and their detection is not possible. However, the formation pions have a momentum in a well-defined range which allows for a clear $^5_\Lambda\text{He}$ tagging. Conversely, the $K_{\text{stop}}^-{^4}\text{He} \rightarrow ^4_\Lambda\text{He} + \pi^−$ reaction cannot be studied in FINUDA, since a liquid Helium target could not be produced also in the $K_{\text{stop}}^-\text{A}$ interaction in nuclei with $A \geq 6$. In solid targets the $^4_\Lambda\text{He}$ hyperfragment, however, cannot escape the target volume and thus be tracked, as was done in emulsion experiments [7,8,9]. In these experiments, the measured yield of hyperfragment production in $K^−$ absorption at rest ranged from $(4.5 \pm 0.5)%$ [10] to the more recent values $(5 \pm 1)%$ [11] and $(6.5 \pm 0.2)%$ [7]. The fraction of the hyperfragment mesonic decay was measured to be around 20%. Hyperfragments were in general observed more copiously when produced by light emulsion nuclei, i.e. up to $^{16}\text{O}$ [11].

2 Outline of the FINUDA experimental apparatus

A short description of the experimental set-up is given here for the sake of clarity. More details can be found, for instance, in Ref. [12]. FINUDA features a cylindrical geometry and is installed in one of the DAΦNE interaction regions, where $\phi(1020)$ mesons from the $e^+e^−$ collisions are produced. The charged kaons from $\phi(1020) \rightarrow K^+ + K^−$ decay (B.R.=0.49) have a momentum of 127 MeV/c at most, and they slow down while crossing the internal region of the apparatus until they interact at rest in a set of targets. The apparatus consists of five position-sensitive layers, arranged coaxially around the beam axis. Four of them are also used for particle identification through energy loss measurements. The tracking region is immersed in a uniform solenoidal magnetic field of 1 T. Three main sectors may be singled out in the detector layout:

- interaction/target region: located at the apparatus center, consisting of a Beryllium beam pipe, a 12 scintillator slab hodoscope (TOFINO) [13] used
for trigger purposes and for charged kaons discrimination, an eight module array of double-side Si microstrip detectors (ISIM) [14] facing eight target tiles. The target set-up for the data used in the present analysis consisted of two (90% enriched) $^6$Li (thickness: 4 mm), two natural isotopic composition $^7$Li (4 mm), two $^9$Be (2 mm), one $^{13}$C (10 mm) and one D$_2$O (liquid filled and mylar walled, 3 mm thick) targets.

- tracking region: consisting of ten Si microstrip modules (OSIM) [14] facing externally the targets, two arrays of eight planar low-mass drift chambers (LMDC’s) [15], filled with a He-iC$_4$H$_{10}$ gas mixture, and a system of six longitudinal-stereo layers of Ar-C$_2$H$_6$ filled straw tubes [16]. The ISIM and OSIM modules feature a spatial resolution better than $\sigma \sim 30 \mu$m for both the $(r\phi)$ and $z$ coordinates. LMDC’s provide a resolution $\sigma_{r\phi} \sim 150 \mu$m and $\sigma_z \sim 1$ cm, while for the straw tube system the resolution is $\sigma_{r\phi} \sim 150 \mu$m and $\sigma_z \sim 500 \mu$m.

- outer scintillator array: a barrel of 72 thick slabs [17], used for first level trigger, time-of-flight measurements with an overall time resolution $\sigma \sim 800$ ps and neutron identification with a $\sim 10\%$ efficiency.

The data used in the present analysis correspond to an integrated $e^+e^-$ luminosity of 966 pb$^{-1}$, collected by FINUDA in the 2006-2007 run.

3 $^4_\Lambda$He $\rightarrow d + d$ and $^4_\Lambda$He $\rightarrow p + t$ decays

The $^4_\Lambda$He hyperfragment can be produced via the reaction $K_{\text{stop}}^-$ $^2_\Lambda$X $\rightarrow ^4_\Lambda$He $+$ $\pi^- + ^4_{\Lambda-2}$X’, where X’ is a recoiling nuclear system (bound or unbound), and the pion momentum is larger than 220 MeV/c. The hyperfragment production can also occur with the emission of a $\pi^0$, that however is undetectable by FINUDA.

The signature of a $dd$ decay event consists of two high momentum back-to-back deuteron tracks. The main source of background is given by the $^4_\Lambda$He $\rightarrow (pn) + (pn)\pi^0$ mesonic decay, whose frequency is almost comparable to the full NM branch [18]. The mean momentum of the $(pn)$ pairs in this three-body decay is around 150 MeV/c; therefore, these events can be easily discarded by applying a cut on the missing mass distribution of the $^4_\Lambda$He $\rightarrow d + d$ decay.

The total inclusive $dd$ collected sample consists of 272 $\pm$ 16 events, over all the FINUDA targets. Fig. 1 shows the momentum distribution of the two observed deuterons. In a pair, one of the deuterons is emitted from the target toward the outer hemisphere, i.e. toward the tracking region: forward track, Fig. 1a). The second deuteron is emitted in the opposite direction, thus crossing twice ISIM, TOFINO, the beam pipe and one of the targets: backward track, Fig. 1b). The forward tracks are required to be reconstructed by a mini-
of three hits, one of which is necessarily located on the OSIM array. The momentum resolution of backward deuterons is spoilt by the larger material budget crossed by the particle, but at least two hits of the track are located on the high resolution ISIM and OSIM detectors. From Monte Carlo simulations the momentum resolution of forward deuterons in FINUDA results to be 3% FWHM (17 MeV/c at 570 MeV/c), while for backward deuterons is 4% FWHM (∼ 22 MeV/c). Both tracks were selected with a track fitting procedure which requires χ² < 20 (C.L. ∼ 95%).

Fig. 1. Momentum distributions for the forward a) and the backward b) deuterons in the two deuteron semi-inclusive sample. The hatched histograms show ⁴ΛHe → d + d at rest decay events. The black histograms correspond to dd events with a high momentum π⁻ (pπ⁻ > 220 MeV/c) in coincidence.

The semi-inclusive momentum distributions are shown as open histograms in Fig. 1. Fig. 2a) shows the distribution of the angle between the two deuteron tracks, while Fig. 2b) displays the invariant mass distribution of the dd pairs. Events with a sharp back-to-back angular correlation (cos Θ < −0.995) are chosen, see inset of Fig. 2a). The dotted histogram in the inset shows the corresponding distribution for simulated ⁴LambdaHe → d + d at rest decays, filtered through the detector acceptance and normalized to the tail of the experimental distribution. The applied cut allows all the searched events to be accepted eliminating dd non-monochromatic pairs emitted in possible heavier hyperfragment production and decay.

In the back-to-back dd sample, exclusive events are then required to have a total energy in the (3–4) GeV range and a total momentum less than 50 MeV/c. A last requirement imposes the missing mass for the ⁴ΛHe → d + d decay to be compatible with zero within a 2σ range (σ = 11 MeV/c²). The events selected for the final yield evaluation are shown in the cross-hatched distributions in Fig. 1 and 2.

Summing over all the targets, the total statistics available after the described selections is 31 ± 6 dd events. 14 ± 4 events, out of the semi-inclusive dd sample, present an additional π⁻ with momentum larger than 220 MeV/c. These events are displayed in the black histograms in Fig. 1 and 2. They can be interpreted
Fig. 2. Distribution of the angle between the two deuterons (a) and of the \( (dd) \) invariant mass (b). Open histogram: semi-inclusive \( dd \) sample. The hatched histograms display \( ^4\text{He} \to d + d \) at rest decay events. The black histograms correspond to \( dd \) events with a high momentum \( \pi^- \left( p_{\pi^-} > 220 \text{ MeV}/c \right) \) in coincidence. The inset in Fig. a) zooms the distribution for \( \cos \theta < -0.99 \) angles. The dotted histogram in the inset, normalized to the tail of the experimental histogram, shows the corresponding distribution for simulated \( ^4\Lambda\text{He} \to d + d \) at rest decays, filtered through the detector acceptance. In Fig. b) the dot-dashed line marks the \( ^4\Lambda\text{He} \) mass value.

as exclusive events in which both the \( ^4\Lambda\text{He} \) hyperfragment formation and its decay have been measured. However, they are not used for yield evaluations as not all of them present strictly back-to-back deuterons, as shown in Fig. 2 a).

The selected sample is affected by a background contribution consistent with zero. Side bin background evaluations have been made selecting different missing mass and momentum ranges, displaced one or two \( \sigma \)'s from the respective reference values. No events matching the required event signature are found in displaced ranges.

A target-by-target measurement of the number of \( ^4\Lambda\text{He} \to d + d \) decays at rest per incident \( K^- \) can be performed. The recorded number of collected \( K^-_{\text{stop}} \) per target depends on the target position, due to the slight \( \phi \) boost, and it varies in the range \((1.1-2.1) \times 10^7\). The results are reported, for different nuclei, in Tab. 1. The yield is basically constant for lighter targets (up to \( ^9\text{Be} \)); for heavier targets an upper limit can be given at 90\% confidence level. The overall efficiency, which takes into account the trigger, the apparatus acceptance, the reconstruction and analysis procedures as well as the efficiency of the detectors, is also a function of the target position and varies in the range \((1.5-3)\%\).

The systematic errors take into account the spread of the values measured in different targets of the same composition and the effect of 1\( \sigma \) variations in the selection criteria. They also take into account the uncertainties in assessing the number of stopped kaons (due to out of target and in-flight interactions, \( K^-/K^+ \) swap in the pattern recognition procedure, backtracking algorithm
An overall average yield can be deduced. The resulting value is \( Y_{\Lambda^4 \text{He} \rightarrow d+d} = (1.37 \pm 0.37) \times 10^{-5}/K^-_{\text{stop}} \), where the overall uncertainty accounts for statistical and systematic errors added in quadrature. Assuming a hyperfragment production rate of about 5\%/K^-_{\text{stop}}, roughly valid up to \( A = 16 \) [11], and under the simple hypothesis that \( \Lambda^4 \text{He} \)'s are the most abundantly produced hyperfragments, this yield corresponds to an upper limit for the \( \Lambda^4 \text{He} \rightarrow d+d \) branching ratio of about \( 3 \times 10^{-4} \).

Concerning the \( \Lambda^4 \text{He} \rightarrow p+t \) decay channel, tritons in FINUDA can be detected only for momenta larger than 550 MeV/c, which exceeds the momentum value expected for the two body \( \Lambda^4 \text{He} \rightarrow p+t \) decay at rest, 508 MeV/c. Tritons with lower momenta, in fact, cannot be reconstructed as they stop in the inner tracking layers of FINUDA. However, if they cross the I/OSIM layers they deposit a large amount of energy, that can be used to tag such events. As a consequence, the \( \Lambda^4 \text{He} \rightarrow p+t \) decay can effectively be measured only through the information on the proton and the momentum of the formation pion. The proton track is selected applying the same quality criteria described above for deuterons. For the pion the quality criteria are released. A cut is applied to eliminate contributions from Quasi-Free (QF) reactions due to the absorption of the \( K^- \) by just one nucleon: \( p_{\pi^-} > 200 \text{ MeV}/c \). On the other hand, pions with \( p_{\pi^-} > 220 \text{ MeV}/c \) are expected from the observation of the coincident \( \pi^- \)'s in the analysis of the \( \Lambda^4 \text{He} \rightarrow d+d \) decay. Events with a detected neutron are moreover rejected to remove possible contaminations due

| target | \( dd \) Events | Yield \( \times 10^{-5}/(K^-_{\text{stop}}) \) | \( pt \) Events | Yield \( \times 10^{-5}/(K^-_{\text{stop}}) \) |
|--------|----------------|---------------------------------|----------------|---------------------------------|
| \(^6\text{Li}\) | 12 ± 3 | \( 3.0 \pm 1.3_{\text{stat}} \pm 0.9_{\text{sys}} \) | 1 ± 1 | \( 5.0 \pm 6.5_{\text{stat}} \pm 0.3_{\text{sys}} \) | \( < 16.8 \ (90\% \text{C.L.}) \) |
| \(^7\text{Li}\) | 7 ± 3 | \( 2.4 \pm 1.3_{\text{stat}} \pm 0.8_{\text{sys}} \) | 1 ± 1 | \( 5.1 \pm 5.8_{\text{stat}} \pm 0.3_{\text{sys}} \) | \( < 14.3 \ (90\% \text{C.L.}) \) |
| \(^9\text{Be}\) | 10 ± 3 | \( 3.3 \pm 1.4_{\text{stat}} \pm 0.4_{\text{sys}} \) | 5 ± 2 | \( 14.9 \pm 7.4_{\text{stat}} \pm 0.9_{\text{sys}} \) |
| \(^{13}\text{C}\) | 1 ± 1 | \( 0.6 \pm 0.6_{\text{stat}} \pm 1.0_{\text{sys}} \) | 1 ± 1 | \( 7.2 \pm 7.8_{\text{stat}} \pm 0.2_{\text{sys}} \) | \( < 30.5 \ (90\% \text{C.L.}) \) |
| \(^{16}\text{O}\) | 1 ± 1 | \( 0.6 \pm 0.6_{\text{stat}} \pm 1.1_{\text{sys}} \) | 2 ± 1 | \( 10.4 \pm 8.0_{\text{stat}} \pm 0.2_{\text{sys}} \) | \( < 2.7 \ (90\% \text{C.L.}) \) |

Table 1
Second and third column, number of events and yields, per \( K^-_{\text{stop}} \), of the \( \Lambda^4 \text{He} \rightarrow d+d \) decay, for hyperfragments produced all targets of given \( A \) (first column). Fourth and fifth column, number of events and yields per \( K^-_{\text{stop}} \) of the \( \Lambda^4 \text{He} \rightarrow p+t \) decay at rest. In case of one event only, an upper limit following Poisson statistics is also quoted.

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to baryon ($\Lambda$, $\Sigma^-$) decays. A total sample of $297023 \pm 545$ semi-inclusive ($p\pi^-$) events is collected. None of the events with a proton selected in the proper momentum band (498–520 MeV/c) feature hits with large energy deposit in silicon layers opposite to the emitted proton track.

The main background source for the $^4\Lambda$He $\rightarrow p + t$ decay channel is played by the QF $K^-(pn) \rightarrow \Sigma^- + p$ two nucleon absorption ($K2N$), which has a large capture rate, $1.62%/K^-_{\text{stop}}$ in $^6\text{Li}$ [12] and an order of magnitude larger in heavier nuclei. The QF signature is similar to that of the studied decay, with a “quasi”-monochromatic proton of about 510 MeV/c momentum, and a fast $\pi^-$. A study of the impact parameters and the angular distributions of the emitted proton and negative pion has been performed to understand how to remove the most sizeable fraction of $K2N$-QF events without losing too much of the searched signal. An optimized cut in the distribution of the $\pi^-$ impact parameter, i.e. the distance between the track and the $K^-$ interaction vertex, rejects about 79% of the $\Sigma^- p$ background, but it also reduces by 60% the searched signal. The ($p\pi^-$) angle in the $K^-(pn) \rightarrow \Sigma^- + p$ absorption displays a marked back-to-back trend. The simulated distributions of the ($p\pi^-$) angle for particles emitted in the $K2N$ reaction (grey area) or from $^4\Lambda$He formation and decay (open histogram) are shown in Fig. 3.

![Fig. 3. Monte Carlo data: distribution of the angle formed between a proton and a $\pi^-$ track in the simulation of the QF $K^-(pn) \rightarrow \Sigma^- p$ (grey histogram), and of the formation of a $^4\Lambda$He hyperfragment and its decay at rest in the $p + t$ channel (open histogram). The two distributions are arbitrarily normalized; the simulated data are modulated by the apparatus acceptance.](image-url)

The distributions are arbitrarily normalized and are filtered through the apparatus acceptance, which suppresses the positive cosine region for both the reactions. Still, it emerges that, due to the apparatus acceptance, in the case of hypernuclear formation and decay one should expect a relatively enhanced emission of tracks on the same side with respect to the target. The selection of such tracks also enhances the contamination of $\Lambda$‘s, though, whose contribu-
tion can be removed by a proper cut on the $p\pi^-$ invariant mass. The selection of $p\pi^-$ pairs emitted in the same hemisphere reduces the available sample of 53%, but the $\Sigma^-p$ contamination is reduced to 12%. This selection criterion is therefore chosen.

The events surviving the mentioned selections fill the histograms in Fig. 4a) and b). The scatter plot in Fig. 4a) shows the proton momentum versus the missing mass of the reaction $K^-\frac{A}{2}X \rightarrow \pi^- + Hyp + \frac{A-4}{2}X'$, where the $Hyp$ system is, presumably, a hyperfragment. In this reaction the $X'$ and $Hyp$ systems are not measured, and $X'$ is assumed to be a spectator. The mass of $X'$ is assumed to be equal to the mass of the most stable nuclear system with $(A-4)$ mass number and $(Z-2)$ protons.

The horizontal band between the dashed lines is centered at the $^4\text{He}$ mass ($m = 3.92 \text{ GeV}/c^2$) and is 50 MeV/c$^2$ wide. The vertical band is, conversely, centered at the nominal proton momentum for the $^4\text{He} \rightarrow p + t$ decay, and is 24 MeV/c wide. The highest intensity of the plot is located around $p_p = 420$ MeV/c (one-nucleon induced NM weak decay). At the intersection of the two bands a small activity can be noticed. The open histogram in Fig. 4b) shows the x-axis projection of this scatter plot.

![Fig. 4. a) Proton momentum vs missing mass of the reaction $K^-\frac{A}{2}X \rightarrow \pi^- + Hyp + \frac{A-4}{2}X'$. The horizontal band between the two dashed lines corresponds to the interval $m(^4\text{He}) \pm 25 \text{ MeV}/c^2$; the vertical band corresponds to the momentum interval $508 \pm 12 \text{ MeV}/c$ across the nominal proton momentum value for the $^4\text{He} \rightarrow p + t$ decay at rest. b) Proton momentum distribution for all events with a high momentum coincident pion (open histogram), and for events selected in the horizontal band of a) having a missing mass for the $^4\text{He} \rightarrow p + t_{\text{miss}}$ decay in the range $(m_t \pm 5) \text{ MeV}/c^2$. The vertical dashed line marks the nominal proton momentum for the $^4\text{He} \rightarrow p + t$ decay at rest.](image-url)
the unmeasured recoiling nuclear system. For this reason, a selection on the measured deuteron momentum is preferred requiring, target by target, the missing mass of the $^4\text{He} \rightarrow p + t_{\text{miss}}$ at rest decay to be in the range $(m_t \pm 5)$ MeV/c$^2$: the selected events are shown in the black histogram in Fig. 4b), which is centred at 508 MeV/c with a width of 15 MeV/c. The momentum resolution for such a proton is 0.7% ($\sigma$). The events in the black histogram are then used for the final evaluation of the yields.

The selected sample, still background inclusive, amounts to a total of $44 \pm 7$ $pt_{\text{miss}}\pi^-$ events (from all available targets). The contamination in the selected sample due to the $\Sigma^-p$ source consists of a few $10^{-5}$ events/$K^-\text{stop}$, being so, presumably, of the same order of magnitude of the yield of the searched signal. In the final sample the signal to background ratio amounts to $S/N = 0.23$, which corresponds to a 2.9$\sigma$ statistical significance of the observed signal. The scatter plot of Fig. 5a) shows the same distribution presented in Fig. 4a) for $K^-(pn) \rightarrow \Sigma^-p$ simulated events, without any kinematic cut. The distribution covers completely the region of the searched signal, indeed it has its maximum close to the intersection of the chosen bands. However, if the described angular selection is applied to these data, the distribution in Fig. 5b) is obtained, which shows that a significant reduction of the background contribution can be achieved, even if an unavoidable contamination is still present in the region under study.

After background subtraction, performed target-by-target by side-bin evaluations in the proton momentum spectra, an assessment of the yield of the $^4\text{He} \rightarrow p + t$ decay is done and the results are reported in columns 5 and 6 of Tab. 1. An overall efficiency for this channel, including acceptance, trigger, reconstruction, analysis cuts as well as detector failures, is estimated to be around $1.4 \times 10^{-3}$ (modulated according to the target position). In case of a single selected event an upper limit, at 90% C.L., may be given. The quoted
systematic uncertainties take into account the maximum spread of values obtained with small variation of the selection cuts and in different targets of the same nuclear composition. They also take into account the uncertainty on the kaon normalization described in the previous section.

From an examination of the obtained yields, the $\Lambda^4$He $\rightarrow p + t$ decay at rest looks favoured in heavier targets. Following the method described above for $dd$ decays, the average value $(7.2 \pm 2.7) \times 10^{-5}/K^{-\text{stop}}$ is obtained. Assuming again a hyperfragment production of about $5\%/K^{-\text{stop}}$, the upper limit for the branching ratio of the $\Lambda^4$He $\rightarrow p + t$ decay is $\sim 1.4 \times 10^{-5}$.

The ratio between the absolute number of events collected in the $dd$ and $pt$ channels can also be evaluated target by target. The trend of the ratio as a function of $A$ is reported in Fig. 6, in which the error bars take into account both statistic and systematic errors.

![Fig. 6. Ratio of the $\Lambda^4$He $\rightarrow d + d$ to $\Lambda^4$He $\rightarrow p + t$ decay yields as a function of the atomic mass number $A$.](image)

The weighted average value over the (6–16) $A$ range is $R(\Lambda^4$He $\rightarrow d + d/\Lambda^4$He $\rightarrow p + t) = (9.9 \pm 5.5) \times 10^{-2}$. In spite of the large errors, a dominance of the $pt$ decay mode over the $dd$ arises, in particular for nuclei with small $A$.

4 $\Lambda^5$He production and $\Lambda^5$He $\rightarrow d + t$ decay in FINUDA

FINUDA can observe both $\Lambda^5$He hypernuclei and hyperfragments, produced in targets heavier than Li. In FINUDA $\Lambda^5$He hypernuclei may be produced via the $K^{-\text{stop}}^6$,$^7$Li interaction. They can be observed by FINUDA in the formation $\pi^-$ momentum spectrum by requiring a proton from the non-mesonic decay of the hypernucleus in coincidence [19].

The data set for the $\Lambda^5$He $\rightarrow dt$ decay is obtained by selecting a negative pion
in the momentum range 267–273 MeV/c along with a deuteron in the 570–630 MeV/c interval; the deuteron from the decay has a nominal momentum of 597 MeV/c. Still, this selection prevents further tritons from being detected. But events with a large energy release on ISIM or OSIM modules opposite to the emitted deuteron track have been found: one event with all the above features has been reconstructed for $^6$Li and two for $^7$Li. No events presenting the same topology and momenta slightly outside the mentioned momentum ranges have been found, so the background contribution to these events is consistent with zero. With an overall efficiency of about $(6-11) \times 10^{-3}$, the yield $Y_{^5\Lambda He \rightarrow d+t} = (2.6 \pm 1.5_{st} \pm 1.1_{sys}) \times 10^{-5}/K_{\text{stop}}$ is found, with a statistical significance of $1.7\sigma$. Normalizing to the absolute number of $^5\Lambda He$ hypernuclei measured by FINUDA in the same run \cite{19}, the branching ratio for this decay channel can be evaluated: $B.R.(^5\Lambda He \rightarrow d+t) = (3.0 \pm 2.3) \times 10^{-3}$. On the same data sample, an assessment of the one-proton induced NM decay rate (inclusive of FSI distortion effects) has been determined, $R(^5\Lambda He) = 0.28 \pm 0.07$ \cite{19}. Taking also into account the non-measured one-neutron and two-nucleon induced decays, the evaluated $dt$ branching ratio is about two orders of magnitude smaller than the NM decay rate, roughly in agreement with the theoretical expectations \cite{2}. The same conclusion can also be attained by deducing the NM branching ratio from the total and mesonic widths of the $^5\Lambda He$ decays \cite{20}.

A second analysis of the $^5\Lambda He \rightarrow dt$ decay is based on the search of $^5\Lambda He$ hyperfragments, following the same analysis pattern applied in the $^4\Lambda He$ case. A total sample of $1056 \pm 32$ $d\pi^-$ inclusive events is available. Such events rely on the measurement of a high-resolution fast $\pi^-$ ($\Delta p/p \sim 0.75\%$, $p_{\pi^-} > 200$ MeV/c) in coincidence with a deuteron. A stringent $\chi^2$ from of the track fitting procedure is required, corresponding to C.L. $\sim 98\%$. The resolution for a deuteron of $\sim 600$ MeV/c momentum is $8$ MeV/c ($\sigma$), corresponding to $\Delta p/p \sim 1.5\%$.

The $K^- \frac{4}{2}X \rightarrow \pi^- + H yp + \frac{4}{2}X'$ events, whose missing mass falls in a region centered at the $^5\Lambda He$ mass (4.85 GeV/c$^2$), 40 MeV/c$^2$ wide, are further studied. In this reaction the recoiling nuclear system is supposed to be produced at rest as a spectator. Furthermore, the $^5\Lambda He$ hyperfragment is assumed to be produced by proton emission from $^6\Lambda Li$ if the $K^-$ is stopped in $^6Li$, while it is assumed to be produced by deuteron emission from $^7\Lambda Li^*$ when $K^-$'s are stopped in other targets. This assumptions change slightly the reaction kinematics for different targets.

The scatter plot of the deuteron momentum versus the missing mass of the above reaction is displayed in Fig. 7a). The horizontal band between the two dashed lines shows the range selected around the $^5\Lambda He$ mass; the spread within the band is again due to the hypothesis made on the kinematics of the recoiling nuclear system. The vertical band centered at 597 MeV/c, 40 MeV/c wide, marks the deuteron momentum range of interest. In the intersection region
Fig. 7. a) Scatter plot of the deuteron momentum vs the missing mass of the $K^- A Z X \rightarrow \pi^- + Hyyp + Z^- 5 X'$ reaction. The horizontal band between the two dashed line corresponds to the interval $m(5 \text{He}) \pm 20 \text{MeV}/c^2$; the vertical band corresponds to the momentum interval $597 \pm 20 \text{MeV}/c$ across the nominal deuteron momentum value for the $^5 \text{He} \rightarrow d + t$ decay at rest.  

b) Deuteron momentum distribution for all events with a high momentum coincident pion (open histogram), and for events selected in the horizontal band of a) so that the missing mass $^5 \text{He} \rightarrow d + t_{\text{miss}}$ at rest decay is in the range $(m_t \pm 12.5) \text{MeV}/c^2$. The vertical dashed line marks the nominal deuteron momentum for the $^4 \text{He} \rightarrow p + t$ decay at rest.

some limited activity can be seen. The events in the horizontal band may be further selected asking the missing mass of the $^5 \text{He} \rightarrow d + t$ at rest decay to belong, target by target, to the interval $(m_t \pm 12.5) \text{MeV}/c^2$ (equivalent to a cut on the deuteron momentum). Events surviving this selection are shown in the black histogram in Fig. 7b), where the deuteron momentum is displayed for inclusive events also (open histogram). These events are located in a range, 30 MeV/c wide, across 597 MeV/c.

Also the background contribution in the $\pi^- dt_{\text{miss}}$ sample is sizeable and mostly due, again, to the $K^- (pn) \rightarrow \Sigma^- + p$ QF reaction, where the $p$ is misidentified as $d$ (which can occur at the level of a few percent). Fig. 8 shows the scatter plot of the momentum vs the missing mass for inclusive $d \pi^-$ events from a simulated $K^- (pn) \rightarrow \Sigma^- p$ sample, selected forcing a proton/deuteron misidentification. A non-negligible background contribution still remains in the signal region. It has been subtracted from the signal, target by target, resorting to side-bins counting in the deuteron momentum distribution. The $S/N$ ratio, averaged over all the available targets, is about 20%. A further source of background could arise from the $K^-$ absorption by three nucleons with deuteron emission. However, this contribution is neglected in this analysis as the reaction is expected to occur at a rate at least one order of magnitude smaller than two-nucleon absorption [21].

Tab. 2 reports the decay rate per $K^-_{\text{stop}}$ of $^5 \text{He}$ hyperfragments in the $dt$ channel. The systematic uncertainty takes into account the spread of the values
due to $1\sigma$ changes in the selection criteria, the different counting in targets of the same nucleus type, as well as the correction factors in the kaon normalization. The overall efficiency is in the range $(3–6)\times10^{-3}$. The yield averaged over the available nuclei is $(1.40 \pm 0.24) \times 10^{-4}/K^-_{\text{stop}}$.

| target | Number of events | Yield$\times10^{-4}/(K^-_{\text{stop}})$ |
|--------|------------------|---------------------------------|
| $^6$Li  | 4 ± 2            | $1.83 \pm 0.93^{\text{stat}} \pm 0.12_{\text{sys}}$ |
| $^7$Li  | 5 ± 2            | $1.12 \pm 0.51^{\text{stat}} \pm 0.08_{\text{sys}}$ |
| $^9$Be  | 13 ± 4           | $1.23 \pm 0.38^{\text{stat}} \pm 0.02_{\text{sys}}$ |
| $^{13}$C | 7 ± 3           | $2.25 \pm 0.87^{\text{stat}} \pm 0.04_{\text{sys}}$ |
| $^{16}$O | 11 ± 3          | $1.58 \pm 0.50^{\text{stat}} \pm 0.03_{\text{sys}}$ |

Table 2
Yield of the $^5_\Lambda$He $\rightarrow d + t\text{miss}$ decay at rest per $K^-_{\text{stop}}$.

5 Summary

FINUDA has been able to measure several features of the two-body decay channels $^4_\Lambda$He $\rightarrow d + d$, $^4_\Lambda$He $\rightarrow p + t$ and $^5_\Lambda$He $\rightarrow d + t$, thus conveying new results useful to complete the meager existing database on two-body non-mesonic decay modes of light hypernuclei. Despite the limited statistics, FINUDA has observed signatures of decay events with a reduced background in some of the studied channels. The particle identification capabilities of the magnetic spectrometer together with its high resolution allow for the detection of a few rare events never observed before.
For $^4\Lambda$He $\rightarrow d + d$ in different targets the decay yields are of the order of a few $10^{-5}/K_{\text{stop}}$, while for the $pt$ decay channel they are some units larger. The $^5\Lambda$He $\rightarrow d + t$ decay yield of $^5\Lambda$He hypernuclei is $(2.6\pm1.5_{\text{stat}}\pm1.1_{\text{sys}})\times10^{-5}/K_{\text{stop}}$. The B.R. for this decay channel has been determined for the first time to be $(3.0\pm2.3)\times10^{-3}$. This is in rough agreement with the theoretical prediction [2] of two orders of magnitude less as compared to the one-nucleon induced NM decay branching ratio [19].

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