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Examining Σ-bound states with FINUDA.

FINUDA collaboration*

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ABSTRACT

A Σ-bound state forms when a Σ-hyperon substitutes a nucleon into a nucleus, the newly formed nucleus acquires a unit of strangeness. In the case of Σ-hypernuclei only one bound state has been detected, $^{4}_{\Sigma}He$ [1) 2)], and there is no a clear evidence of any other bound state with atomic number higher than four. Data analysis of a Σ-hypernuclear system is rather complex, and a comprehensive picture of the interaction has not been established yet. In the present paper, the results of a search of Σ-hypernuclei with FINUDA are discussed. Σ-hypernuclei are expected to form via the $K^- + {}^AZ \rightarrow {}^{A}_{\Sigma^{\pm,0}}Z + \pi^{\pm}$ reactions, where ^AZ is a segmented target consisting of 5 different elements, ^{6}Li, ^{7}Li, ^{12}C, ^{27}Al, ^{51}V, and kaons are absorbed at rest. In order to suppress the overwhelming $\pi^{\pm}$ background due to quasi-free reactions, a tagging method is discussed, which is based on the tracking capabilities of FINUDA.

1 Introduction

FINUDA has recently concluded the first run of data taking by recording an integrated luminosity of about $\mathcal{L}$= 220 pb^{-1} [3)]. The spectrometer [4)] was designed for systematic studies of Λ-hypernuclei production and decay, with high momentum resolution and large detection acceptance. In the case of FINUDA, the hypernuclei are formed by stopping K^- mesons in a variety of targets: ^6Li, ^7Li, ^{12}C, ^{27}Al, ^{51}V. Negative kaons are produced by ϕ decays, which in turn are originated by e^+e^- collisions at DAΦNE, Laboratori Nazionali di Frascati. For the Λ-hypernucleus studies, the magnetic field of the spectrometer was set at 1.0 T. With such a high field only a fraction of the Σ-hypernuclei produced could be examined; however, the collected statistics and the tracking capabilities of FINUDA makes the search for Σ-hypernucleus bound states possible.

2 Σ-hypernuclei in FINUDA

At the FINUDA interacting region, the center-of-mass e^+e^- collisions produce $\phi(1020)$ mesons, which decay into pairs of charged kaons K^+ K^- at a rate of 49.1%. Negative kaons are brought at rest in a segmented target, which consists of $2 \times^6 Li$ + $1 \times^7 Li$ + $3 \times^{12} C$ + $1 \times^{27} Al$ + $1 \times^{51} V$ thin plates (200÷300 mg/cm^2). Negative kaons are initially caught by external atomic

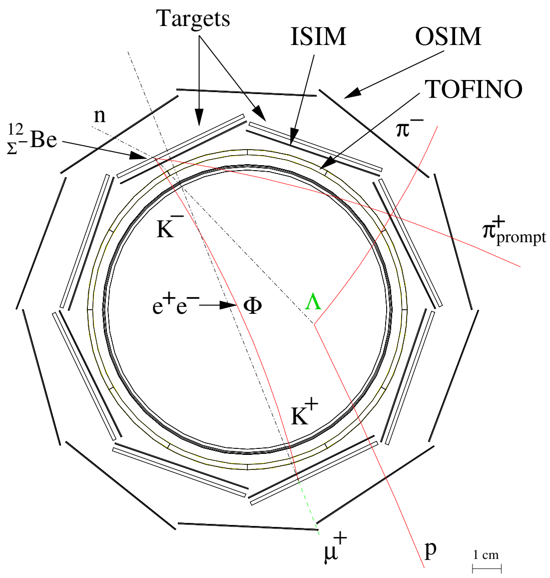

Figure 1: *Enlarged front view of the FINUDA vertex region with a simulated Σ^--hypernuclear event at $B = 1.0$ T. The figure shows the prompt pion trajectory (π^+_{prompt}) from the $K^-_{stop} + ^{12}C \rightarrow ^{12}_{\Sigma^-} Be + \pi^+_{prompt}$ reaction. Two vertices corresponding to the Σ-hypernucleus formation ($^{12}_{\Sigma^-}Be$) and $\Lambda \rightarrow \pi^- p$ decay (Λ) are also shown.*

orbitals and finally absorbed at rest (K^-_{stop}) by a a nucleus (^AZ) such as to form a hyperon. The hypernucleus formation is promptly followed by the emission of a pion ($\pi^\pm_{prompt}$). A Σ bound state formation ($^A_\Sigma Z$) is originated by the reaction:

$$K^-_{stop} + \ ^AZ \rightarrow \ ^A_{\Sigma^{\pm,0}}Z + \ \pi^\pm_{prompt} \tag{1}$$

The Σ hyperon successively converts into a Λ hyperon through the *conversion reaction*:

$$\Sigma + N \rightarrow \Lambda + N \tag{2}$$

where N indicates a nucleon of $^A_\Sigma Z$. The Λ-hyperon acquires energy due to the Σ - Λ mass difference. This allows the Λ to move out from the nucleus and then to decay into the free space. A simulated Σ-hypernuclear event in FINUDA is displayed in Fig. 1. Two vertices can be distinguished: the first describes the topology of the $^{12}_{\Sigma^-}Be$ production and decay, while the second shows the $\Lambda \rightarrow \pi^- p$ decay following the $\Sigma \rightarrow \Lambda$ conversion reaction. The two vertices can be clearly separated from one to an another since the vertex detector (see Sect.3) is capable of high intrinsic spatial resolution ($\Delta r \sim 30\,\mu$m).

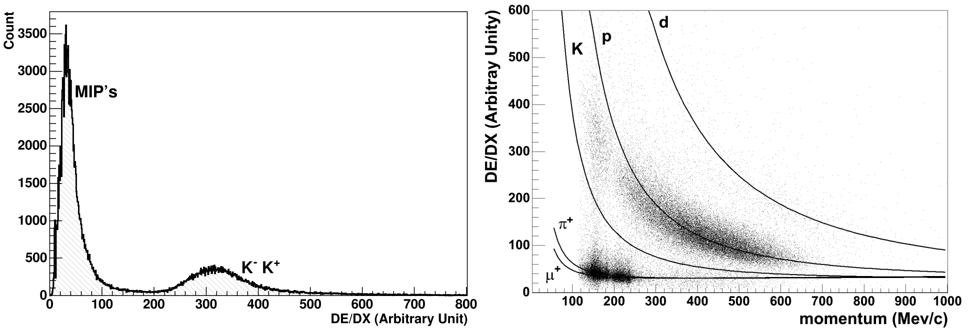

Figure 2: *Left panel: kaons are identified in FINUDA by the energy deposited in ISIM. Right panel: pions are discriminated from protons and from deuterons via the observed $\Delta E/\Delta x$ signal in OSIM versus the particle momentum, which is determined by the spectrometer.*

The topology of the Σ-hypernucleus production and decay indicates a possible strategy for tagging Σ events. This is based on the detection of π^+_{prompt}'s in coincidence with (π^-, p) pairs. In order to make sure that a coincidence (π^-, p) event originates from a Λ decay, the invariant mass of each event is reconstructed in combination with the $\Delta r > 30\,\mu$m requirement.

3 FINUDA Silicon Vertex Detector

It is crucial for the Σ-hypernuclear search to discriminate positive pions from protons and from deuterons deriving from the K^--^AZ interaction. In the case of FINUDA, this is performed by the vertex detector, which was designed to mass-discriminate pions from protons (and from deuterons). The inner array of the FINUDA vertex detector consists of 8 double-sided silicon microstrip detectors (ISIM), whose geometry resembles that of an octagonal prism, see Fig. 1. The ISIM modules measure the particle trajectories with a resolution better than 30 μm, which allows the stopping position of a K^- to be determined with a precision better than 600 μm. All the modules have an analogue readout with a dynamic range of 20 MIP's; so that, particles crossing them can be identified according to their $\Delta E/\Delta x$ [5]. Kaons are identified by the energy deposited in ISIM (Fig. 2, left panel). The targets face the ISIM modules at an average distance of 2 mm. An outer layer of 10 silicon modules (OSIM) surrounds the octagonal target ladder, and is the first element of the FINUDA tracking system. In the case of OSIM, charged particles ($\pi^{\pm}$, p and d) are mass-identified by combining the observed energy loss in the modules with

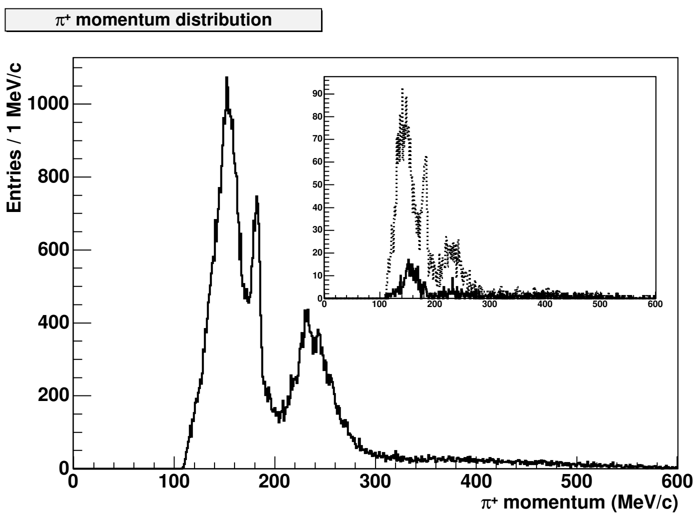

Figure 3: *Momentum distributions of π^+_{prompt}'s for the ^{12}C targets. The inset diagrams show the π^+_{prompt} distributions in coincidence with negative pions (dotted diagram) and protons (solid diagram) from reaction (3).*

their momentum, the latter being measured by the tracking system of FINUDA (Fig. 2, right panel).

4 Results

The present analysis relies on the reactions of Σ-hypernuclear formation and decay:

$$
\begin{aligned}
K^-_{stop} + ^{12}C \quad &\rightarrow \quad ^{12}_{\Sigma^-}Be + \pi^+_{prompt} \\
&\quad ^{12}_{\Sigma^-}Be \rightarrow ^{10}Be + \Lambda + n \\
&\qquad\qquad\qquad \Lambda \rightarrow \pi^- + p
\end{aligned}
\tag{3}
$$

The Σ-hypernuclear spectroscopy is based on the measurement of the π^+_{prompt} momentum distribution. Furthermore, FINUDA is designed to reconstruct the full Σ-hypernuclear event; therefore, it is possible to select exclusive events, which only involve particles of reaction (3). The inclusive momentum distribution of positive prompt pions is shown in Fig. 3 for ^{12}C (solid line). The diagrams in the inset depict the π^+_{prompt} momentum distribution in coincidence with a negative pion (dotted diagram) and a proton from reaction (3). This simple requirement drastically reduces the inclusive π^+_{prompt} yield, which is pri-

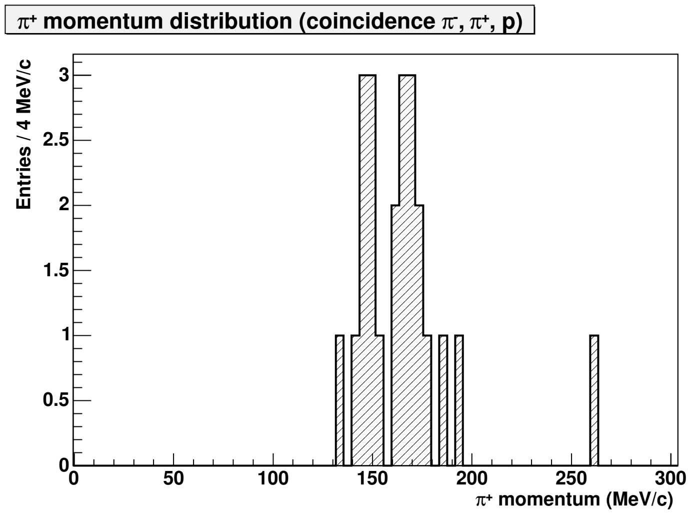

Figure 4: *The exclusive* π^+_{prompt} *momentum for* ^{12}C*. Positive pions are detected in coincidence with* (π^-*, p) pairs from reaction (3).*

mary to select Σ events out from the overwhelming quasi-free background. The momentum distribution of π^+_{prompt}'s detected in coincidence with (π^-, p) pairs is shown in Fig. 4. The two bumps appearing in the 150-200 MeV/c region have a width of about 6 Mev/c, which is mainly due to $\Sigma \rightarrow \Lambda$ conversion reaction. The existence of these bumps was earlier predicted by a work of [6], which yielded a Σ^- binding energy (width) of about 15 MeV (7 MeV) and 2 MeV (4 MeV) for the 1s and 1p orbitals, respectively.

In order to check whether the two peaks are due to Σ-bound states, one can examine the topology of events populating the two peaks. This approach exploits the tracking capabilities of FINUDA. A riconstructed event is displayed in Fig. 5. The reaction vertex of a hypernuclear formation (i.e., $K^-_{stop} \rightarrow \pi^+_{prompt}$) clearly happens into the ^{12}C target. The secondary vertex accounting for the decay $\Lambda \rightarrow \pi^- p$ (i.e., $\Sigma N \rightarrow \Lambda N$ followed by the Λ decay) is present at about 1 cm from the primary vertex. This is a unique signature of a Σ-hypernuclear event (i.e., reaction (3)).

The dynamics of Σ-hypernuclear formation and decay is far from being understood. Some authors [6], predict that Σ-nucleus potential to be actrative, others [7] give a repulsive behavior for it, thus inhibiting the formation of Σ-hypernuclei. Although the FINUDA data analysis must be improved, the

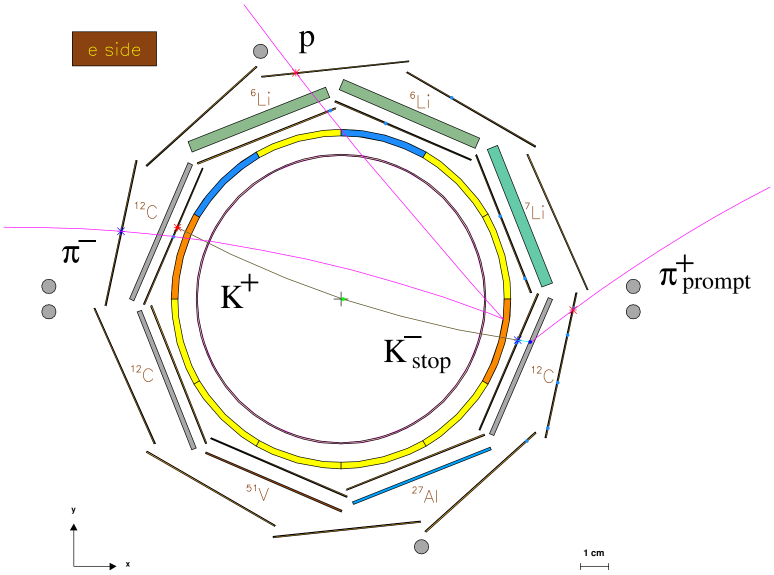

Figure 5: *Front view of a candidate Σ-hypernuclear event: two vertices are clearly visible, the former represents the hypernuclear formation in ^{12}C, $K^-_{stop} \rightarrow \pi^+_{prompt}$ (176 MeV/c), the latter describes the Λ decay to π^- p. The invariant mass of (π^-, p) system is 1116 MeV/c^2.*

present results show that FINUDA is entitled to solve the controversial existence of bound Σ-hypernuclei.

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