Exclusive Measurement of the $^{12}C(K^-, p)$ Reaction for Probing the K^--Nucleus Interaction at J-PARC

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Abstract. The antikaon-nucleus optical potential remains uncertain because kaonic atoms mainly constrain the nuclear surface, while inclusive in-flight reactions have limited sensitivity to absorption. We summarize the first coincident measurement of the inclusive $^{12}C(K^-, p)$ and exclusive $^{12}C(K^-, pK^-_{esc})$ reactions in J-PARC E42, recently reported in Physical Review Letters. The measured escape fraction is $29 \pm 2\,(\text{stat.})^{+0}_{-4}\,(\text{syst.})\%$. A simultaneous Green's-function fit gives $V_0 = -72$ MeV and $W_0 = -100$ MeV at the nuclear center, with the quoted statistical and systematic uncertainties. The absorptive strength exceeds one-nucleon impulse-approximation expectations, but does not by itself identify the underlying reaction mechanism. We place the result alongside earlier optical-potential constraints and outline ongoing studies of non-escape final states and possible few-body escape-kaon measurements.

1 Motivation and previous constraints

The antikaon ($\bar{K}$) interaction with nuclear matter is relevant to the formation and decay of kaonic nuclei. Its real part controls attraction, while its imaginary part describes loss of the antikaon flux from the elastic channel. A common parametrization is $U_{\text{opt}}(r) = (V_0 + iW_0)\rho(r)/\rho(0)$, where $\rho(r)$ is the nuclear density at radius r and $\rho(0)$ is its central value. The parameters V_0 and W_0 therefore denote the potential strengths at the nuclear center. In the J-PARC E42 fit, these central parameters were then converted to the normal nuclear density $\rho_0 = 0.17\,\text{fm}^{-3}$ for comparison with other analyses. The two conventions must be distinguished when quoting potential depths.

Kaonic-atom X-ray shifts and widths have established a strongly attractive and absorptive interaction, but do not uniquely determine the real-potential depth. In the $t\rho$ approximation the optical potential is built as $U \approx t\rho$ from the elementary $\bar{K}N$ amplitude t. Chiral coupled-channel calculations in this approximation favor a shallow real part, $V_0 \sim -80$ to -50 MeV, and an imaginary part from one-nucleon absorption, $W_0 \sim -40$ to -20 MeV [4,5]. Phenomenological, density-dependent fits can instead accommodate a deeper real part, $V_0 \sim -200$ to -150 MeV, and strong absorption, $W_0 \sim -100$ to -60 MeV, while reproducing the atomic data [2,3]. This ambiguity is linked to the surface-weighted atomic wave functions and to correlations between the real and imaginary terms. Recent high-precision kaonic-helium data have improved the input, yet a global analysis still finds distinct shallow and deep solutions, with representative values at ρ_0 of $(-V_0, -W_0) = (90, 120)$ and $(280, 70)$

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MeV [6]. That analysis favors the shallow solution in χ^2, but the atomic data alone do not remove the deep solution.

In-flight (K^-, N) reactions provide complementary information from a broader nuclear-volume region. An earlier KEK-PS E548 analysis reported a deep potential, although its coincidence selection limited direct comparison with inclusive-spectrum calculations [9]. The J-PARC E05 inclusive $^{12}\mathrm{C}(K^-, p)$ measurement constrained the real part but left the imaginary strength comparatively weakly determined [7]. The key difference in the J-PARC E42 measurement is the additional detection of a low-momentum recoil kaon. Its survival probability through the residual nucleus carries information on absorption that is not available from the forward proton spectrum alone. The primary J-PARC E42 measurement and optical-potential result have been published in Ref. [1]; the present proceedings give a concise context and outlook rather than a new independent measurement.

2 Exclusive K^- escape measurement and result

The J-PARC E42 experiment used a 1.8 GeV/c K^- beam on a diamond ^{12}C target. The forward proton from the quasi-free $K^- p \to K^- p$ process defines the missing-mass spectrum. In the exclusive sample, a recoil K^- was also reconstructed in the Superconducting Hyperon Spectrometer (SHS). The escape spectrum is formed from the bin-by-bin ratio of the background-subtracted K^- yield to the inclusive (K^-, p) yield, after acceptance and efficiency corrections [1]. The escape fraction below is a different quantity: the ratio of that escape cross section to the quasi-free elastic cross section. For the earlier inclusive estimate $(V_0, W_0) \sim (-80, -40)$ MeV, the same calculation gives $P_{\mathrm{esc}} \sim 50\%$; the measured 29% is smaller.

For the analyzed quasi-free region, $3.5^\circ < \theta_{Kp} < 4.5^\circ$, the escape fraction and the angle-differential escape cross section integrated over $-0.04 \le -B_K \le 0.2$ GeV are

$$P_{\mathrm{esc}} = 29 \pm 2\,(\mathrm{stat.})^{+0}_{-4}\,(\mathrm{syst.})\%,$$
$$(d\sigma/d\Omega)_{\mathrm{esc}} = 436 \pm 6\,(\mathrm{stat.}) \pm 44\,(\mathrm{syst.})\ \mu\mathrm{b/sr}.$$

Here $-B_K = M_{\mathrm{miss}} - (M_{^{11}\mathrm{B}} + M_{K^-})$, with M_{miss} obtained from the incident K^- and the forward proton. Positive $-B_K$ lies above the $K^- + {}^{11}$B threshold. These are experimental observables. The optical-potential parameters come from comparing both spectra with Green's-function calculations [1], which treat the bound and quasi-free regions in one distorted wave. Absorption of the recoil K^- enters through the imaginary potential.

At the nuclear center, the simultaneous fit gives [1]

$$V_0 = -72^{+3}_{-5}\,(\mathrm{stat.})^{+0}_{-8}\,(\mathrm{syst.})\ \mathrm{MeV},$$
$$W_0 = -100^{+7}_{-1}\,(\mathrm{stat.})^{+0}_{-16}\,(\mathrm{syst.})\ \mathrm{MeV}.$$

Converted to ρ_0, the same central values are $(V_0, W_0) = (-67, -93)$ MeV, or $(-V_0, -W_0) = (67, 93)$ MeV on the positive-depth axes of Fig. 1. The corresponding J-PARC E05 values at ρ_0 are about $(-74, -37)$ MeV [1,7]. The real parts are similar, while the imaginary parts differ markedly. The fit constrains the imaginary part much more strongly than the inclusive-only result, because the optical potential changes both the spectral shape and the probability that the recoil kaon emerges from the nucleus.

The exclusive selection requires a reconstructed recoil track in coincidence with the forward proton. The kaon is identified from the energy loss in the Hyperon Time Projection Chamber (HypTPC) and the mass squared measured with the SHS and the Hyperon Time-of-Flight (HTOF) hodoscope. The kaon-identification purity was $S/(S + N) \sim 99\%$ in the

calibration sample. In $0 < -B_K < 0.05$ GeV, the estimated $K^- p \to K^- \pi^0 p$ contribution was below 5% of the selected escape yield. These checks matter because the escape spectrum is substantially smaller than the inclusive spectrum, and a misidentified or unmodeled component could bias its normalization. The efficiency for the diamond-target sample was evaluated with detector simulation and checked against the hydrogen component of a polyethylene target; the resulting uncertainty was included in the reported systematic error [1].

The analysis uses both spectra, rather than interpreting the total escape yield alone. The inclusive spectrum is described by a quasi-free elastic Green's-function component plus simulated inelastic backgrounds, while the exclusive spectrum is compared with the corresponding escape calculation. The joint likelihood uses the common potential parameters and the distinct response of the two observables to attraction and absorption. The inclusive spectrum anchors the formation strength and spectral distribution, while the loss of recoil kaons along their paths through the residual nucleus supplies the additional absorptive sensitivity.

The fitted uncertainties include the statistical precision and the systematic variation of the escape-spectrum normalization. Within this Green's-function framework the escape spectrum directly constrains W_0. Varying the distortion cross section by ±10% shifts V_0 by at most ±7 MeV and leaves W_0 unchanged [1]. The quoted values belong to this framework. They do not show that one energy-independent potential describes every antikaon observable.

3 Comparison and outlook

Figure 1 compares the J-PARC E42 and J-PARC E05 extractions with the shallow and deep solutions of the global kaonic-atom analysis that includes the J-PARC E62 data [6]. The blue and purple regions show representative chiral-unitary $t\rho$ and phenomenological ranges. Kaonic atoms probe the interaction near $B_K \approx 0$, whereas the present fit covers $-0.04 \leq -B_K \leq 0.2$ GeV, so the comparison is qualitative. The volume-sensitive result disfavors the deep-real solutions: the real part is shallow and the absorption is strong. The energy dependence of W_0, and the microscopic decomposition of that absorption, remain open.

The extracted central value $W_0 = -100$ MeV is substantially larger in magnitude than the one-nucleon $t\rho$ expectation, $W_0 \sim -40$ to -20 MeV [4,5]. This suggests additional loss, such as multi-nucleon absorption or K^-"N" $\to \bar{K}N$ rescattering followed by core breakup, which adds to W_0 for $-B_K > 0$. In J-PARC E42, the forward proton selects events consistent with quasi-elastic $K^- p \to K^- p$ scattering. If the recoil K^- from this reaction is subsequently absorbed in the residual nucleus, it cannot appear in the reconstructed escape sample. Recoil-kaon absorption is therefore a physically motivated contributor to the attenuation represented by the large imaginary part. The escape measurement alone does not identify the reaction mechanism: a kaon not reconstructed as escaping may also have undergone inelastic scattering or charge exchange, decayed, or been lost through detector acceptance or reconstruction inefficiency.

The same J-PARC E42 data set includes (K^-, p) events with no reconstructed recoil K^-. After acceptance and efficiency corrections, this non-escape sample still mixes mesonic absorption ($K^- N \to Y\pi$), non-mesonic absorption ($K^- NN \to YN$), charge exchange, inelastic rescattering, in-flight decay, and residual reconstruction loss. An ongoing analysis of the charged particles accompanying the forward proton, and of the missing mass, tests whether the sample is consistent with a substantial multi-nucleon component. Because a π^0, neutron, or $\bar{K}^0$ can escape detection, a missing charged pion does not by itself establish non-mesonic absorption. A yield can be assigned to one mechanism only if that assignment is stable against the acceptance and the reaction model. This is the decomposition left open by the published fit [1].

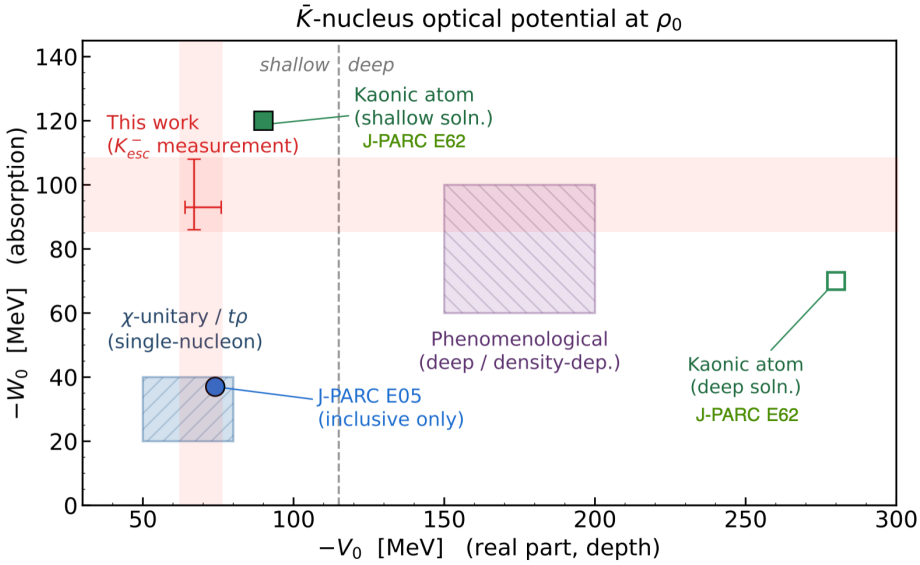


Figure 1. Depths at $\rho_0 = 0.17\,\mathrm{fm}^{-3}$, shown as positive $-V_0$ and $-W_0$. The red point, labeled "This work" on the figure, is the J-PARC E42 result $(67, 93)$ MeV [1]. The red intervals and pale-red bands are guides to the eye: the published asymmetric uncertainties are not propagated to ρ_0. The blue point is J-PARC E05 at $(74, 37)$ MeV [1,7]. The green points are the shallow and deep solutions of the global analysis that includes the J-PARC E62 data, $(90, 120)$ and $(280, 70)$ MeV [6]. The dashed divider is not a measured boundary. Blue and purple boxes are indicative $t\rho$ [4,5] and phenomenological [2,3,8] ranges, not confidence regions.

A measurement of the same escape fraction on few-body targets would show how recoil-K^- loss changes with the number of nucleons. For $A = 3$ and $A = 4$, mesonic absorption, non-mesonic absorption, and charge exchange are easier to separate than in ^{12}C, where one optical potential averages over the nuclear volume, and the A dependence connects that loss to light kaonic nuclei. J-PARC E80 studies $^4\mathrm{He}(K^-, N)$ and J-PARC E89 addresses the $\bar{K}NN$ system with ^{3}He [10,11]; escape-kaon detection is outside those approved measurements. One example, considered by the author and not a decision of the J-PARC E42 Collaboration, is a byproduct escape-kaon measurement at the J-PARC K1.8BR beamline. It is not part of the present main program there, and its feasibility depends on the acceptance and the running plan of that beamline.

The J-PARC E42 result thus adds a volume-sensitive handle on antikaon absorption to the atom and inclusive-reaction constraints. Combining it with the non-escape study above and, where a beamline program can accommodate it, a byproduct few-body escape measurement offers a path toward a more systematic description of the $\bar{K}$-nucleus interaction.

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