The \((K^-, p)\) absorption in flight and the binding of \(K^-\) in nuclei


Chiral dynamical approach to Kbar N and Kbar Nucleus interaction
Kaonic atoms
The \((K^-, p)\) reaction in flight and claims for a deep Kbar-nucleus potential
Reinterpretation of the results.
Chiral Lagrangian for pseudoscalar-baryon interaction

At lowest order in momentum the interaction Lagrangian reduces to

\[ L_1^{(B)} = \langle \bar{B} i \gamma^\mu \frac{1}{4 f^2} \left[ (\Phi \partial_\mu \Phi - \partial_\mu \Phi \Phi) \right] B - B (\Phi \partial_\mu \Phi - \partial_\mu \Phi \Phi) \rangle \]

there are 10 channels, namely \( K^- p, \bar{K}^0 n, \pi^0 \Lambda, \pi^0 \Sigma^0, \pi^+ \Sigma^-, \pi^- \Sigma^+, \eta \Lambda, \eta \Sigma^0, K^+ \Xi^- \) and \( K^0 \Xi^0 \). In the case of \( K^- n \) scattering the coupled channels are: \( K^- n, \pi^0 \Sigma^-, \pi^- \Sigma^0, \pi^- \Lambda, \eta \Sigma^- \) and \( K^0 \Xi^- \). These amplitudes have the form

\[ V_{ij} = -C_{ij} \frac{1}{4 f^2} (k^0_j + k^0_i) \]

One solves the Bethe- Salpeter equation in coupled channels

\[ T = (1-VG)^{-1} V \]

This produces transition amplitudes from \( K^- p \) to any other channel. Gives rise to resonances, \( \Lambda(1405), \Lambda(1670), \Sigma(1650) \)...
The lowest order calculations have been improved recently in


Common features: two poles for the $\Lambda(1405)$, one around 1420 MeV with narrow width ($\sim 30\,\text{MeV}$). The second one at lower energies, wider but changes much from model to model. Observation of the $\Lambda(1405)$ with different shapes in different reactions should further constraint the models.

Some differences: predictions for the scattering lengths. More experimental work on $K^-p$ atoms is needed.

Results with lowest order Lagrangian compatible with theoretical band determined by Borasoy et al.
In the medium Pauli blocking effect on the nucleons is considered, plus baryon selfenergy, and K selfenergy is accounted for selfconsistently.

$2 \omega V_{\text{opt}} = \Pi_{\mathcal{K}}^{\text{s}}(q^0, \vec{q}, \rho) = 2 \int \frac{d^3p}{(2\pi)^3} n(\vec{p}) \left[ T^\mathcal{K}_{\text{eff}}(P^0, \vec{F}, \rho) + T^\mathcal{K}_{\text{eff}}(P^0, \vec{F}, \rho) \right]$
Atomic orbits, Coulomb plus strong K optical potential

Hirenzaki, Okumura et al.

This discrepancy recently solved by Hayano et al. 2008
New experiment in agreement with theory
Phenomenological potentials with 200 MeV attraction reproduce atom data and lead to more deeply bound states. Gal et al., Akaishi, Yamazaki.
Brief history of deeply bound Kaonic atoms

\[ \rightarrow K^- \text{ bound in a trinucleon with 195 MeV binding and narrow, around 20 MeV} \]

E. Oset, H. Toki (Phys. Rev. C (2006)) interpret the peak as due to absorption of K with nucleon pairs K\(^-\)NN\[ \rightarrow \]p Σ . The width is not calculated.
Predict peak to appear narrower in bigger nuclei and gradually disappear as A becomes larger.
Predictions confirmed by FINUDA (proton spectra), Agnello Nucl. Phys A (2006)
In 6Li. The peak nearly fades away in 12C.

FINUDA makes another experiment looking at K absorption in light nuclei looking at Λ p in coincidence.
They claim evidence for a K\(^-\) bound in the pp system with 115 MeV binding and width 67 MeV.

Magas, Oset, Ramos, Toki, Phys. Rev. C (2006) interpret the peak as K\(^-\)pp \[ \rightarrow \]p Λ followed by rescattering of p or Λ in the nucleus.
Akaishi, Yamazaki criticize approach of Oset, Toki and Magas, Oset, Ramos, Toki In Nucl. Phys. A (2007), in particular “the small width” of the peak in Oset and Toki which actually was never calculated, nor quoted.

Magas, Oset, Ramos, Toki rebute criticisms: three papers
1) Straight answer nucl-th/0701023 →
New result: the width of p spectra corresponding to the KEK experiment is calculated. It is not narrow, rather broad, around 70-80 MeV/c


Correlated $\Lambda d$ pairs emitted after the absorption of negative kaons at rest $K_{\text{stop}}^- A \rightarrow \Lambda d A'$ in light nuclei $^6 \text{Li}$ and $^{12} \text{C}$. 
Conclusion on experimental situation

No evidence of deeply bound K states on nuclei has been found. All peaks claimed as states could be interpreted in terms of “conventional” “unavoidable” and “controllable” reactions.

Work continues searching for these states in JPARC, FINUDA, AMADEUS, DISTO ...
See talks by: Morton, Shevchenko, Grishina, Vazquez Poce, Lio, Okada Camerini and Tsukada

Positive side: we are learning new and interesting physics about K absorption by two and three nucleons, and can learn more.
Another “evidence” for a very deeply attractive \( K^- \) nucleus potential:

**The \((K^-,p)\) reaction on \(^{12}\text{C}\) at KEK**


\[
K^- + ^{12}\text{C} \rightarrow p + X
\]

\(p_K = 1\ \text{GeV/c} \quad \rightarrow \text{in-flight kaons}\)

\(\theta_p < 4.1^\circ \quad \rightarrow \text{forward nucleons (the most energetic)}\)

plus “coincidence requirement”:
(at least one charged particle in decay counters surrounding the target)
claimed not to affect the spectrum shape

\[
-E_B = \sqrt{(E_K + M_{^{12}\text{C}} - E_p)^2 - (\vec{p}_K - \vec{p}_p)^2 - M_{^{11}\text{B}}} - M_K
\]

The \((K^-,p)\) reaction on nuclei with in-flight kaons

- Process: quasielastic scattering $K^- p \rightarrow K^- p$ in nuclei
- Green’s function method
- Normalization: fitted to experiment
- Background: fitted to experiment

The $(K^-, p)$ reaction on nuclei with in-flight kaons

$^{12}C(K^-, n)$

$^{12}C(K^-, p)$

- $\text{Re } U_K = -60 \text{ MeV}$
- $\text{Im } U_K = -60 \text{ MeV}$

- $\text{Re } U_K = -190 \text{ MeV}$
- $\text{Im } U_K = -40 \text{ MeV}$

- $\text{Re } U_K = -160 \text{ MeV}$
- $\text{Im } U_K = -50 \text{ MeV}$
The only mechanism for fast proton emission in the Green’s function method is the quasielastic process $K^- p \rightarrow K^- p$ where the low-energy kaon in the final state feels a nuclear optical potential and can occupy stable orbits (no width), unstable orbits, or be in the continuum (quasifree process).

However, there are other mechanisms that can contribute:

- **Multistep processes:**
  - $K^- p$ and/or $N$ undergo secondary collisions as they leave the nucleus

- **One-nucleon absorption:**
  - $K^- N \rightarrow p \Lambda$ and $K^- N \rightarrow p \Sigma$
  - followed by decay of $\Lambda$ or $\Sigma$ into $\pi p$

- **Two-body absorption:**
  - $K^- N N \rightarrow \Sigma N$ and $K^- N N \rightarrow \Lambda N$
  - followed by hyperon decays

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<thead>
<tr>
<th>Process</th>
<th>$T_p$ [MeV]</th>
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<tr>
<td>$K^- p p \rightarrow \Lambda \bar{\pi}$</td>
<td>798.89</td>
</tr>
<tr>
<td>$K^- N N \rightarrow \Sigma \bar{\pi}$</td>
<td>749.32</td>
</tr>
<tr>
<td>$K^- N N \rightarrow N \Sigma$</td>
<td>$\Sigma \rightarrow \pi \bar{\pi}$</td>
</tr>
<tr>
<td>$K^- p N \rightarrow N \Lambda$</td>
<td>$\Lambda \rightarrow \pi^- \bar{\pi}$</td>
</tr>
<tr>
<td>$K^- p \rightarrow \pi^- \Sigma^+$</td>
<td>$\Sigma^+ \rightarrow \pi^0 \bar{\pi}$</td>
</tr>
<tr>
<td>$K^- p \rightarrow \pi^0 \Lambda$</td>
<td>$\Lambda \rightarrow \pi^- \bar{\pi}$</td>
</tr>
<tr>
<td>$K^- p \rightarrow \pi^- \Sigma^+$</td>
<td>$\pi^- p p \rightarrow n \bar{\pi}$</td>
</tr>
<tr>
<td>$K^- p \rightarrow \pi^0 \Sigma^0$</td>
<td>$\pi^0 p N \rightarrow N \bar{\pi}$</td>
</tr>
<tr>
<td>$K^- p \rightarrow \pi^+ \Sigma^-$</td>
<td>$\pi^+ n N \rightarrow N \bar{\pi}$</td>
</tr>
<tr>
<td>$K^- p \rightarrow \pi^0 \Lambda$</td>
<td>$\pi^0 p N \rightarrow N \bar{\pi}$</td>
</tr>
</tbody>
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Taken from J. Yamagata and S. Hirenzaki, Eur. Phys. J. A 31, 255(262 (2007))

We implement these processes in a Monte Carlo simulation of $K^-$ absorption in nuclei.
Monte Carlo simulation

- The nucleus is described by a nuclear density profile $\rho(r)$

- The incoming $K^-$ will experience a certain process (quasielastic, one-nucleon or two-nucleon absorption) at a point $r$ with a probability given by $\sigma_{\text{qe}} \rho \delta l$, $\sigma_{1N} \rho \delta l$ or $\sigma_{2N} \rho \delta l$ where $\delta l$ is a typical step size.

- Once a process has been decided, we determine the local momenta of the emitted particles according to phase space

- Further collisions of the emitted particles as they cross the nucleus are considered according to the probability that they collide with nucleons. We follow: the $K^-$ until it leaves the nucleus or gets absorbed all energetic nucleons (until they leave the nucleus) all energetic $\Lambda$ and $\Sigma$ (until they leave the nucleus and decay into

- Finally, we represent the spectra of the emerging protons
Cross sections: → taken from the PDG

Quasielastic scattering

\[ K^- p \rightarrow K^- p \hspace{1cm} K^- p \rightarrow \bar{K}^0 n \hspace{1cm} K^- n \rightarrow K^- n \]

\[ \sigma_{K^- p \rightarrow K^- p} = 21.22 \text{ mb}, \hspace{0.5cm} \sigma_{K^- p \rightarrow K^0 n} = 7.15 \text{ mb}, \hspace{0.5cm} \sigma_{K^- n \rightarrow K^- n} = 18.5 \text{ mb} \]

One-nucleon absorption

\[ K^- N \rightarrow \pi \Lambda \hspace{1cm} K^- N \rightarrow \pi \Sigma \] (and all possible charge combinations)

\[ \sigma_{K^- p \rightarrow \pi^0 \Lambda} = 4.32 \text{ mb}, \hspace{0.5cm} \sigma_{K^- p \rightarrow \pi^+ \Sigma^-} = 1.76 \text{ mb} \]
\[ \sigma_{K^- p \rightarrow \pi^- \Sigma^+} = 1.4 \text{ mb}, \hspace{0.5cm} \sigma_{K^- p \rightarrow \pi^0 \Sigma^0} = 1.58 \text{ mb} \]
\[ \sigma_{K^- n \rightarrow \pi^- \Lambda} = 6.35 \text{ mb}, \hspace{0.5cm} \sigma_{K^- n \rightarrow \pi^- \Sigma^0} = 0.97 \text{ mb}, \hspace{0.5cm} \sigma_{K^- n \rightarrow \pi^0 \Sigma^-} = 1.15 \text{ mb} \]

\[ \sigma_{K^- p}^{\text{total}} = 51.7 \text{ mb}, \hspace{0.5cm} \sigma_{K^- n}^{\text{total}} = 38 \text{ mb} \]
Two-nucleon absorption

\[ K^- NN \rightarrow \Lambda N \quad K^- NN \rightarrow \Sigma N \] (and all possible charge combinations)

We assume:

1. A probability per unit length for two-body absorption given by:

\[ P_{KNN} = C_{\text{abs}} \rho^2 \quad C_{\text{abs}} \sim 6 \text{ fm}^5 \]

\text{(2N-absorption is 20\% of 1N-absorption)}


2. Partial widths for the various channels according to a microscopic K-meson exchange picture
The \((K^-,p)\) reaction on nuclei with in-flight kaons
Kaon optical potential:

The antikaon is assumed to have a mass distribution

\[ S_K(\tilde{M}_K) = \frac{1}{\pi} \frac{-2M_K \text{Im} U_K}{(\tilde{M}_K^2 - M_K^2 - 2M_K \text{Re} U_K)^2 + (2M_K \text{Im} U_K)^2} \]

which peaks at a mass shifted by \( \text{Re} U_K \)

\[ \tilde{M}_K = M_K + \text{Re} U_K \]

and has a width determined by \( \text{Im} U_K \)

\[ \Gamma = -2 \text{Im} U_K \]

\[-600 \frac{\rho}{\rho_0} < \text{Re} U_K < -60 \frac{\rho}{\rho_0} \]

\[ \text{Im} U_K = -60 \frac{\rho}{\rho_0} \]
**Test: quasielastic process**

Our simulation is tested by calculating the **quasielastic contribution** from the **direct evaluation** of the corresponding many-body Feynman diagram.

\[
\frac{d\sigma}{d\Omega(\hat{p}) E(\tilde{p})} = -4p \left. \frac{d\sigma}{\hat{p}^2 d\Omega(\hat{p})} \right|_{\text{lab}} \int d^3 r e^{-\int_{-\infty}^{\infty} \sigma_{\rho(b,z')} dz'} \int \frac{d^3 p_{N}}{(2\pi)^3} n(\vec{p}_{N}, \vec{r}') \frac{M}{E(\vec{p}_{N})} \theta(q^0) \\
\times [\hat{p} (k_0^0 + M) - E(\vec{p}) k] \frac{1}{\pi} \text{Im} \frac{1}{q^{02} - \bar{q}'^{2} - m_{K}^{2} - \Pi(q^{0}, \bar{q}')} |q^0 = k_0^0 + E(\vec{p}_{N}) - \Delta - E(\vec{p})| \]

- **distortion factor** \( \sigma_{K} \sim \sigma_{N} \sim 40 \text{ mb} = \sigma \)
- **Normalization OK!** (without distortions we recover 6 times the elementary differential cross-section)

The \((K-, p)\) reaction on nuclei with in-flight kaons.
Monte Carlo results – sensitivity to kaon potential

\[ ^{12}C(K^{-}, p) \]

Only \( K^{-}p \to K^{-}p \) quasielastic scattering
Monte Carlo results – all contributions

\[ \frac{d\sigma}{dE_B} \text{ [\(\mu b/\text{sr}\cdot\text{MeV}\)]} \]

- $V_{opt} = (-60,-60)$ \(\rho/\rho_0\) - all processes
- $V_{opt} = (-60,-60)$ \(\rho/\rho_0\) - only QE

$^{12}C(K^-,\rho)$

No coincidence
Monte Carlo results – all contributions

2N nucleon absorption contributes starting from almost -300 MeV

No coincidence

1N absorption, rescattering
How to simulate the coincidence requirement in MC?

“have at least one charged particle in decay counters surrounding the target”

The simulation of such coincidence requirement is tremendously difficult, because it would imply keeping track of all charged particles coming out from all possible scatterings and decays.
How to simulate the coincidence requirement in MC?

The main source of energetic protons is the $K^-p$ quasielastic scattering process.

1) We can eliminate processes that, for sure, cannot have a coincidence: these are the events where neither a proton, nor a $K^-$ have had any other collision than a primary quasi-elastic event with a “good” (energetic and forward) proton. (The negatively charged kaon escapes undetected through the back and cannot produce a coincidence)
Monte Carlo results – coincidence simulations

\[12C(K^-, p)\]

The graph shows the differential cross section \(\frac{d\sigma}{dE_B}\) [\(\mu b/\text{sr}\cdot\text{MeV}\)] as a function of the energy \(-E_B\) [MeV]. The graph compares
- All processes (green dashed line)
- No one K\(^-\) N QE scattering (red line)
- Experimental data (blue line)

The peaks at around 50 MeV are significant features in the graph.
Monte Carlo results – coincidence simulations

The coincidence requirement removes a substantial fraction of events and changes the shape of the spectrum drastically.
How to simulate the coincidence requirement in MC?

The remaining events are also suppressed by the coincidence requirement.
(decay counter do not cover 4π)

2) In the first approximation we can assume that all other events are suppressed by the same factor.
Monte Carlo results – coincidence simulations

\[ \frac{d \sigma}{d E_B} \text{ [\(\mu b/\text{sr}\cdot\text{MeV}\)]} \]

- Red: Coincidence simulation: \(\times 1.0\)
- Green: Coincidence simulation: \(\times 0.8\)
- Black: Coincidence simulation: \(\times 0.6\)
- Blue: Exp. data

\[ ^{12}\text{C}(K^-, \rho) \]
Conclusions

- The results of the in-flight $^{12}$C(K$^-$,N) reaction at KEK (PS-E548) can probably be explained with a conventional kaon potential.

- Actually, the point of our analysis is not to state that the data supports an attraction of $-60$ MeV instead of $\sim -200$ MeV.

- We have seen that the coincidence requirement introduces a non-negligible distortion in the spectrum.

- This distortion is comparable in size (even bigger) than that produced by different kaon optical potential.

- This is not a good experiment to learn about the size of attraction of the K$^-$ nucleus optical potential.

- The claims for a deep K$^-$ nucleus potential from the analysis of Kishimoto et al are unfounded.
Simplest cluster: $K^-pp$ system

<table>
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<th>Method</th>
<th>properties</th>
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<th>$\Gamma[\text{MeV}]$</th>
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<td>Schevchenko et al.</td>
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Chiral dynamics $\rightarrow$ small binding, large width (larger than binding)