Kaonic nuclei excited by the in-flight \((\text{K}^-,\text{n})\) reaction

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Neutron Stars

No Strangeness
~2 Solar mass

Strangeness
~1.5 Solar mass

$\rho \sim 3-5 \rho_0$
Nuclear matter
with hyperons

Kaon condensation
K-nucleus interaction

M~1.4 solar mass

Talk by I. Bombaci
Hyperons in Neutrons Stars

- Negative charged particle
- $\Sigma^-$ repulsive
- Electron Chemical potential
- Fermi Surface
- Charge neutrality
- Kaon condensation
- K-N int
K-nucleus interaction

- Atomic X ray data suggest two solutions (Batty, Freedman, Gal, PR287,385'97)
  - deep ~180 MeV K-con ($m_K \sim 2.5 \rho U$)
  - shallow ~80 MeV no K-con
  - Phase shift of K- w.f. at the nuclear surface

- Heavy Ion reaction attractive
  - KAOS talk by V. Koch

- $\Lambda(1405)$
  - KN bound state
  - $K^- p$ X ray data
    - repulsive (bound state) strongly attractive
Atomic X ray data

Konic atom
Wave function

Nodes
Imaginary part

| R |
( fm • )

CK
1s

Coulomb only

Real part only

Imaginary part only

Full potential

r (fm)

| R |² (fm²)

0 0.02 0.04 0.06
0 20 40 60
Dispute in theoretical calculations on the antikaon-nucleus potential

- Shallow potential (40-80 MeV)
  - Chirally motivated models
  - Meson Exchange
    Gal, Oset, Ramos, Weise, Toki, ..........Many
- Deep potential (~200 MeV)
  - Phenomenological models
    Akaishi, Yamazaki,
Kaonic Nuclei

• Experimental information so far $\rightarrow$ peripheral
• Put a K in the core of a nucleus
  – Kaonic nuclei
• Direct information on the K-nucleus Interaction
• Can we observe the states?
  – $\text{BE}_{1s} \sim \frac{3}{2} \hbar \nu - U$
  – Width could be as narrow as 10-20 MeV
    • For deeply bound states (Waas, Kaiser, Weise, PLB 379, 34'96)
    • $\Gamma \sim 100$ MeV at the threshold (BFG, PR287)
  – Cross section reasonably large TK, PRL’99
Production of Kaonic Nuclei by the in-flight \((K^-, N)\) reactions

- **Virtual Kaon Beam**
- **Background ~ Spreading width**
- **Highest energy nucleons**

TK, PRL83,4701, ’99

Many others; Yamazaki, Akaishi, Iwasaki, Nagae
Characteristic of the reaction

- **Momentum transfer**
  - $\sim 400$ MeV/c
  - $(\pi^+, K^+)$ for hypernuclear production

- **Similar Gross structure of spectrum**

![Graph showing Kaonic nuclei and Free proton target with BE = 150 MeV]
Cross section

$$\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{L,0}^{N^{-N\rightarrow NK^{-}}} \times N_{\text{eff}}.$$  

Elementary cross section

$$N_{\text{eff}}^{\text{pw}} = (2J + 1)(2j_N + 1)(2\ell_K + 1) \times \begin{pmatrix} \ell_K & j_N & J \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}^2 F(q).$$

Harmonic Oscillator

Form factor

$$F(q) = \frac{(2Z)^L e^{-Z}}{[2L + 1]!!^2} \frac{[\Gamma(L + 3/2)]^2}{\Gamma(\ell_K + 3/2)\Gamma(\ell_N + 3/2)} \frac{z}{(bq)^2/2}.$$
Elementary cross section
Experiment

- E930 parasite
  - $^{16}\text{O}(K^{-}\pi^{-}\gamma)^{16}_{\Lambda}\text{O}$ (Hyperball)
- $P_{K} = 930$ MeV/c $\Rightarrow$ Best for $(K^{-},N)$ reaction too
- Measured neutrons from the $^{16}\text{O}(K^{-}, n)$
- Neutron counters
  - 100cm(W) x 20cm(H) x 20cm(D)
  - 0 degrees
  - 7m from the target
- $4.7$ G $K^{-}$
Setup of the Experiment

Parasite E930

E930 setup

AGS-D6

Hyperball

Tag Kaonic nuclear events

~0.2 \((4\pi)\)

TOF

Flight length

~ 7m
Decay Counter (Hyperball)

To tag decay products from Kaonic nuclei

- Kaonic nuclei
  \[ \Lambda (1405) \rightarrow \Sigma \pi \rightarrow N \pi \pi \]
  or YN production
  ! Charged particles

- Background process
  \[ p(K^-, K^0)n \]
  \[ K^0 \rightarrow \text{fast neutron} \]
  no charged particle
  n ! calibration

- Kaon decay

- solid angle
  \[ \sim 20\% \ \text{(Ge detector)} \]

- \[ E_{\text{max}} \sim 7 \text{ MeV} \]
TOF(1/\beta) spectra

before

Neutral Kaon 
\((K^-,K^0) @TGT\) 
\((K^0 \sim \text{fast neutron})\)

goes away

Bound region

Raw

Hyperball + dE/dX cut
Excitation energy spectrum

µb/sr/MeV

μb/sr/7MeV

Early version

QF+p(K^-,n)K^0 + hyperon production

QF

p(K^-,n)K^0

hyperon production

0
250
500
750
1000
1250
1500
1750
2000
2250
2500

-200
-150
-100
-50
50
MeV

Threshold

¢ Strength in bound region
¢ Interesting structure although

Results were not stable
TOF(1/β) spectra

Raw

after

No hits in FD1-3
No Ge help

Kaon decay

Goes away

γ from K- ! π^- π^0

target
veto
FD1

K-

π^-
Momentum spectrum
Inclusive (FD cut)

\[ p(K^-, n)K^0 \]

P calibration
Only by TOF

\[ p_n \sim 1.2 \text{ GeV/c} \]

\[ p_n(\text{mes}) - p_n(\text{cal}) \]
Energy Spectrum (Ge cut)

- Attractive K-nucleus interaction
- Hyperon production
- Cross section (Gopal)

\[ \mu b / sr / 10 \text{ MeV} \]

\[ ^{16}\text{O}(K^-,n) \]

\[ p(K^-,n)K^0 \]

Resolution (TOF)

- Bound
- Unbound

\[ M(^{15}\text{O}+K^-) \]
Source of energetic neutron background

• 2 nucleon absorption
  – $K^-\, NN \rightarrow YN$ not seen so far

• Hyperon production
  – $N(K^-,\, \pi)Y$ where $\pi$ scattered backwards
  – $\Lambda\, (\Sigma) \rightarrow n\, \pi\, n$: forward
  – Cross section (Gopal), GEANT

• Production of $\Lambda$ or $\Sigma$ hypernuclei
  – Not seen so far
2 nucleon absorption background

Simulation for the KNN ! YN

\[2 \text{ nucleon absorption background}\]
Backgrounds

No strange system

Threshold of \( \Lambda \) Hypernuclei

Background
Flat

- \( -BE = 200-500 \) MeV
21 events
0.7 events/10 MeV

2 nucleon absorption KNN ! Yn
Bound region

Peak position
-130 MeV  s
-90 MeV  p
-50 MeV  d
Simple Estimate of the Potential Depth

- Lowest Energy state
  - ~130 MeV bound
- Second Excited state
  - ~90 MeV bound
- Third
  - ~50 MeV (?)

\[
\begin{align*}
\hbar \omega & \sim 40 \text{MeV} \\
BE & \sim 130 \text{MeV} \\
-BE &= U + 3/2 \hbar \omega \\
U & \sim -190 \text{MeV}
\end{align*}
\]
Shell Spacing

\[ \hbar \omega_K \sim \hbar \omega_N \sqrt{V_K / V_N} \sqrt{m_N / m_K} \]

\[ \hbar \omega_N \sim 15 \text{MeV} \]

\[ \sqrt{V_K / V_N} \sim \sqrt{190 / 50} \]

\[ \sqrt{m_N / m_K} \sim \sqrt{0.94 / 0.5} \]

\[ \hbar \omega_K \sim 40 \text{MeV} \]

U\sim190 \text{ MeV}
Decay Modes I

- Konic Nuclei $\sim \Lambda(1405)$
- $I=0$, $J^\pi=1/2^-$
- $\Lambda(1405) \rightarrow \pi^+ \Sigma^- \rightarrow \pi^- n (1/3)$
  $\pi^- \Sigma^+ \rightarrow \pi^+ n (1/6)$
  $\pi^0 p (1/6)$
  $\pi^0 \Sigma^0 \rightarrow \gamma \Lambda \rightarrow \pi^- p (2/9)$
  $\pi^0 n (1/9)$

2 charged $\pi$ 1/2
1 charged $\pi$ 2/9
2 $\pi^0$ 1/9

Charged particle track vertex
Decay Modes II

• BE > 100 MeV
  – $\Lambda (1405)! \Sigma \pi$ energetically forbidden

• KNN ! YN (N: p n, Y: $\Lambda \Sigma^{+0-}$)

• Ge efficiency
  – GEANT simulation
    • all YN and $\Lambda (1405)$ decay
  – Efficiency 10~13% (Br is not known)
  – 11% (30 % systematic error)
Cross Section $^{16}\text{O}(K^- , n)$

- **Experimental value**
  - GS(s) $\sim 80 \ \text{µb/sr}$ (50% stat. 30% syst. error) $13-4=9$
  - 1st(p) $\sim 450 \ \text{µb/sr}$ (20% stat. 30% syst. error)
  - 2nd(d) $0.5\sim1 \ \text{mb/sr}$

- **Calculation (TK PRL)**
  - $^{12}\text{C}$ gs $100(490) \ \text{µb/sr}$ ($\sim 50 \ \text{µb/sr}$ Gal et al.)
  - $^{16}\text{O}$ gs $50\sim100 \ \text{µb/sr}$
  - $\sigma_s: \sigma_p: \sigma_d = 1: 6: 7$
  - cross sections agree
A little annoying

**Width**

Observed width
\[ \Gamma \approx 26 \text{ MeV} \quad s(-130 \text{ MeV}) \]
\[ \Gamma \approx 27 \text{ MeV} \quad p(-90 \text{ MeV}) \]

Experimental resolution
37 MeV

TOF resolution \( \approx 120 \text{ps} \)
(\( \pi \) Beam though)

1. Recoil proton (larger pulse height)
   better TOF res.
2. Statistics

Waas, Weise, PLB379(96)34

\( \Gamma \) could be \( \approx 10 \text{ MeV} \)
Results

• States are seen @
  – -130, -90, -50 MeV
  – $\sim \omega \sim 40$ MeV

• If lowest bound state is @ -130 MeV
  – All are consistent with $U \sim 190$ MeV
  – $\sim \omega$, Cross section

• Our spectrum is highly inconsistent with potential $U \sim 40$-80 MeV

• Our results show that potential depth is as deep as 200 MeV.
Current and future studies

- $^{12}\text{C}(K^-, p)$ E522
  - under analysis
- $^{16}\text{O}(K^-, p)$ excites $l=1$, though $(K^-, n)$ $l=0, 1$
  - $l=0$ (KN) pairs $\sum(1 - \tau^K \phi^N) / 4$
  - 4.5 for $l=0$, 3.5 for $l=1$
  - $^{16}\text{O}(K^-, p)$: less deep potential! Experiment

- Future J-PARC
  - Day 1 experiment
- Many interesting future experiment