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Constraints on the threshold K^- nuclear potential from FINUDA $^{A}\mathrm{Z}(K^-_{\mathrm{stop}}, \pi^-)^{A}_{\Lambda}\mathrm{Z}$ spectra

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ABSTRACT

$1s_\Lambda$ hypernuclear formation rates in stopped K^- reactions on several p-shell targets are derived from hypernuclear formation spectra measured recently by the FINUDA Collaboration and are compared with calculated $1s_\Lambda$ formation rates based on a chirally motivated coupled channel model. The calculated rates are about 15% of the derived rates, and in contrast with previous calculations depend weakly on the depth of the threshold K^- nuclear potential. The A dependence of the calculated $1s_\Lambda$ rates is in fair agreement with that of the derived $1s_\Lambda$ rates, showing a slight preference for a deep density dependent potential, $\mathrm{Re}\,V_{K^-}(\rho_0) \sim -(150\text{–}200)$ MeV, over a shallow potential, $\mathrm{Re}\,V_{K^-}(\rho_0) \sim -50$ MeV. These new features originate from a substantial energy and density dependence found for the in-medium subthreshold $K^- n \to \pi^- \Lambda$ branching ratio that enters the hypernuclear formation rate calculations.

1. Introduction

How strong is the K^- nuclear interaction? Various scenarios proposed for kaon condensation in dense neutron-star matter [1], and more recently for quasibound K^- nuclear clusters [2] and for self-bound strange hadronic matter [3] depend on the answer to this question which has not been resolved todate. A modern theoretical framework for the underlying low-energy $\bar{K}N$ interaction is provided by the leading-order Tomozawa–Weinberg vector term of the chiral effective Lagrangian which, in Born approximation, yields a moderately attractive K^- nuclear potential V_{K^-}:

$$V_{K^-} = -\frac{3}{8f_\pi^2}\rho \sim -57\frac{\rho}{\rho_0} \quad \text{(in MeV)} \tag{1}$$

where ρ is the nuclear density, $\rho_0 = 0.17\ \mathrm{fm}^{-3}$, and $f_\pi \sim 93$ MeV is the pion decay constant. This attraction is doubled, roughly, within chirally based coupled-channel $\bar{K}N$–$\pi\Sigma$–$\pi\Lambda$ calculations which provide also for a strong absorptivity [4]. Shallower potentials, $\mathrm{Re}\,V_{K^-}(\rho_0) \sim -(40\text{–}60)$ MeV at threshold, are obtained by requiring that the in-medium K^-N $t(\rho)$ matrix is derived self-consistently with the potential $V_{K^-} = t(\rho)\rho$ it generates [5,6]. In contrast, comprehensive global fits to K^--atom strong-interaction shifts and widths yield very deep density dependent K^- nuclear potentials at threshold, in the range $\mathrm{Re}\,V_{K^-}(\rho_0) \sim -(150\text{–}200)$ MeV [7]. In this Letter we discuss recent FINUDA measurements that might bear on this issue by providing constraints on how deep $\mathrm{Re}\,V_{K^-}$ is at threshold.

In the preceding Letter [8], the FINUDA Collaboration at DAΦNE, Frascati, reported on Λ-hypernuclear excitation spectra taken in the $K^-_{\mathrm{stop}} + {}^{A}\mathrm{Z} \to \pi^- + {}^{A}_{\Lambda}\mathrm{Z}$ reaction on several p-shell nuclear targets. Formation rates were given per stopped K^- for bound states and for low lying continuum states. In ${}^{16}_{\Lambda}\mathrm{O}$ the bound state formation rates agree nicely with a previous KEK measurement [9]. The recent FINUDA data allow for the first time to consider the A dependence of the formation rates in detail within the nuclear p shell where nuclear structure effects may be reliably separated out. It is our purpose in this companion Letter to apply one's knowledge of the nuclear structure aspect of the problem in order to extract the dynamical contents of the measured formation rates, particularly that part which concerns the K^- nuclear dynamics at threshold. In doing so we transform the partial formation rates reported for well defined and spectroscopically sound final Λ hypernuclear states into $1s_\Lambda$ hypernuclear formation rates that allow direct comparison with DWIA calculations.

The expression for the formation rate of hypernuclear final state f in capture at rest on target g.s. i, apart from kinematical factors, is a product of two dynamical factors [6,10–12]: (i) the branching ratio for $K^- n \to \pi^- \Lambda$ in K^- absorption at rest in the nuclear medium, here denoted BR; and (ii) the absolute value squared of a DWIA amplitude given by

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Table 1

$1s_\Lambda$ formation rates $R(1s_\Lambda)$ per stopped K^-, derived from the strongest hypernuclear bound state peak for each of the listed targets [procedure (a)]. Data are taken from the preceding Letter [8], and for ${}^{12}_{\Lambda}$C from [14]. The errors are statistical and systematic, in this order. The $1s_\Lambda$ structure fractions are from [15] and, if unlisted there, from [13]. Listed in the last column, for comparison, are $1s_\Lambda$ forward-angle integrated (π^+, K^+) cross sections, also derived by using procedure (a) from KEK-E336 measurements [16].

Target ^{A}Z	Peak J^π_{core}	E^*_{core} (MeV)	$1s_\Lambda$ frac.	$R(1s_\Lambda) \times 10^3$ per stopped K^-	$\sigma_{1s_\Lambda}(\mu b)$ (π^+, K^+)
^{7}Li	3^+	2.19	0.311	$1.48 \pm 0.16 \pm 0.19$	1.56 ± 0.10
^{9}Be	2^+	2.94	0.242	$0.87 \pm 0.08 \pm 0.12$	1.40 ± 0.05
^{12}C	$(3/2)^-$	g.s.	0.810	$1.25 \pm 0.14 \pm 0.12$	1.78 ± 0.04
^{13}C	2^+	4.44	0.224	$0.85 \pm 0.09 \pm 0.13$	1.87 ± 0.09
^{16}O	$(3/2)^-$	6.18	0.618	$0.42 \pm 0.06 \pm 0.06$	1.47 ± 0.05

Table 2

Same as in Table 1 except for using several (rather than one) well defined $1s_\Lambda$ bound states for each of the listed targets [procedure (b)].

Target ^{A}Z	Peaks	$1s_\Lambda$ frac.	$R(1s_\Lambda) \times 10^3$ per stopped K^-	$\sigma_{1s_\Lambda}(\mu b)$ (π^+, K^+)
^{7}Li	1, 2, 3	0.833	$1.25 \pm 0.14 \pm 0.17$	1.29 ± 0.12
^{9}Be	1, 2	0.435	$0.85 \pm 0.09 \pm 0.11$	1.20 ± 0.05
^{12}C	1, 2, 3	0.995	$1.67 \pm 0.23 \pm 0.23$	1.92 ± 0.07
^{13}C	1, 2	0.347	$0.84 \pm 0.12 \pm 0.12$	1.93 ± 0.12
^{16}O	1, 2	1.000	$0.36 \pm 0.06 \pm 0.05$	1.32 ± 0.05

$$T^{\text{DWIA}}_{fi}(\mathbf{q}_f) = \int \chi^{(-)*}_{\mathbf{q}_f}(\mathbf{r}) \rho_{fi}(\mathbf{r}) \Psi_{nLM}(\mathbf{r})\, d^3 r, \tag{2}$$

divided for a proper normalization by the integral $\bar{\rho}$ of the K^- atomic density overlap with the nuclear density $\rho(r)$

$$\bar{\rho} = \int \rho(r) \left|\Psi_{nLM}(\mathbf{r})\right|^2 d^3 r. \tag{3}$$

Here ρ_{fi} stands for the nuclear to hypernuclear transition form factor, $\chi^{(-)}_{\mathbf{q}_f}$ is an outgoing pion distorted wave generated by a pion optical potential fitted to scattering data, and Ψ_{nLM} is a K^- atomic wavefunction obtained by solving the Klein–Gordon equation with a K^- nuclear strong interaction potential V_{K^-} added to the appropriate Coulomb potential. The integration on the r.h.s. of Eq. (2) is confined by the bound-state form factor ρ_{fi} to within the nucleus, where Ψ_{nLM} is primarily determined by the strong-interaction V_{K^-}, although Ψ_{nLM} is an atomic wavefunction that peaks far outside the nucleus. The sensitivity of the DWIA amplitude Eq. (2) to V_{K^-} arises from the interference of Ψ_{nLM} with the pion oscillatory distorted wave $\chi^{(-)}_{\mathbf{q}_f}$. In particular, once V_{K^-} is sufficiently deep to provide a strong-interaction bound state for a given L, the atomic Ψ_{nLM} also becomes oscillatory within the nucleus which magnifies the effects of interference, as verified in past DWIA calculations [6,12].

In this Letter we point out another strong sensitivity to the initial-state K^- nuclear dynamics arising from the energy and density dependence of the $K^- n \to \pi^- \Lambda$ BR. We show how to incorporate this energy and density dependence into the calculation of a properly averaged value $\overline{\text{BR}}$ which depends on the K^- atomic orbit through L and on the mass number A of the target. The resulting calculated $1s_\Lambda$ formation rates are then compared to those derived from the FINUDA data and conclusions are made on the deep vs. shallow K^- nuclear potential issue.

2. Derivation of $1s_\Lambda$ capture rates from FINUDA data

The FINUDA spectra show distinct peaks for several $1s_\Lambda$ and $1p_\Lambda$ states in the nuclear p shell. In general, the derivation of the $1p_\Lambda$ formation rate is ambiguous given that the $1p_\Lambda$ formation strength is often obscured by a rising Λ continuum. In ${}^9_\Lambda$Be and in ${}^{13}_\Lambda$C it is also mixed with a substantial part of the $1s_\Lambda$ formation strength owing particularly to high lying $T = 1$ parent states in the corresponding core nuclei. For this reason, we here deal only with the $1s_\Lambda$ formation strength, deriving it in each p-shell Λ hypernucleus from unambiguously identified *low lying* $1s_\Lambda$ states. According to Ref. [13], the corresponding hypernuclear formation rates are given by a $1s_\Lambda$ formation rate $R(1s_\Lambda)$, which is independent of the particular hypernuclear excitation considered, times a structure fraction derived from neutron pick-up spectroscopic factors in the target nucleus. This theoretical framework is also applicable to forward cross sections of in-flight reactions such as (π^+, K^+) and $(e, e'K^+)$. In Table 1 we present $1s_\Lambda$ formation rates derived from the FINUDA K^- capture at rest hypernuclear spectra [8,14] for a procedure denoted (a). In each spectrum we focus on the strongest low-lying particle-stable hypernuclear excitation which is also well described in terms of a Λ hyperon weakly coupled to a nuclear core parent state. These core parent states are listed in the table. The measured formation rates for the corresponding hypernuclear excitations from Refs. [8,14] are then divided by the structure fractions listed in the table to obtain values of $R(1s_\Lambda)$. For comparison, we display in the last column the $1s_\Lambda$ component of forward-angle integrated (π^+, K^+) cross sections, also derived using the peaks listed in the second and third columns. These (π^+, K^+) strengths show little A dependence, in contrast to the K^- capture at rest $1s_\Lambda$ formation rates that decrease by a factor 3.5 in going from ^{7}Li to ^{16}O.

In the second procedure, denoted (b) and presented in Table 2, we consider all the particle-stable $1s_\Lambda$ states corresponding to observed peaks for which the shell model offers reliable identification. For three of the five targets listed, this procedure saturates or is close to saturating the $1s_\Lambda$ formation strength. However, in both ${}^9_\Lambda$Be and ${}^{13}_\Lambda$C the $1s_\Lambda$ particle stable hypernuclear states represent less than half of the full $1s_\Lambda$ strength. In the last column of Table 2 we assembled $1s_\Lambda$ forward-angle integrated (π^+, K^+) cross sections, derived this time by applying procedure (b). Similarly to Table 1, the weak A dependence of these $1s_\Lambda$ (π^+, K^+) cross sections is in stark contrast to the fast decrease of the $1s_\Lambda$ formation rates, again by a factor 3.5, going from ^{7}Li to ^{16}O in K^- capture at rest. The strong A dependence of the $(K^-_{\text{stop}}, \pi^-)$ rates with respect to the weak A dependence of the (π^+, K^+) cross sections reflects the sizable difference between the strongly attractive K^- nuclear interaction at threshold and the weakly repulsive K^+ nuclear interaction.

It is encouraging to see that both sets of $R(1s_\Lambda)$ values in Tables 1 and 2 are consistent within statistical uncertainties with each other, except marginally for ^{12}C which dates back to a sep-