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Search for ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H with the $(K^-_{\text{stop}}, \pi^+)$ reaction

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This paper is dedicated to the memory of our colleague and friend Valerio Filippini

Abstract

The production of neutron rich Λ-hypernuclei via the $(K^-_{\text{stop}}, \pi^+)$ reaction has been studied using data collected with the FINUDA spectrometer at the DAΦNE ϕ-factory (LNF). The analysis of the inclusive π^+ momentum spectra is presented and an upper limit for the production of ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H from ^{6}Li and ^{7}Li, is assessed for the first time.

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1. Introduction

As pointed out by Majling [1], Λ-hypernuclei may be even better candidates than ordinary nuclei to exhibit unusually large values of N/Z and halo phenomena. In fact, a Λ-hypernucleus is more stable than an ordinary nucleus due to the compression of the nuclear core and to the addition of extra binding energy from the Λ hyperon (playing the so-called "glue-like role of the Λ") [2]. From the hypernuclear physics point of view, the attempt to extend our knowledge towards the limits of nuclear stability, exploring strange systems with high N/Z ratio, can provide more information both on baryon-baryon interactions and on the behavior of hyperons in a medium with much lower density than ordinary Λ-hypernuclei. Furthermore, the role of the three-body ΛNN force related to the "coherent Λ–Σ coupling" has connections with nuclear astrophysics [3], as previously proposed in theoretical calculations of high density nuclear matter (neutron stars) [4,5]. In particular, there is great interest in the possible existence of ${}^{6}_{\Lambda}$H; in fact, theoretical calculations predict the existence of a stable single-particle state with a binding energy of 5.8 MeV from the ^{5}H $+ \Lambda$ threshold (+1.7 MeV [6]), when the Λ–Σ coupling term is considered. Without this coupling force the state would be very close to the ${}^{4}_{\Lambda}$H $+ 2n$ threshold [7,8].

Experimentally, the production of neutron rich Λ-hypernuclei is more difficult than standard Λ-hypernuclei, whose one-step direct production reactions, such as (K^-, π^-) and (π^+, K^+), access only a limited region in the hypernuclear chart, rather close to the stability region. On the contrary, neutron rich Λ-hypernuclei can be produced by means of different reactions based on the double charge-exchange (DCX) mechanism, such as (π^-, K^+) and (K^-, π^+). The latter reaction, studied in this Letter, proceeds through the following two elementary reactions:

$$K^- + p \to \Lambda + \pi^0; \quad \pi^0 + p \to n + \pi^+, \tag{1}$$

$$K^- + p \to \Sigma^- + \pi^+; \quad \Sigma^- p \leftrightarrow \Lambda n. \tag{2}$$

Process (1) is a two step reaction in which a strangeness exchange is followed by a pion charge exchange. Process (2) is a single step reaction with a Σ^- admixture (due to the $\Sigma^- p \leftrightarrow \Lambda n$ coupling [9]). Owing to these features, both processes usually have lower cross sections than one step reactions.

The first experimental attempt to produce neutron rich Λ-hypernuclei via the $(K^-_{\text{stop}}, \pi^+)$ reaction was carried out at KEK [10]. An upper production limit (per stopped kaon) was obtained for ${}^{12}_{\Lambda}$Be, ${}^{9}_{\Lambda}$He and ${}^{16}_{\Lambda}$C hypernuclei. The results are in the range $(0.6–2) \times 10^{-4}$; note that the theoretical values calculated by Tetryakova and Lanskoy [9] on ${}^{12}_{\Lambda}$Be and ${}^{16}_{\Lambda}$C are in the range $(10^{-6}–10^{-7})$ per stopped kaon, i.e. at least one order of magnitude less than the experimental upper limits and three orders smaller than the usual $(K^-_{\text{stop}}, \pi^-)$ one-step reaction rates on the same targets (10^{-3}). Recently, a KEK experiment [11] claimed to have observed the production of ${}^{10}_{\Lambda}$Li in the (π^-, K^+) reaction on a ^{10}B target. The published results are not directly comparable with theoretical predictions, since no discrete structure was observed and the production cross section has been integrated over the whole bound region $(0 < B_\Lambda < 20$ MeV). Furthermore, the experimental trend of the cross section energy dependence strongly disagrees with theoretical predictions [12].

This circumstance has stimulated a renewed interest in neutron rich Λ-hypernuclei, in particular in ${}^{6}_{\Lambda}$H and ${}^{7}_{\Lambda}$H. Their production rates have no theoretical predictions nor experimental measurements.

The present Letter shows results concerning these neutron rich Λ-hypernuclei studied in the FINUDA experiment, where they can be produced through processes (1) and (2) with a K^- at rest. In both cases a final state with a π^+ and a Λ-hypernucleus is produced. The overall production reaction is:

$$K^-_{\text{stop}} + {}^{A}(Z) \to {}^{A}_{\Lambda}(Z-2) + \pi^+. \tag{3}$$

The residual Λ-hypernucleus has two protons less and one neutron more than the target nucleus.

In the following, after a short description of the FINUDA experimental apparatus, the analysis of the π^+ inclusive momentum spectra is presented and discussed.

2. The FINUDA spectrometer

A detailed description of the apparatus can be found in Refs. [13–15]. We recall here only some features, mainly related to the present analysis. The main goal of the experiment is to study the formation and the decay properties of Λ-hypernuclei produced by the strangeness exchange reaction $(K^-_{\text{stop}}, \pi^-)$. The K^- comes from the decay at rest of the ϕ produced by DAΦNE. Its low kinetic energy allows it to be slowed down and stopped in thin targets (0.21–0.38 g/cm^2). Thus prompt π^-'s emitted after hypernuclei formation are minimally degraded and their momentum is measured with a small uncertainty (0.6% FWHM choosing high quality tracks). This allows the determination of the hypernuclear levels with a resolution of ~ 1 MeV FWHM.

The (K^+K^-) pairs are detected by a barrel of 12 scintillator slabs (TOFINO) 2.3 mm thick and 20 cm long, surrounding the beam pipe. This detector provides fast trigger signals and, together with the external scintillator barrel (TOFONE), measures the time of flight (TOF) of charged and neutral particles, with a resolution σ_{TOF} (TOFONE–TOFINO) ~ 420 ps. The TOFINO barrel is surrounded by an octagonal Inner array of silicon micro-strip detectors (ISIM). This detector is used to identify the (K^+K^-) pairs with a $\Delta E/\Delta x$ resolution of 20% and to determine their interaction points in the targets with a resolution of a few hundred microns (mainly due to multiple

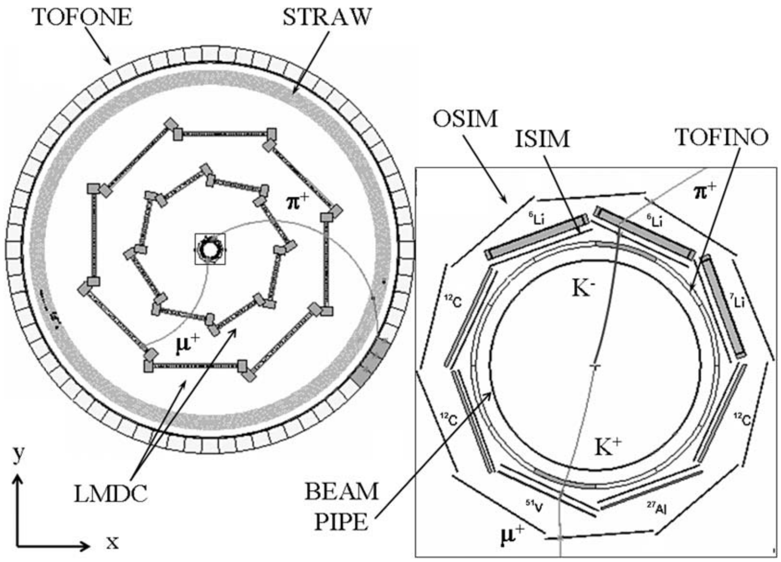

Fig. 1. Picture of a π^+, coming from a K^- stopped in a ^{6}Li target, recorded by the FINUDA tracking region (positive tracks turn clockwise). The track coming from the K^+ stopping point is a μ^+ from $K_{\mu 2}$ decay. In the inset, the (K^+, K^-) pair from ϕ decay recorded by the FINUDA vertex detector and the eight targets employed can be seen.

scattering). Eight targets surround the ISIM modules, as shown in Fig. 1. Five different target materials were used during the first data taking: two targets of ^{6}Li, one of ^{7}Li, three of ^{12}C, one of ^{27}Al and one of ^{51}V. Charged particle tracks coming from the targets are measured by an Outer array of ten double-sided silicon micro-strip detector modules (OSIM), two arrays of eight planar low-mass drift chambers (LMDC), immersed in a He atmosphere to reduce Coulomb multiple scattering, and a straw tube detector assembly (STRAW), composed by six layers of longitudinal and stereo tubes. The crossing point of the incident particles can be extrapolated using the information of the fired tubes, with a spatial resolution $\sigma_z \sim 500$ μm and $\sigma_{\rho\phi} \sim 150$ μm.

The external time of flight detector barrel (TOFONE) is composed of 72 scintillator slabs, 10 cm thick and 255 cm long, providing fast signals to the trigger and TOF.

Particle identification of the track is allowed by the energy loss $\Delta E/\Delta x$ in OSIM and the TOF. Note that the TOF evaluated between TOFINO and TOFONE include, for tracks emerging from a target and reaching TOFONE, the negligible contribution of 200 ps due to the K^- time of flight from TOFINO to its stopping point in the target, well within TOF timing resolution.

A sample of data, corresponding to an integrated luminosity of about 190 pb^{-1}, has been collected during the first FINUDA data taking.

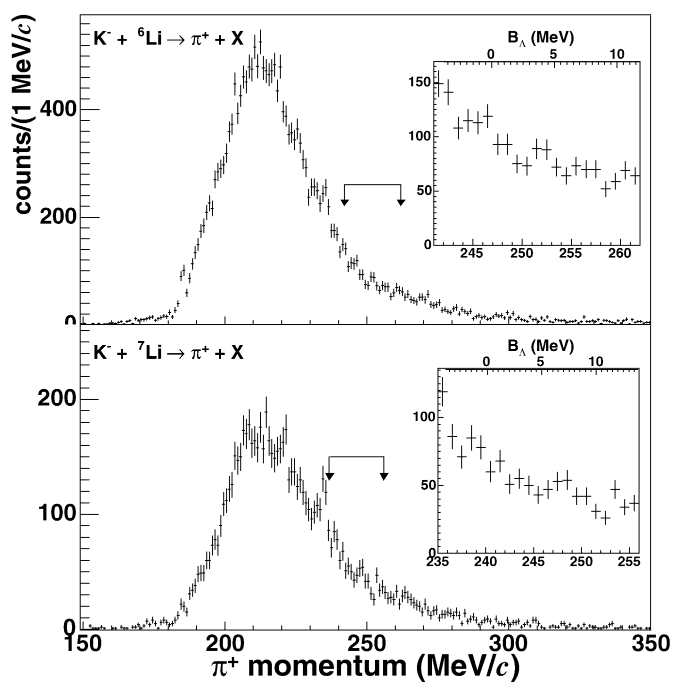

Fig. 2. Inclusive π^+ momentum spectra. Expanded views of the regions between the two arrows are shown in the insets, with the corresponding Λ binding energy values on top.

3. Analysis of π^+ inclusive momentum distributions

The data used for this analysis ($\sim 4 \times 10^6$ K^-_{stop} events) refer to the lighter targets, namely two of ^{6}Li and one of ^{7}Li, where the two elementary processes (1) and (2) lead to the formation of the following hypernuclei:

$$K^-_{\text{stop}} + {}^6\text{Li} \to {}^6_\Lambda\text{H} + \pi^+, \tag{4}$$

$$K^-_{\text{stop}} + {}^7\text{Li} \to {}^7_\Lambda\text{H} + \pi^+. \tag{5}$$

The emitted π^+ momenta are related to the Λ binding energies B_Λ of the predicted hypernuclear ground state of ${}^6_\Lambda$H ($B_\Lambda =$ 4.1 MeV [7]) and of ${}^7_\Lambda$H ($B_\Lambda = 5.2$ MeV [1]) through momentum and energy conservation, and are evaluated as ~ 252 and ~ 246 MeV$/c$, respectively. The candidate events were selected by requiring a successfully reconstructed positive track associated with a K^- stopped in the selected target. The positive particle associated with this track is identified as a π^+ by means of its $\Delta E/\Delta x$ and of its TOF ("*soft*" cuts). The momentum spectra of the selected π^+ are shown in Fig. 2. The spectra are not corrected for acceptance. This influences their shape mainly in the momentum region 180–220 MeV/c, due to the kinematic cut of the spectrometer. In the same figure a residual 236 MeV/c peak, due to $K_{\mu 2}$ decay contamination, coming from a few K^+/K^- misidentified events and not completely removed by TOF selection, can be seen. No significant structures are observed in the B_Λ region ($0 < B_\Lambda < 10$ MeV) as can be seen in the inset of Fig. 2.

The bulk of the spectrum is due to π^+ coming from Σ^+ decay, produced in the following two quasi-free reactions [16]:

$$K^- + p \to \Sigma^+ + \pi^- \quad \hookrightarrow n + \pi^+ \quad (\sim 130 < p_{\pi^+} < \sim 250\ \text{MeV}/c), \tag{6}$$

$$K^- + pp \to \Sigma^+ + n \quad \hookrightarrow n + \pi^+ \quad (\sim 100 < p_{\pi^+} < \sim 320\ \text{MeV}/c). \tag{7}$$

In particular, the π^+ counts in the momentum region of interest are mostly due to reaction (7), to some $K_{\mu 2}$ in-flight decay contamination and a small contribution from the high momentum tail of reaction (6).

In order to reduce the contribution of the above events to the π^+ counts in the momentum region of interest, further event selections can be applied, taking advantage of the tracking capabilities of the FINUDA spectrometer. To this purpose, we focused on the distance between the K^- absorption point and the π^+ origin point, estimated by the reconstruction algorithm as the point of closest approach between the two extrapolated tracks beyond ISIM and back from OSIM respectively, towards a plane in the target volume. A cut on the value of this distance can reduce the contribution from in-flight Σ^+ decay of reactions (6) and (7) and from in-flight contamination; in fact, the π^+ or μ^+ coming from these decays can be reconstructed some millimeters apart from the K^- stopping point (whereas, the π^+ following the hypernuclear formation is produced at the same point in which the K^- is absorbed at rest). Using two distinct simulations, one for the background and one for the signal, a 2 mm cut (in the following referred to as "*hard*" cut) in such a distance selects almost 50% of pions coming from the hypernuclear formation and 10% of background. Therefore, this selection improves the signal-to-noise ratio by a factor ~ 5. Applying this cut, any contributions in the high momentum tail due to in-flight decays, is greatly reduced (see Fig. 3, to be compared with Fig. 2). The $K_{\mu 2}$ contamination at 236 MeV/c produced in the misidentified vertex is not affected by the "*hard*" cut, as expected. From the inset of Fig. 3 for ^{6}Li, there is an indication for a peak at ~ 254 MeV/c, corresponding to a B_Λ of ~ 5.6 MeV. We studied the statistical significance for such a signal with three different hypothesis on the background, due to the reactions (6) and (7), that has been parametrized as in [13] but we found that the C.L. is $< 90\%$. Therefore an upper limit at 90% C.L. for the experimental production rate of the neutron rich Λ-hypernuclei $^6_\Lambda$H and $^7_\Lambda$H is evaluated.

To this purpose the maximum number of π^+ counts to be ascribed to neutron rich Λ-hypernuclei formation has to be estimated. Therefore a region of interest (ROI) is defined in each

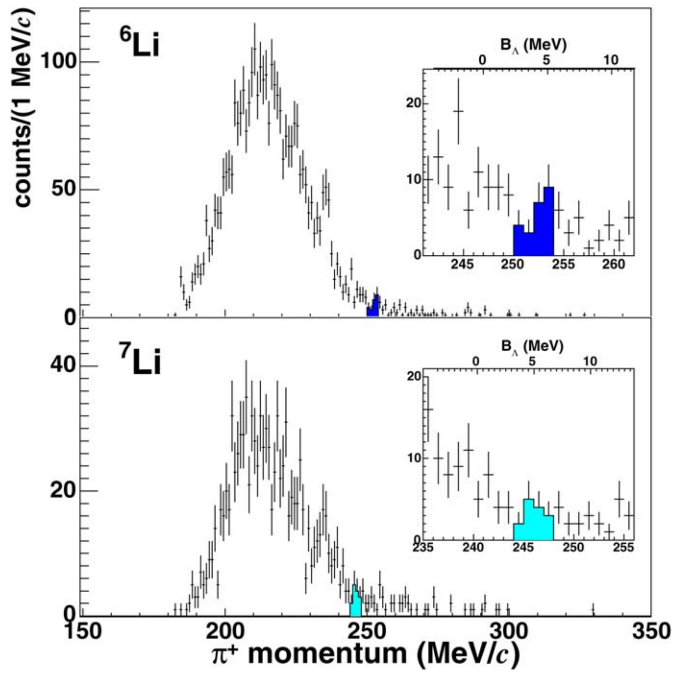

Fig. 3. Inclusive π^+ momentum spectra after the background reduction carried out as described in the text. ROIs are highlighted and enlarged views of the same spectra around the ROIs, with the Λ binding energy axis, are shown in the insets.

spectrum, centered at the π^+ momentum value corresponding to the predicted B_Λ. The ROI widths have been set to $\pm 2\sigma_p$, where σ_p is the standard deviation of the peak momentum resolution (0.9% FWHM). This value is estimated using the monochromatic μ^+ peak at 236 MeV/c using the track selection conditions of the present analysis. We do not require high quality tracks, in order to have as much statistics as possible to study such rare events.

4. Production rates and upper limit evaluation

The π^+ production rate R per stopped K^- is given by the ratio of the number of the π^+ produced by any concurrent reaction following the K^- stopping in the target and the number of the stopped K^- ($N(K^-_{\text{stop}})$) considered in the analysis. The number of produced π^+ is given by the number (N_{π^+}) of measured π^+ weighted by the intrinsic detector efficiency $\varepsilon_D\ (\pi^+)$ and the global efficiency $\varepsilon_G\ (\pi^+)$ in the ROI. Hence:

$$R = \frac{N_{\pi^+}}{N(K^-_{\text{stop}}) \cdot \varepsilon_D(\pi^+) \cdot \varepsilon_G(\pi^+)}, \tag{8}$$

where $\varepsilon_G\ (\pi^+)$ takes into account the trigger efficiency, the apparatus geometrical acceptance and the efficiency of the reconstruction algorithm.

Instead of measuring directly these efficiencies we exploit the FINUDA unique feature of being able to detect back-to-back (K^-, K^+) pairs, to relate them to the μ^+ particles as follows. The number of measured μ^+ (N_{μ^+}) coming from $K_{\mu 2}$ decay and emerging from the same target (i.e. a different sample of data) can be entered in the following Branching Ratio

Table 1
Upper limits (U.L.) at a 90% C.L. of neutron rich Λ-hypernuclei production rate per stopped K^- for the (K^-_{stop}, π^+) reaction on the two light target nuclei considered in the analysis. The last two columns represent the variations in the U.L. values obtained shifting the center of the ROI at ± 1 MeV/c, respectively

Target	Λ-Hyp	U.L. (90% C.L.)	Δ (U.L.) @ + 1 MeV/c	Δ (U.L.) @ − 1 MeV/c
^{6}Li	$^6_\Lambda$H	$(2.5 \pm 0.4_{stat}\,{}^{+0.4}_{-0.1}{}_{syst}) \times 10^{-5}$	-0.4×10^{-5}	$+0.0 \times 10^{-5}$
^{7}Li	$^7_\Lambda$H	$(4.5 \pm 0.9_{stat}\,{}^{+0.4}_{-0.1}{}_{syst}) \times 10^{-5}$	-0.5×10^{-5}	$+0.1 \times 10^{-5}$

definition:

$$\mathrm{BR}(K_{\mu 2}) = \frac{N_{\mu^+}}{N(K^+_{stop}) \cdot \varepsilon_D(\mu^+) \cdot \varepsilon_G(\mu^+)}, \tag{9}$$

where $N(K^+_{stop})$ is the number of K^+ stopped in the same target, ε_D (μ^+) the intrinsic detector efficiency and ε_G (μ^+) the global μ^+ efficiency. The rate R is then estimated in terms of the known branching ratio of the $K_{\mu 2}$ decay process ($\mathrm{BR}(K_{\mu 2}) = 0.6343$) using the following formula (folding (8) and (9)):

$$R = \frac{N_{\pi^+}}{N_{\mu^+}} \cdot \frac{N(K^+_{stop})}{N(K^-_{stop})} \cdot \frac{\varepsilon_D(\mu^+)}{\varepsilon_D(\pi^+)} \cdot \frac{\varepsilon_G(\mu^+)}{\varepsilon_G(\pi^+)} \cdot \mathrm{BR}(K_{\mu 2}). \tag{10}$$

It is reasonable to assume that μ^+ and π^+ from each target cross the same section of the FINUDA apparatus and then the terms ε_D (π^+) and ε_D (μ^+) cancel out, whereas the ε_G factors for the two different particles can be estimated by means of the FINUDA Monte Carlo simulation program [15].

In order to evaluate the upper limit (U.L.) from the π^+ counting rate, this has to be scaled down by a statistical factor which estimates the maximum fraction of the π^+ counts that may be ascribed to neutron rich Λ-hypernuclei formation, within the considered confidence level (C.L.). We consider the total number of counts in the ROI as the sum of the signal counts S and of the background counts B ($N_{\pi^+} = S + B$). The statistical factor is defined as S/N_{π^+}. In addition, since the sample of N_{π^+} as well as S and B obey Poisson statistics, the minimum value of B compatible with the fluctuations, within the fixed C.L., can be evaluated numerically from the following integral equations:

$$\begin{cases} \int_{N_{C.L.}}^{\infty} \frac{\mu^{N_{\pi^+}}}{N_{\pi^+}!} e^{-\mu}\, d\mu = \mathrm{C.L.}, \\ \int_0^{B_{C.L.}} \frac{\mu^B}{B!} e^{-\mu}\, d\mu = \mathrm{C.L.} \end{cases} \tag{11}$$

The minimum B value satisfying the condition $B_{C.L.} \geqslant N_{C.L.}$ is computed with an iterative procedure. Table 1 shows the U.L. values of production rate per stopped kaon at a 90% C.L. for $^6\mathrm{Li}(K^-_{stop}, \pi^+)\,^6_\Lambda\mathrm{H}$ and $^7\mathrm{Li}(K^-_{stop}, \pi^+)\,^7_\Lambda\mathrm{H}$ reactions. The U.L. values corresponding to the ROIs shifted at ± 1 MeV/c do not show great variations with respect to previous ones (last columns in Table 1).

It is worth mentioning that the same procedures, described in this Letter, have been applied to the three ^{12}C targets. There is no evidence of $^{12}_\Lambda$Be production and the upper production rate limit is $(2.0 \pm 0.4_{stat}\,{}^{+0.3}_{-0.1}{}_{syst}) \times 10^{-5}/K^-_{stop}$ which improves the value published by Kubota et al. [10] that is $6.1 \times 10^{-5}/K^-_{stop}$. The U.L. values evaluated for the ROI center shifted at ± 1 MeV/c do not show any significant variations with respect to the previous one.

5. Conclusions

In order to investigate the production of neutron rich Λ-hypernuclei, events with a π^+ in the final state have been selected and analyzed after the first FINUDA data taking. In the analysis presented here, we have applied either only "*soft*" cuts on the π^+ momentum, with the aim of identifying good π^+ while retaining as many events as possible, or the same plus an additional "*hard*" cut, designed to improve the signal-to-noise ratio within the chosen ROIs. None of the approaches showed any significant structure at minimum 90% C.L. either in the ROIs or in the whole Λ bound region. Upper limits for the production rate of $^6_\Lambda$H and $^7_\Lambda$H at 90% C.L., in (K^-_{stop}, π^+) reactions, are $(2.5 \pm 0.4_{stat}\,{}^{+0.4}_{-0.1}{}_{syst}) \times 10^{-5}/K^-_{stop}$ and $(4.5 \pm 0.9_{stat}\,{}^{+0.4}_{-0.1}{}_{syst}) \times 10^{-5}/K^-_{stop}$ respectively.

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