KEK-PS E548
Study of Kaonic nuclei by the (K^-, p) reaction

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- Production mechanism of kaonic nuclei
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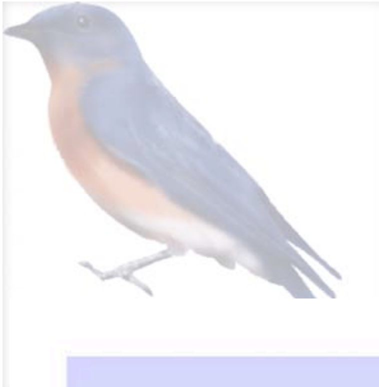
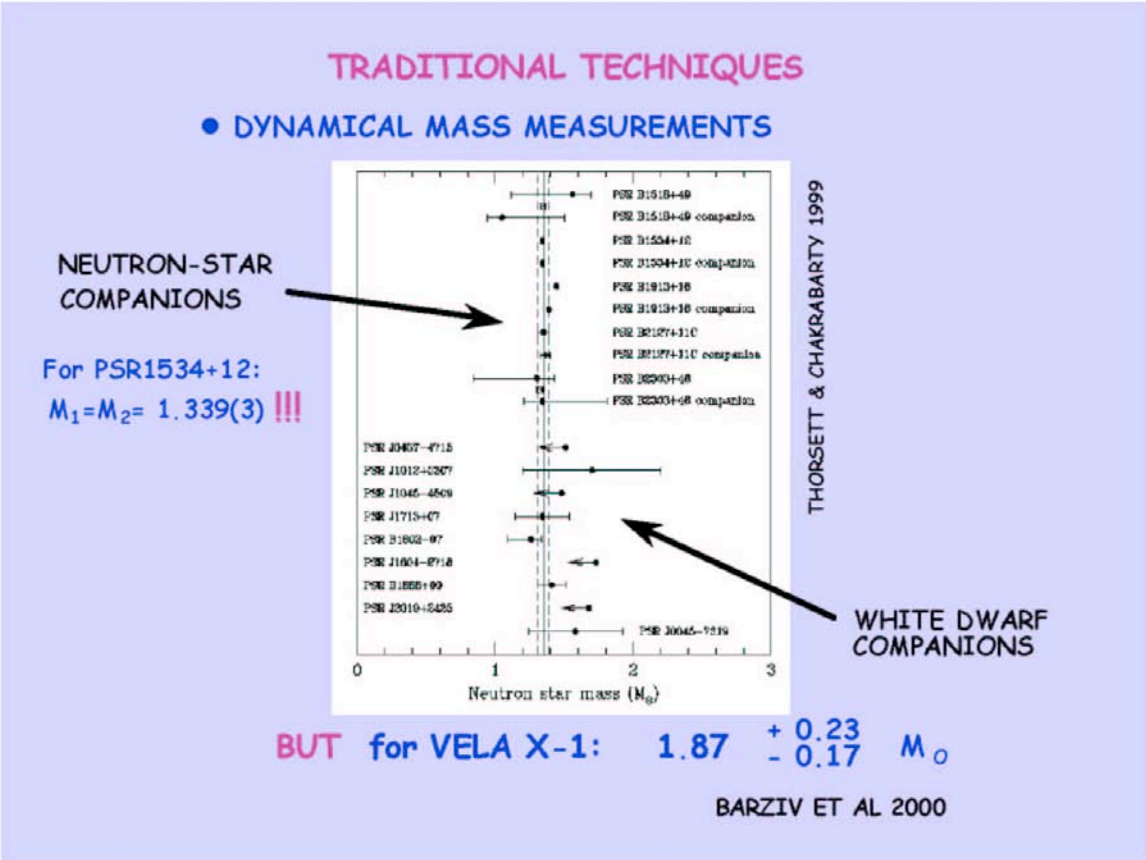
- (K^-, n) reaction at BNL: E930
- (K^-, n) and (K^-, p) reaction at KEK: E548
  - Comparison with theoretical calculation
- Summary



Neutron Stars



No Strangeness
~2 Solar mass

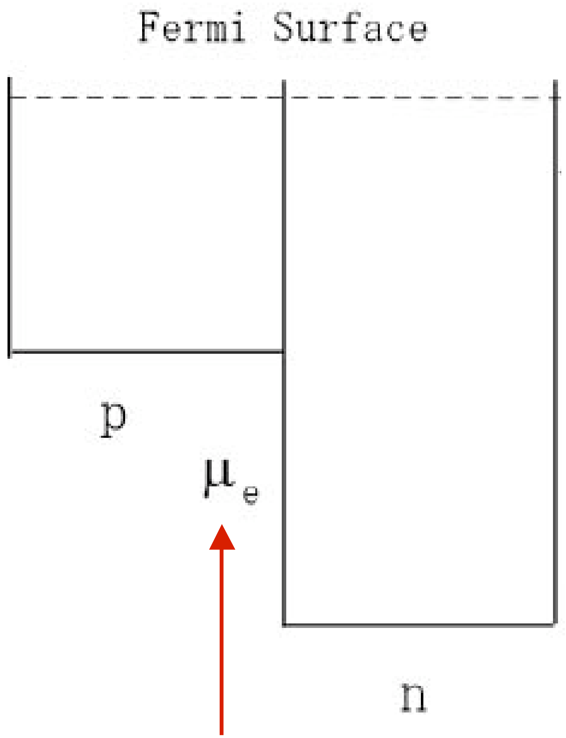
Strangeness
~1.5 Solar mass

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

Kaon condensation
KN Σ term ($s\bar{s}$)
K-nucleus interaction

M~1.4 solar mass

Hyperons in Neutrons Stars



Electron Chemical potential

Charge neutrality

Negative charged particle

Σ^- repulsive

Kaon condensation

K-N int (Σ term)

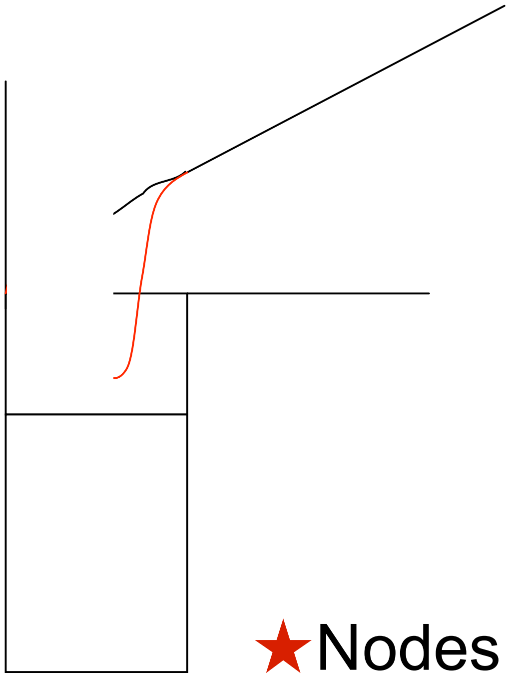
K-nucleus interaction

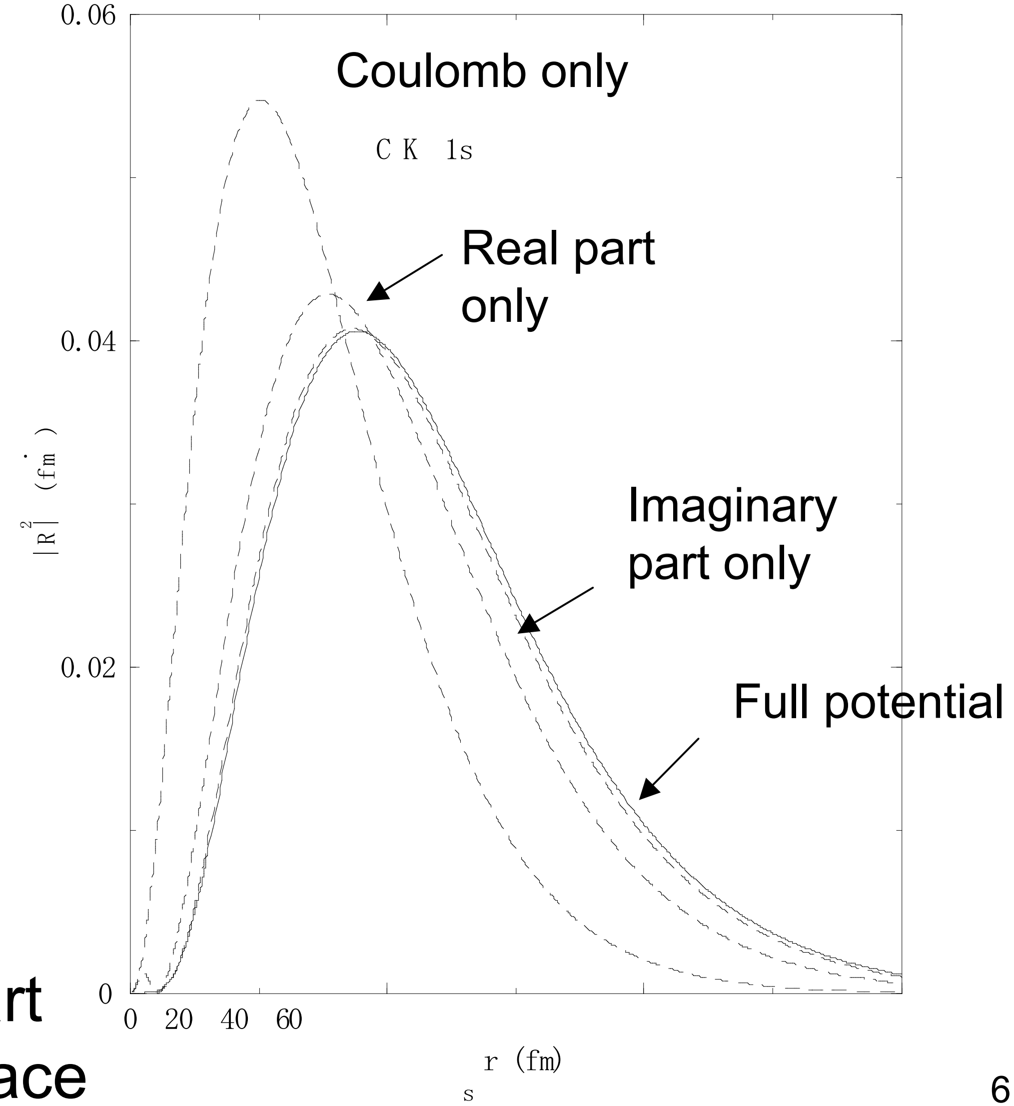
- Kaon condensation in neutron stars
- Atomic X ray data: two solutions (Batty, Friedman, Gal, PR287,385'97)
  - deep ~180 MeV K-con (m_K~2.5 ρ U)
  - shalow ~80 MeV no K-con
  - Recent reanalysis (PLB606, 295 '05; NPA770, 84 '06)
    - prefers 180 MeV sol.
- K^- production in HI reaction: attractive
- Λ(1405)
  - K^- p X ray data
    - repulsive shift: (bound state Λ(1405)) strongly attractive
  - phenomenological potential (Akaishi Yamazaki)
- Recent experiments: controversial

Kaonic nuclei

Atomic X ray data

Konic atom
Wave function

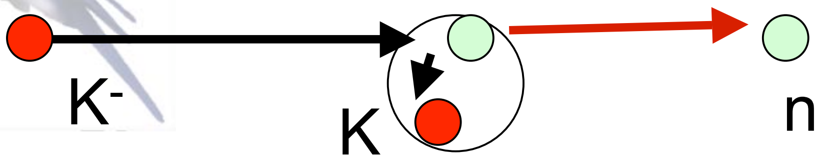




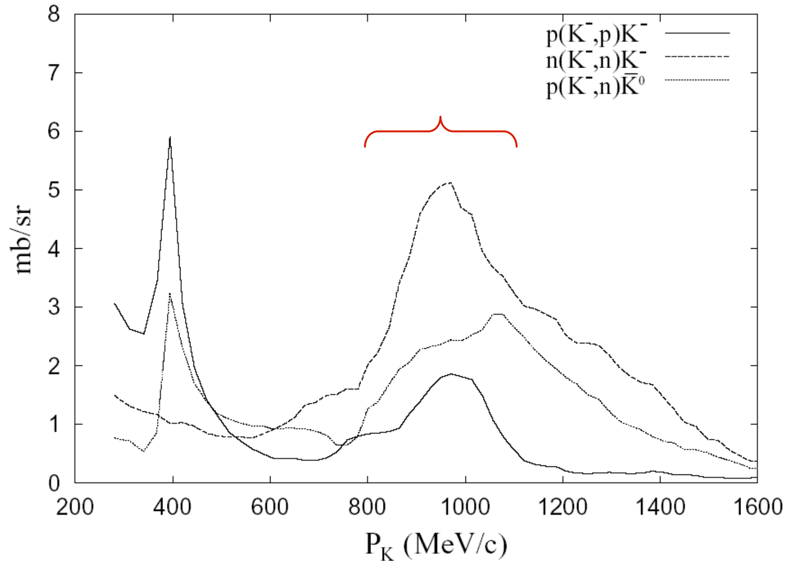
★Nodes
★Imaginary part
Treatment surface

Study of Kaonic Nuclei by the in-flight (K^-,N) reactions

TK, PRL 83, 4701, '99



Elementary σ



$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)^{K^-N\to NK^-}_{L,0^\circ} N_{\rm eff}$$

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

$$F(q) = \left(\int r^2\, dr\, R_K(r) R_N(r) j_L(qr)\right)^2$$

$d\sigma/d\Omega(\text{lab}) = (P_l/P_{cm})^2 d\sigma/d\Omega(\text{CM})$ ~10mb/sr

- Initial and final wf, q ~ 0.3 GeV/c ~ p_F

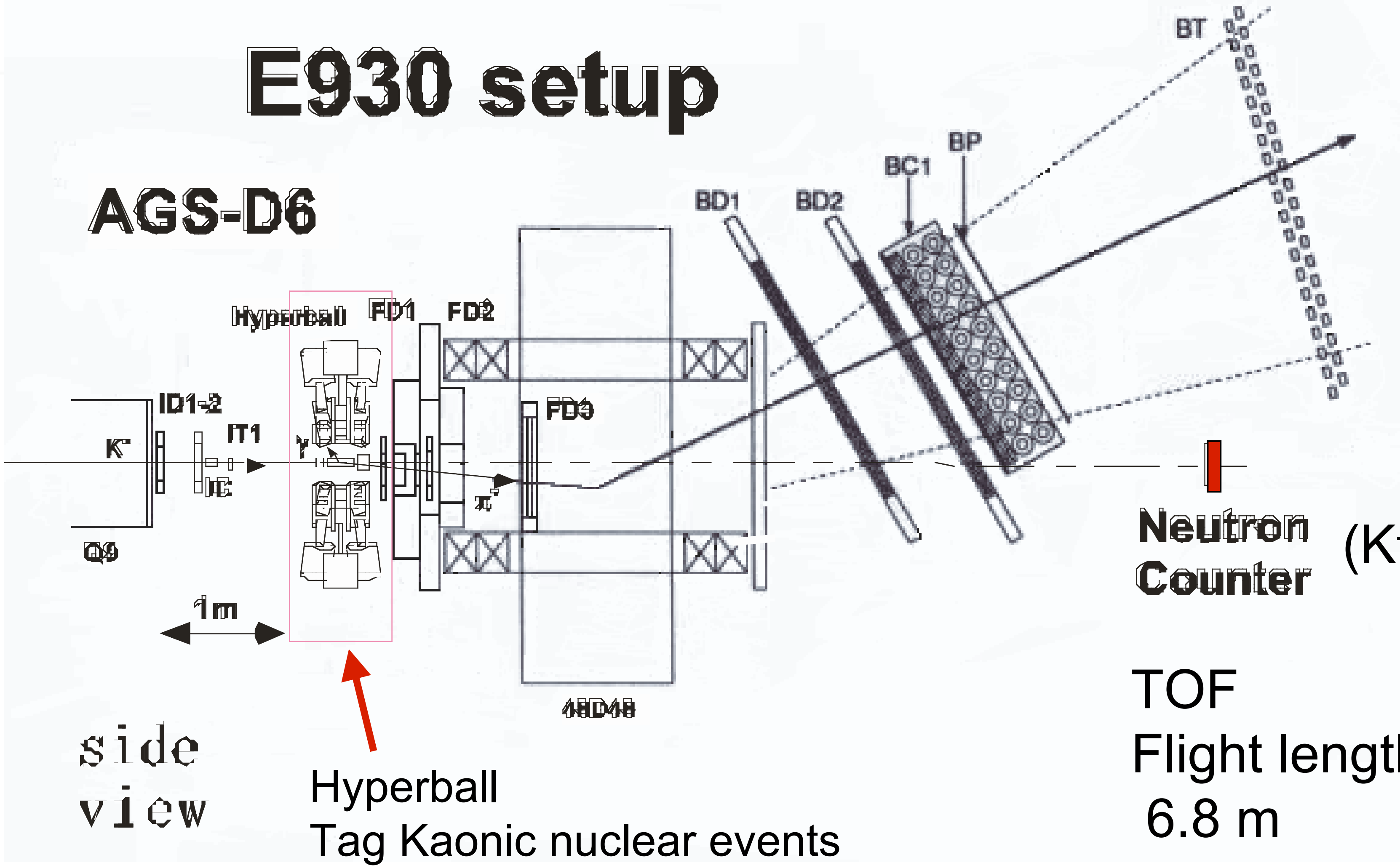
★Known mechanism (predictable cross section)
★Least background (p_N~1.3GeV/c for p_K~1 GeV/c)

Exploratory Experiment at BNL

- E930 parasite
  - $^{16}O(K^-,\pi^-\gamma)^{16}{}_{\Lambda}O$ (Hyperball)
- P_K = 930 MeV/c ⇨ suited for (K^-,N) reaction too
- Measured neutrons from the $^{16}O(K^-, n)$ (water)
- Neutron counters
  - 2 sets of Plastic scintillator
    4 layers 100(w)x10(h)x5(t)cm^3 + 1cm thick (veto)
  - 0 degrees
  - 6.8 m from the target
- 4.7 G K^-

Setup of the Experiment

Parasite E930

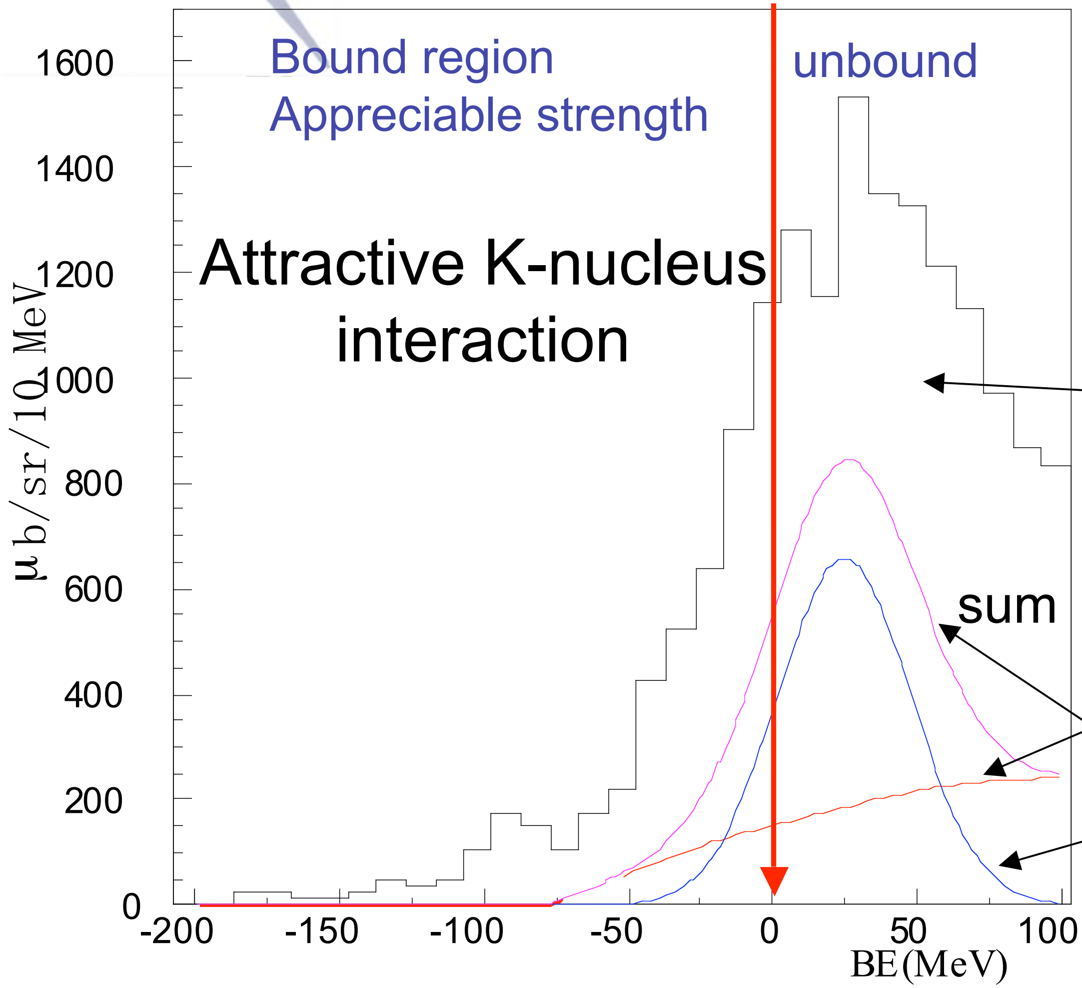


Neutron Counter (K⁻,n)

TOF
Flight length
6.8 m

Hyperball
Tag Kaonic nuclear events
~0.2 (4π)

Energy Spectrum (Ge cut)



$^{16}O(K^-,n)$
water target
^{16}O kinematics

Hyperon production

$p(K^-, n)K^0$
Resolution (TOF)

$M(^{15}O+K^-)$

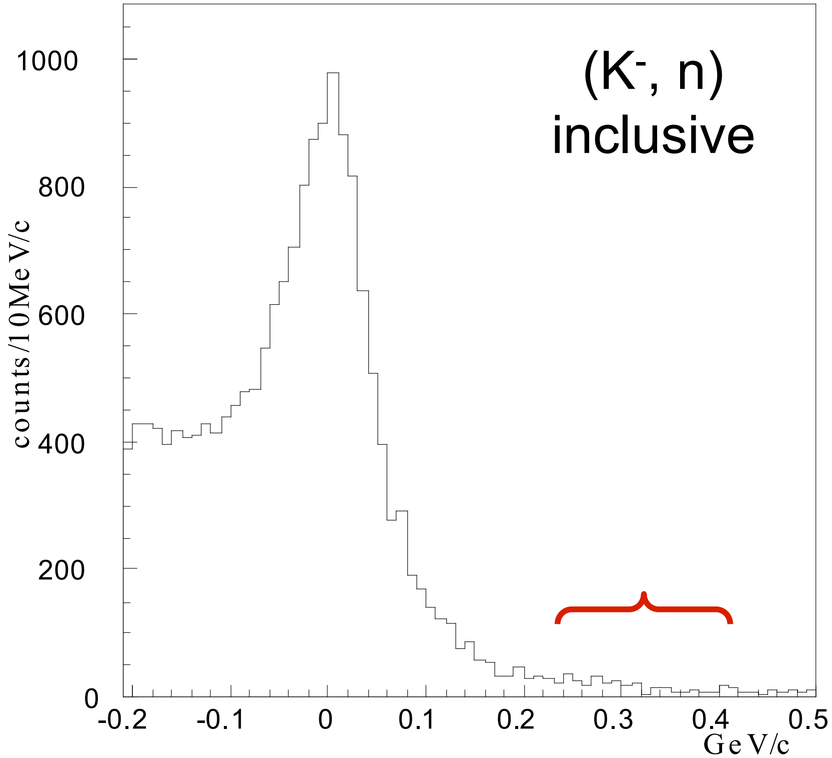
Cross section (Gopal)

Backgrounds

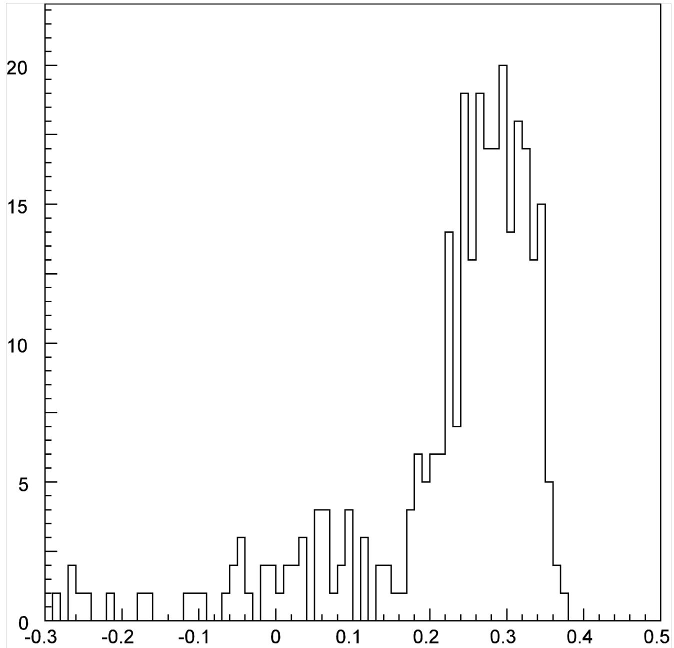
- 2 nucleon absorption → not seen
  - K^- NN → YN
- Hyperon production → estimated small
  - N(K^-, π)Y where π scattered backwaords
  - Λ (Σ) → n π n: forward
  - Cross section (Gopal), GEANT
- Production of Λ or Σ hypernuclei → not seen
  - Should be very small

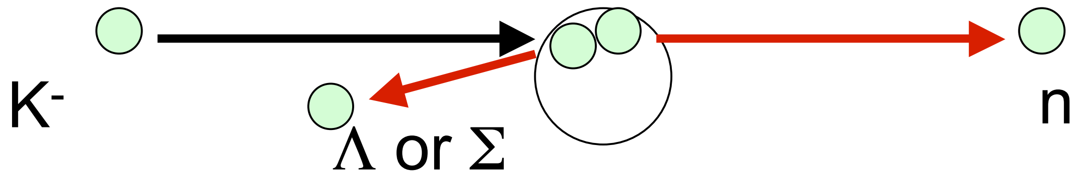
Little 2 nucleon absorption backgrounds

Data

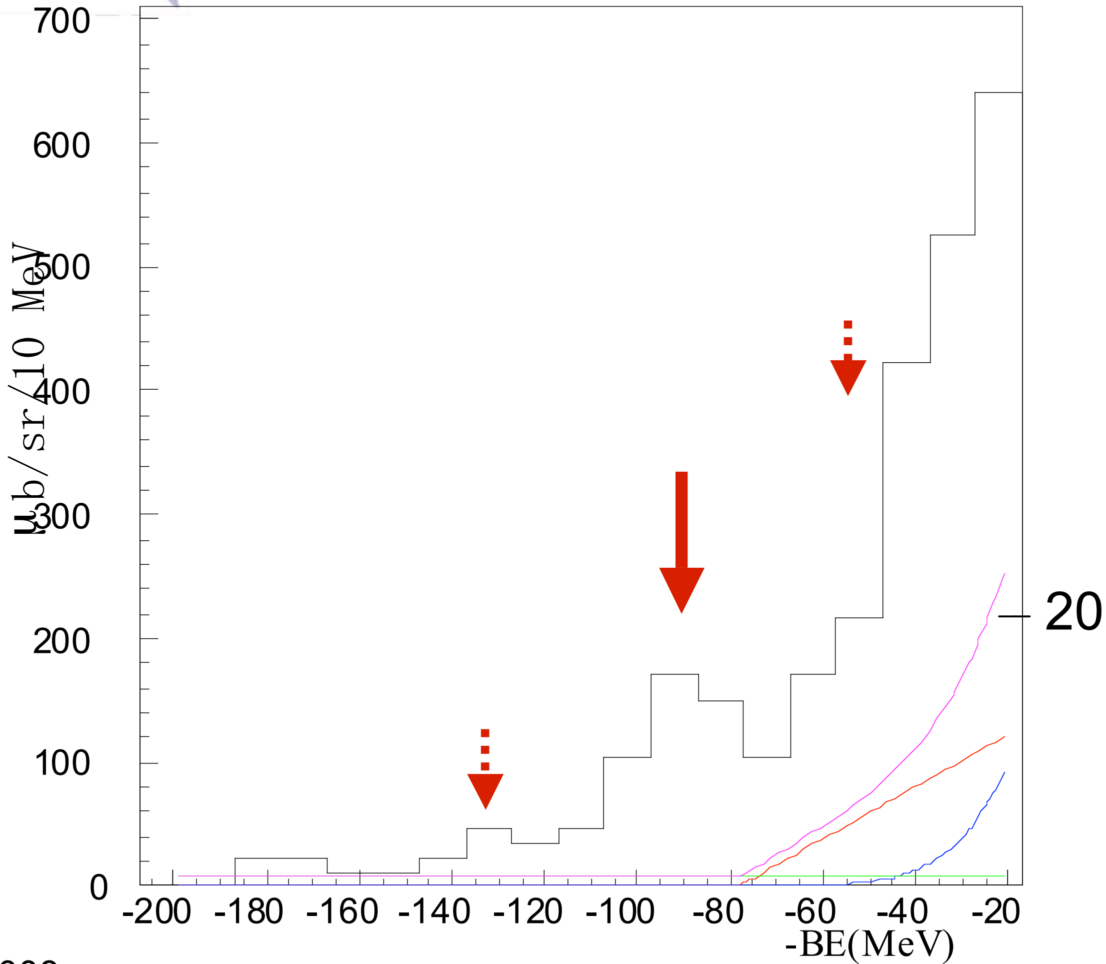


Simulation for the KNN ! YN





Bound region



Broad bumps

~ -90 MeV

-130 MeV

- 50 MeV

V~ -200MeV

The $^{16}O(K^{-},n)$ at BNL

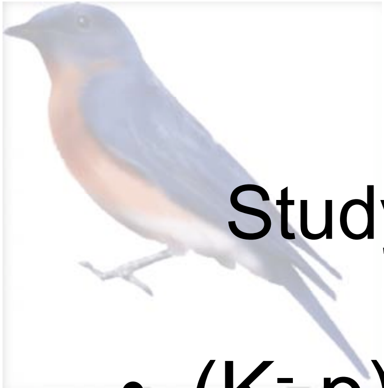
- Deep potential (~200MeV) was suggested
  - Appreciable strength in the bound region
- Cross section is consistent
- Negligible contribution from 2 nucleon absorption

- Hydrogen in water target obscured the conclusion
- Limited statistics

↓

- KEK E548 experiment

T. K et al., PTP. Suppl. 149 (2003), 264
Nucl.Phys.A754:383-390,2005

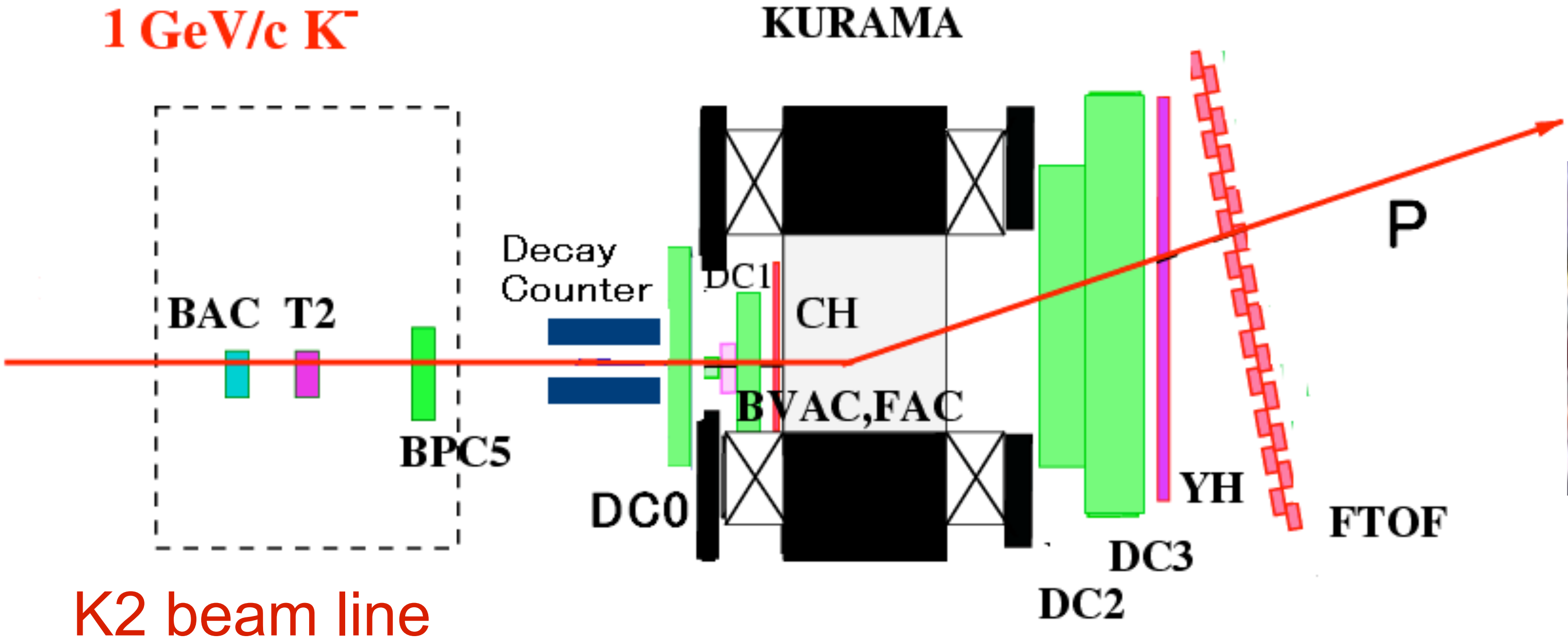


KEK-PS E548

Study of Kaonic Nuclei by the (K^-,p) reaction

- (K^-,p) and (K^-,n) reactions on
  - ^{16}O (water target)
  - ^{12}C (graphite and CH_2 targets)
- Improvements over BNL experiment
  - Proton (KURAMA spectrometer): 12MeV(σ)@BE=150MeV
  - Neutron counter: ~20msr, 10MeV(σ)@BE=150MeV
  - Decay counter (NaI array): ~0.5 of 4π
- 52 shifts in April/2005
  - Kaonic nuclei, X particle search (~10 shifts)

Beam line and spectrometer



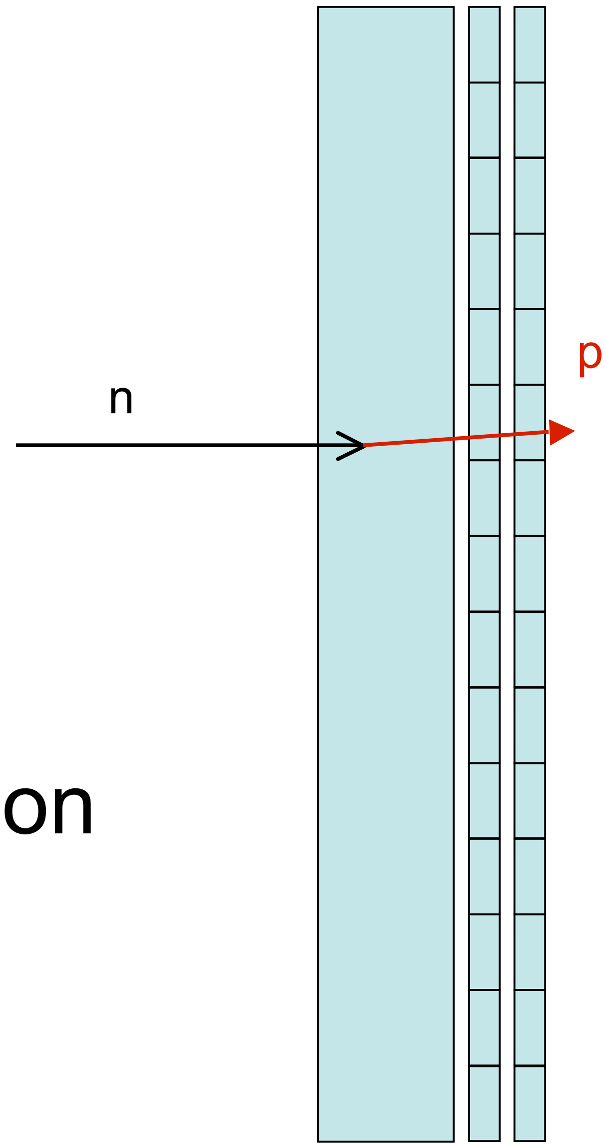
K2 beam line

p_K=1 GeV/c (p_N=1.2~1.3 GeV/c)
10k K^- for 3Tp (~1/10 of BNL)
Trigger rate → ~500/spill
~1GK- on Target

Liquid scintillator
for Neutron counter

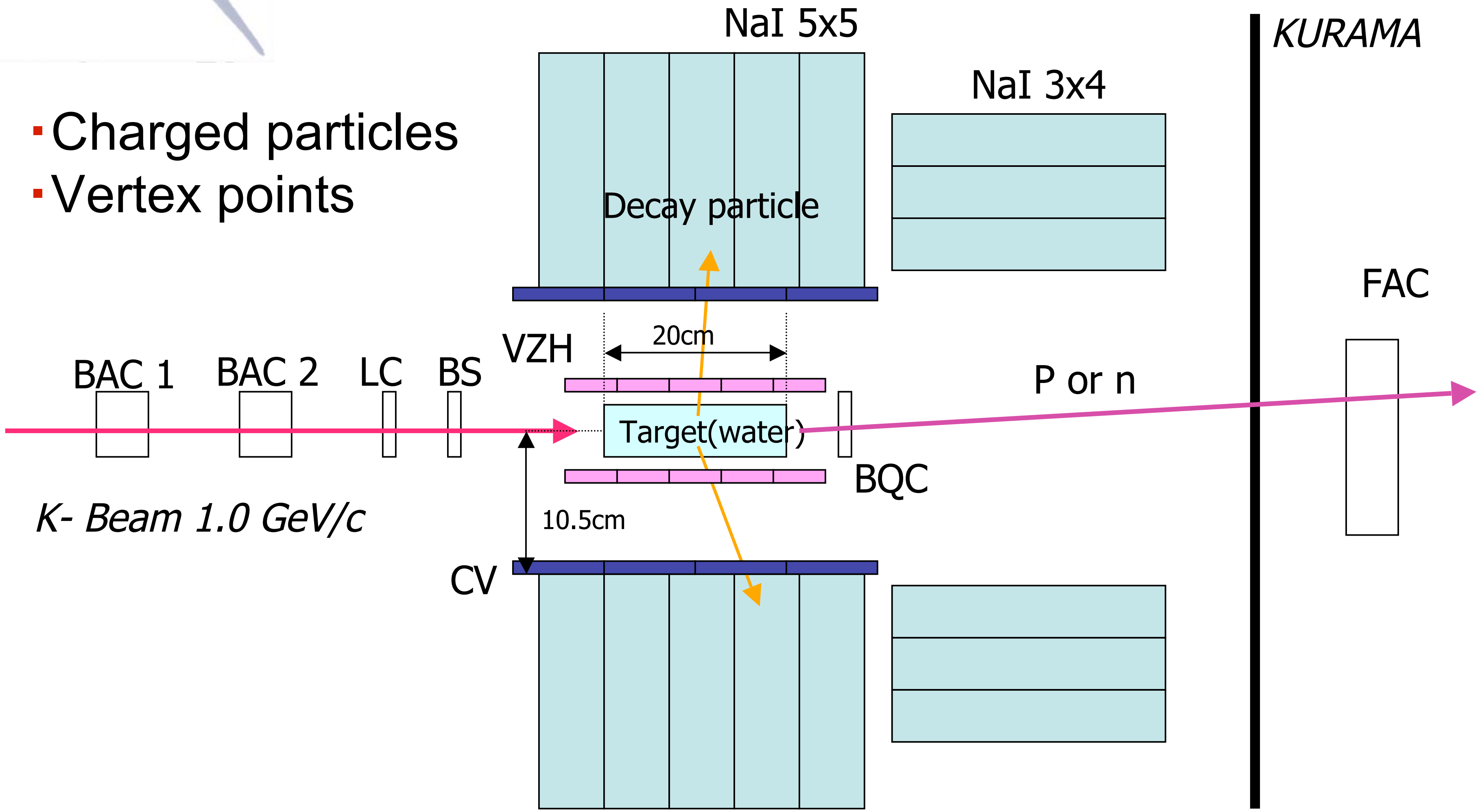
Neuron counters

- Plastic scintillator array
  - 2 layers of 5cm thick plastic
  - 1.5m x 1.5m
- Conversion layer
  - Liquid scintillator container
  - 20cm thick 1.5m x 1.5m
- Efficiency and time resolution
- 9.8m from the target



Decay counter

- Charged particles
- Vertex points

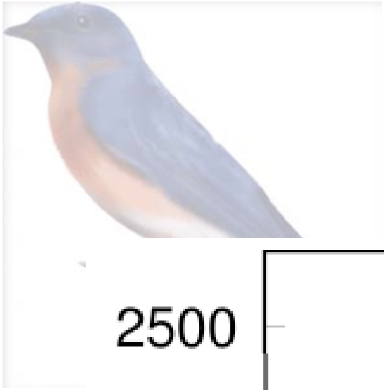


VZH is to identify vertex to give neutron flight length

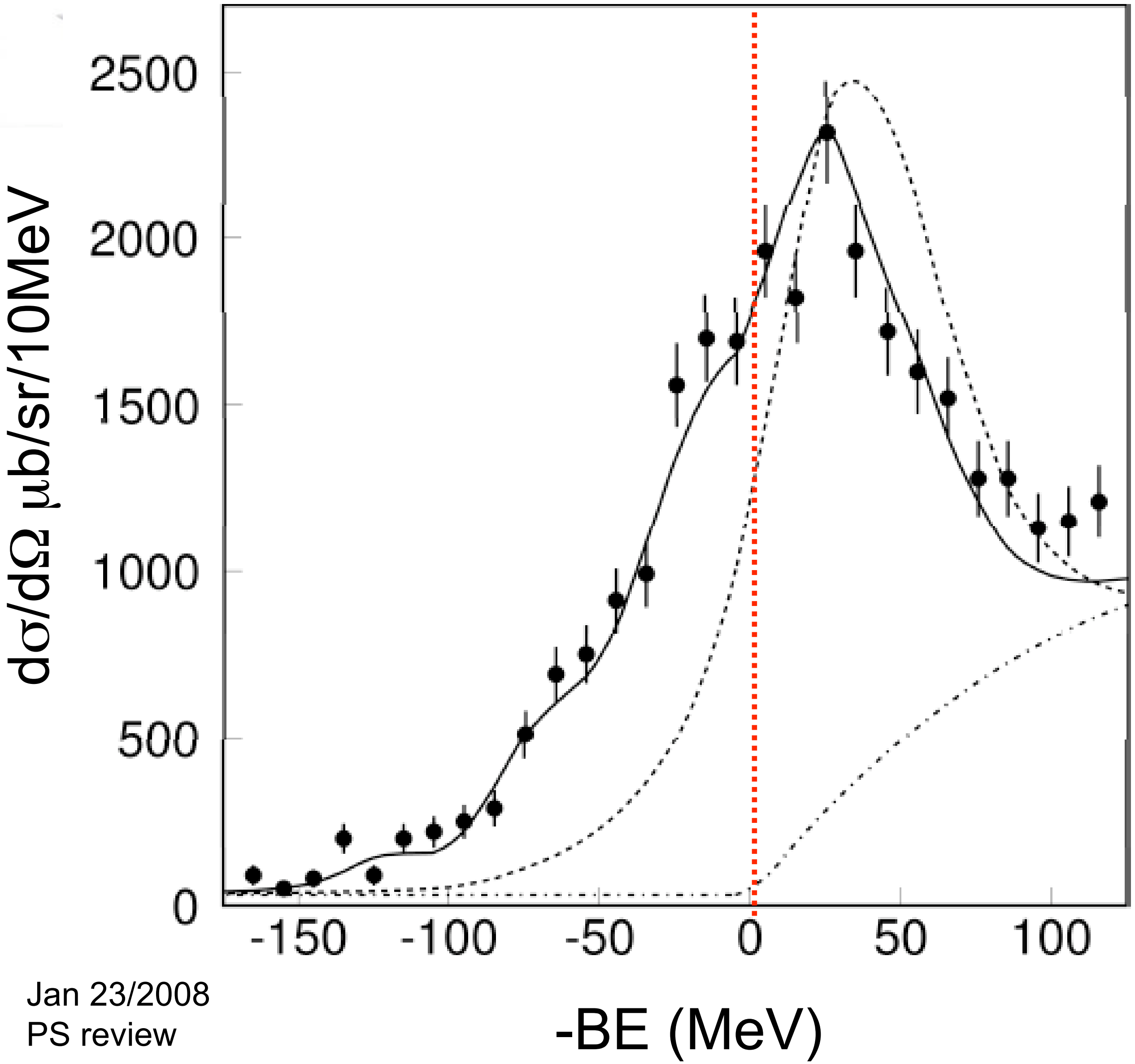
Missing mass spectra

- (K^-, p) and (K^-, n) reaction on ^{12}C ($\theta < 4.3^{o}$)
  - (K^-, p): little BG inclusive
  - (K^-, n): BG from K_L production
- Comparison with (K^-, p) and (K^-, n) reaction
  - multi.(decay)>=1
  - Eff(BE) ~ constant

Multiplicity ~1.5
for both pion emission
and 2 nucleon absorption

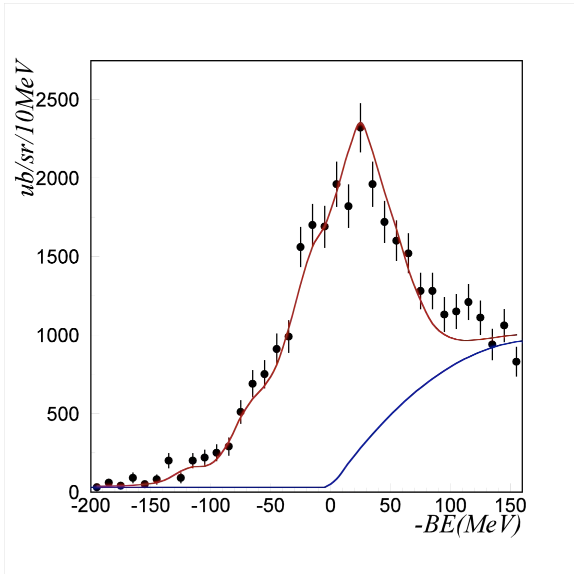


$^{12}C(K-, n)$

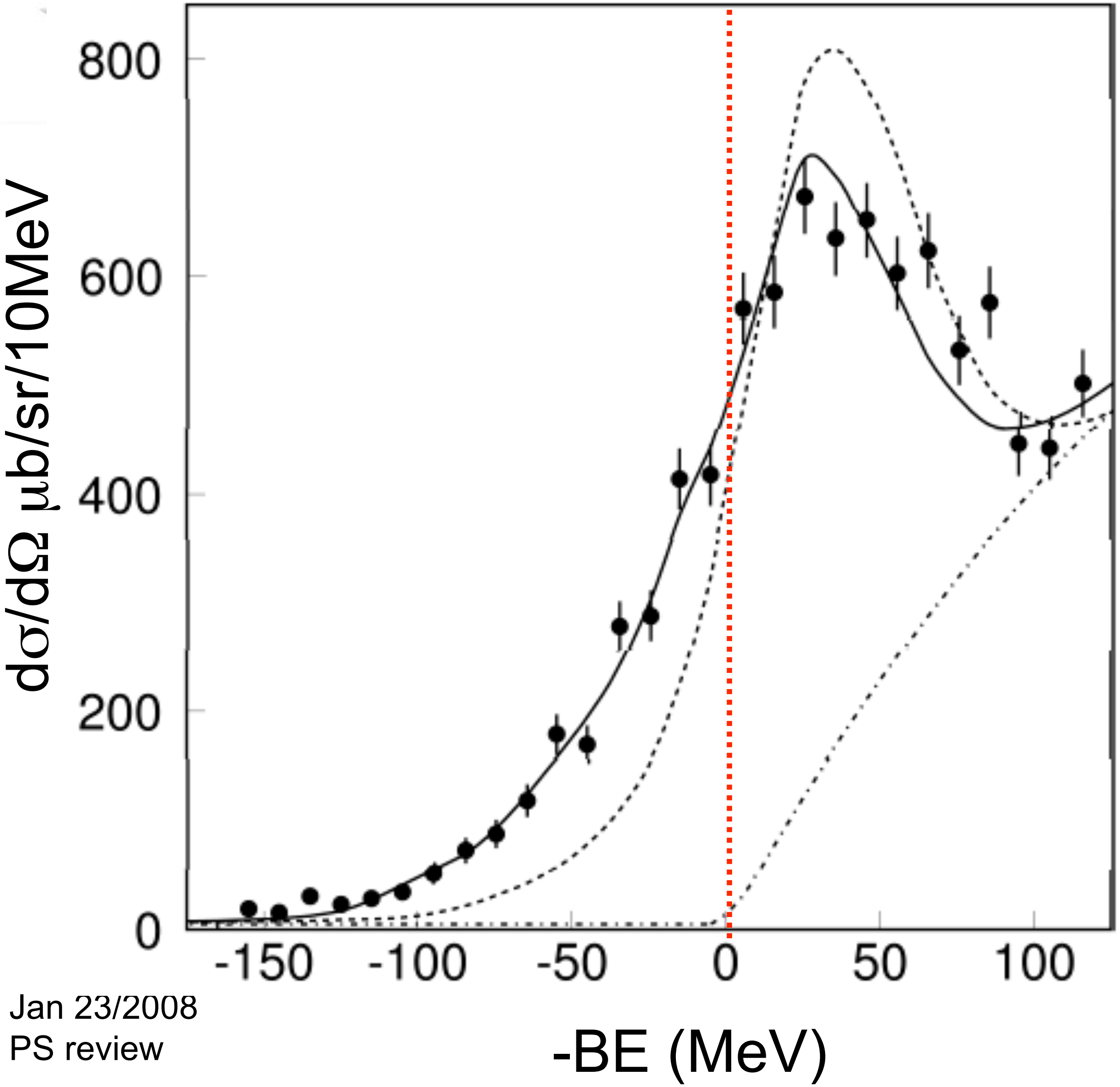


Solid line: best fit
Re(V)=-190MeV
Im(V)=-40 MeV

Dotted line: Chiral
Re(V)=-60 MeV
Im(V)=-60 MeV

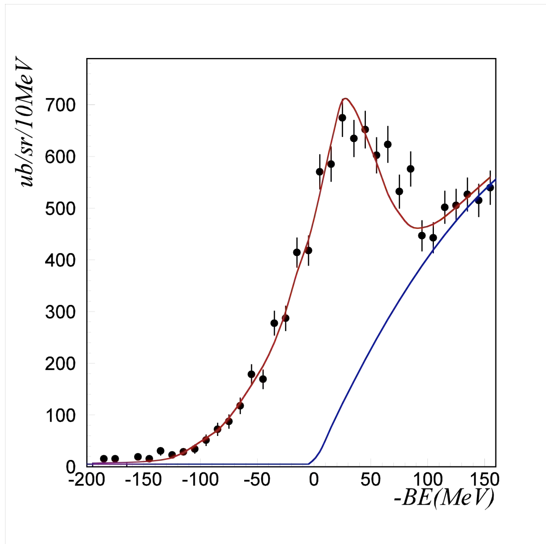


$^{12}C(K-, p)$



Solid line: best fit
Re(V)=-160MeV
Im(V)=-50 MeV

Dotted line: Chiral
Re(V)=-60 MeV
Im(V)=-60 MeV



Potential depth by comparison with calculated spectra

- Green function method
  - Consistent description of bound to unbound region with imaginary part (all final states)
  - J. Yamagata, S. Hirenzaki et al., nucl-th/0503039 and 0602021
  - T. Hayakawa (PhD)
- Quantitative comparison
  - Potential
    - Re(V)
    - Im(V(Eex))
  - Spectrum shape
  - Absolute cross section

Pion emission energy dependence

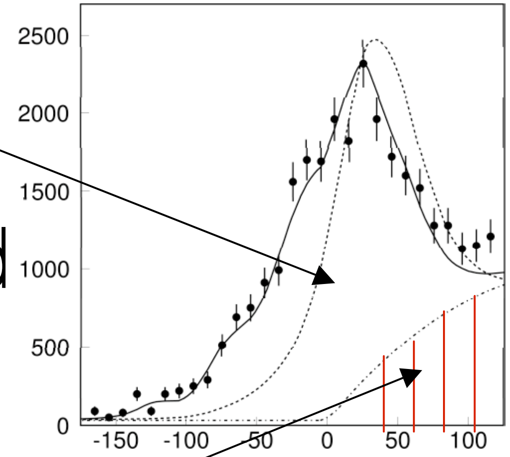
$$f^{\mathrm{MFG}}(E) = 0.8 f_1^{\mathrm{MFG}}(E) + 0.2 f_2^{\mathrm{MFG}}(E)$$

Two nucleon absorption

Effective nucleon number N_{eff}

- $N_{eff} = \sigma(^{12}C(K^-, N)) / \sigma(p(K^-, N))$
  - ~1.5

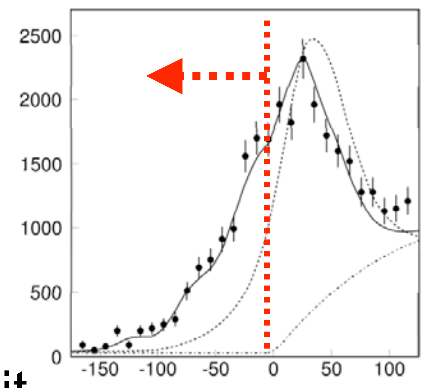
σ~20 mb/sr



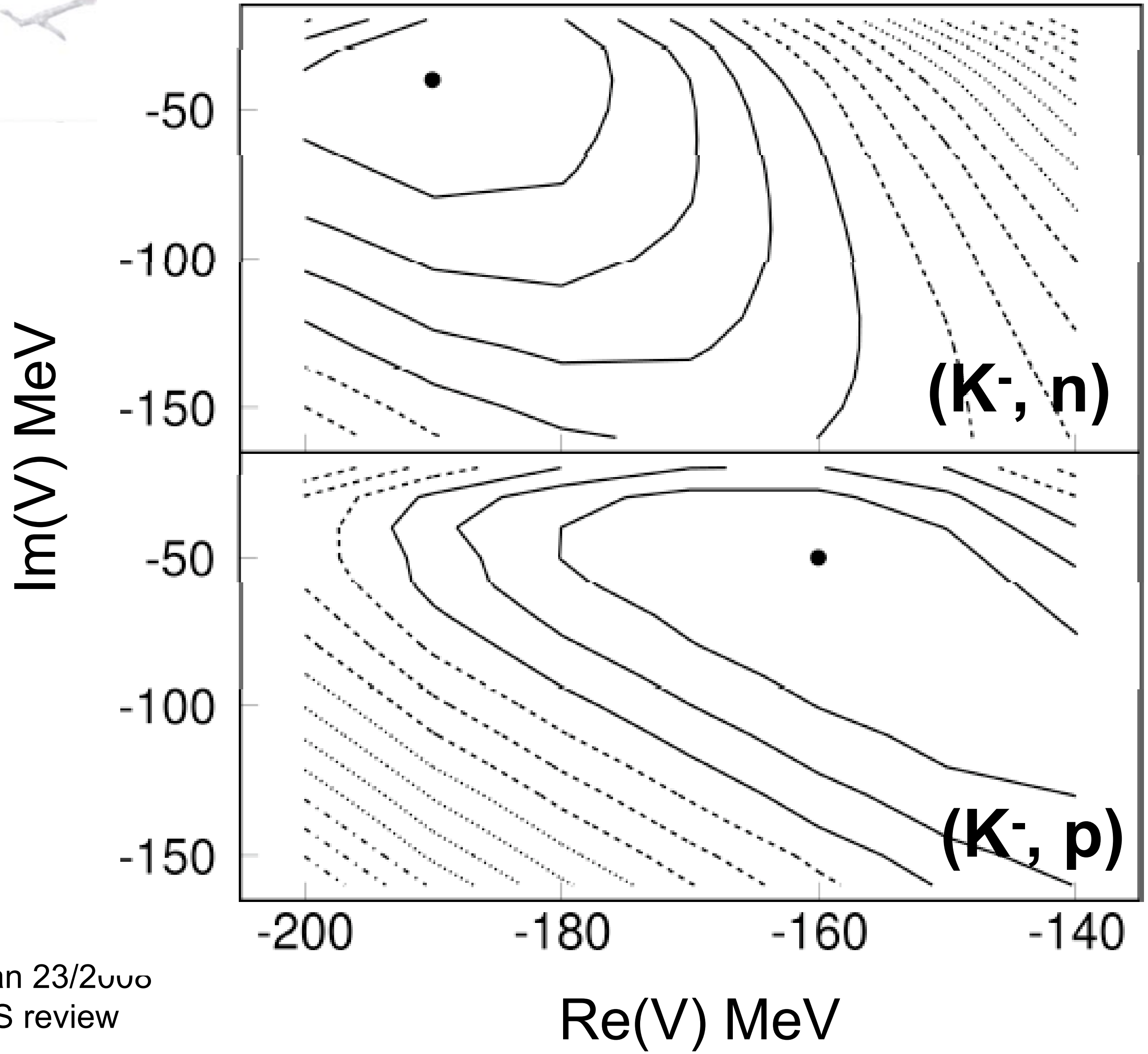
- calculation (40 mb for σ(KN) and
  - N_{eff}(Eik)~1.27
  - N_{eff}(Eik)~1.44 (with A-1 correction)
- Background process
  - Fitting of -BE=100~200 MeV region
    - quadratic function
  - multi-step?

We are seeing (K-, N) reaction not backgrounds

χ^2 contour plot



Fit
1. whole region
2. bound region



Re(V)=-190 MeV
Im(V)=-40 MeV

Re(V)=-160 MeV
Im(V)=-50 MeV

60 MeV ×

Isospin dependence of potential

attractive interaction is from I=0 KN system
Potential depth $\propto$ # of I=0 pairs in a Kaonic nucleus

$^{12}C(K^-, n)$ produce T=0, and T=1
$^{12}C(K^-, p)$ produce T=1 only

T: total isospin of a Kaonic nucleus

	# of I=0 pair			
T=0	3.5	$^{12}C(K^-, n)$, T=0, 1	3.0	if 190 MeV
T=1	2.5	$^{12}C(K-, p)$, T=1	2.5	then 160 MeV

Consistent with data

Conclusion

- Missing mass spectra of $^{12}C(K^-, N)$ indicate
  - ^{12}C (K^-, n): $V_r \sim 190$MeV $V_i \sim -40$ MeV,
  - ^{12}C (K^-, p): $V_r \sim 160$MeV $V_i \sim -50$ MeV,
- $V_r \sim 200$ MeV ⇨ Kaon condensation
- Isospin dependence may be consistent
- Published in PTP 118, 181 (2007)
- Study of ^{16}O(K-, N): paper preparation
  - A little deeper potential
- Future study at J-PARC

End of my slides

Backup slides

Decay Modes

- $\bar{K}N$ attraction ~ $\Lambda(1405)$ I=0, $J^{\pi}=1/2^{-}$
- $\Lambda(1405)$

$\pi^+ \Sigma^- \Rightarrow \pi^- n$ (1/3)

$\pi^- \Sigma^+ \Rightarrow \pi^+ n$ (1/6)

↳ $\pi^0 p$ (1/6)

} $\pi^+\pi^-$

π^-

$\pi^0 \Sigma^0 \Rightarrow \gamma\ \Lambda \Rightarrow \pi^- p$ (2/9)

↳ $\pi^0 n$ (1/9)

Multi~1.5

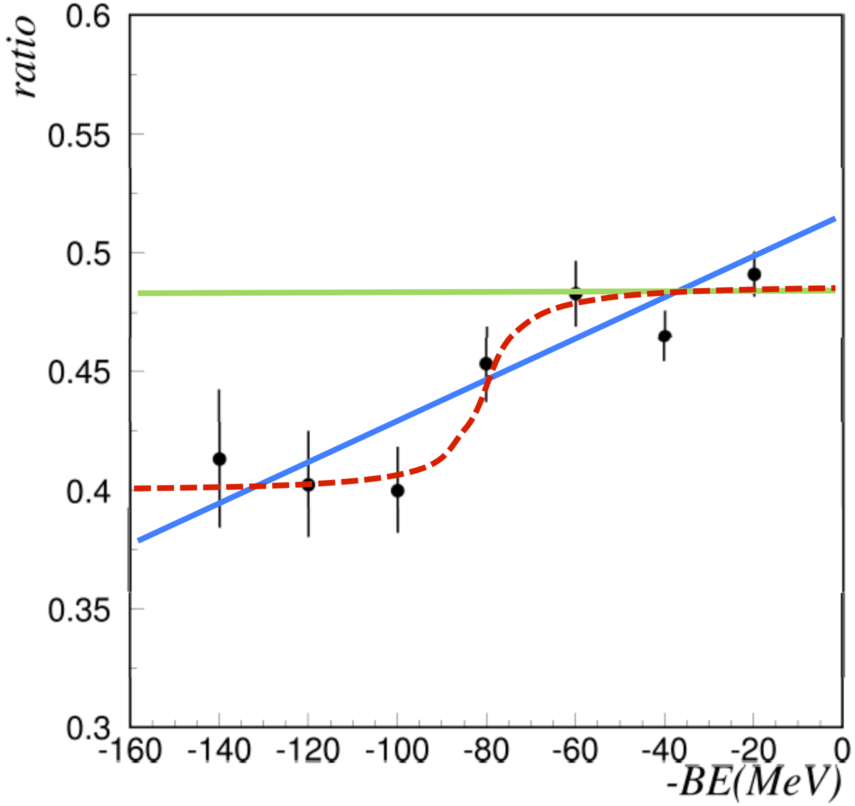
- Below π threshold

$\Lambda(1405)(p,n) \rightarrow \Sigma(p,n)$

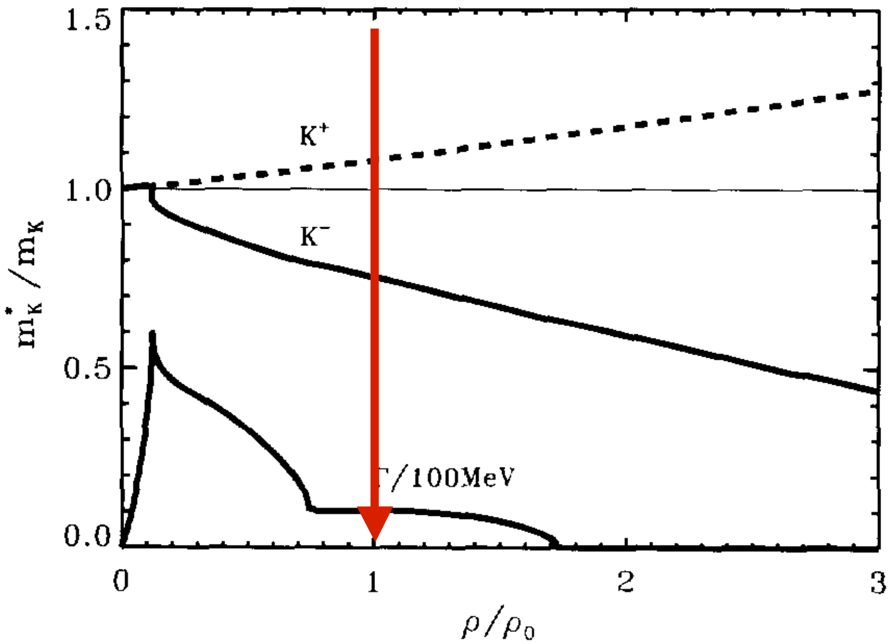
$\Sigma \rightarrow \pi^+\pi^-(p,n)$

Multi~1.5

(mult.>1)/inclusive

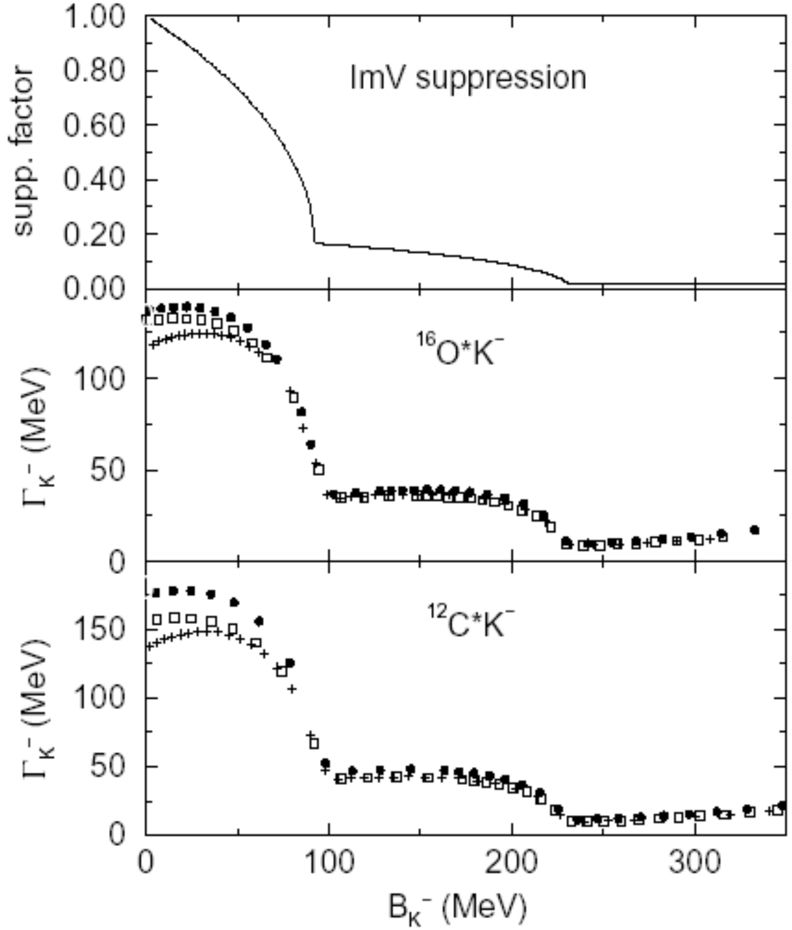


Width (theory)



Waas, Weise, PLB379(96)34

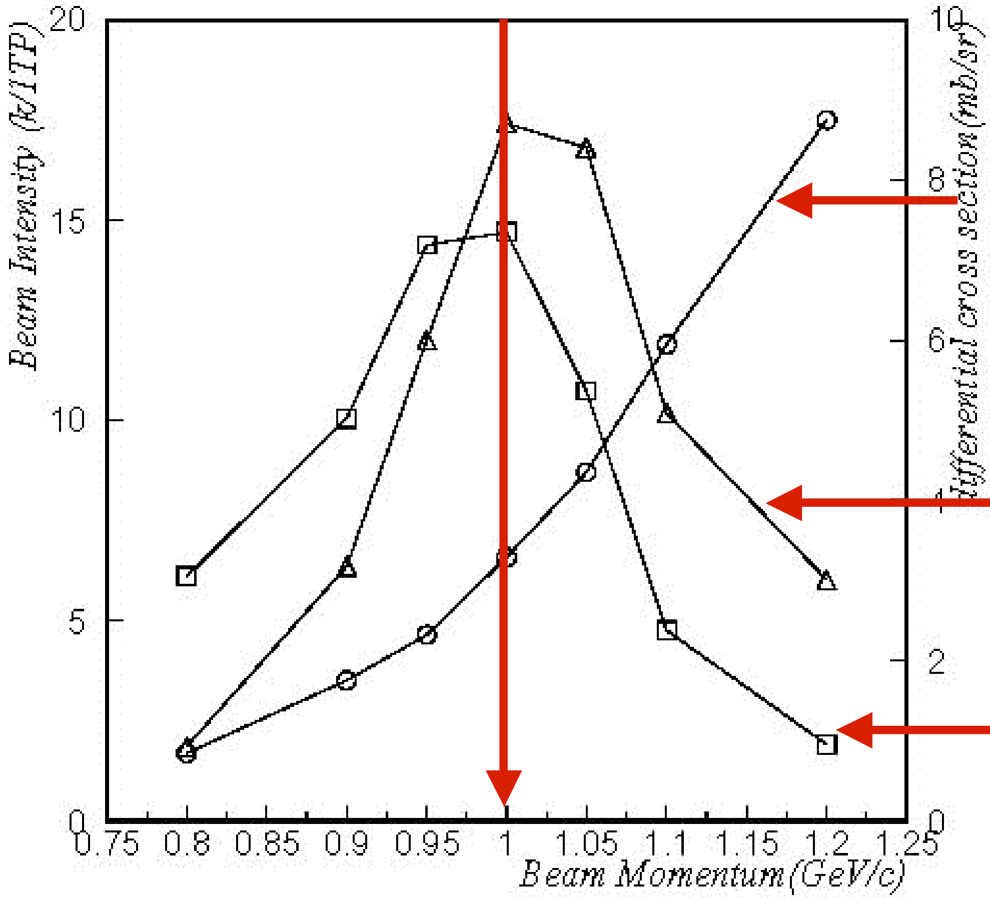
Γ could be ~ 10 MeV

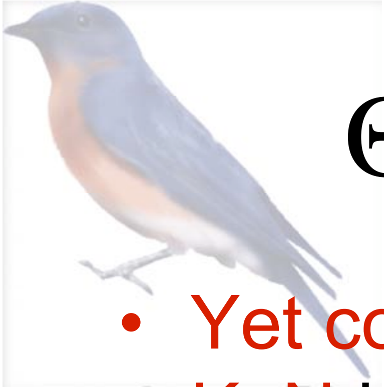


J. Mare¡s, E. Friedman, A. Gal
nucl-th/0407063 **Γ ~ 30 MeV**

K^- momentum

p_K=1.0 GeV/c





Θ^+: Another explanation

- Yet consistent theoretical models are needed
- $K\pi N$ bound state
  - arXiv:hep-ex/0312003 (T.K and T.Sato and others)
- Mass ~1540 MeV
  - M($K\pi N$) ~1570 MeV (30 MeV bound)
  - 10 MeV/particle (usual)
- Spin parity ½+ (original prediction)
  - K π N system (s-wave) ½+
- This conjecture explains all Θ^+ properties particularly
  - Narrow width
  - Seen in Low Q, unseen in High Q
- But

Θ^+ as a KπN bound state

- Known two Body interaction
  - πN: weakly attractive
  - KN: weakly repulsive
  - Kπ weakly attractive

→ **No bound state**

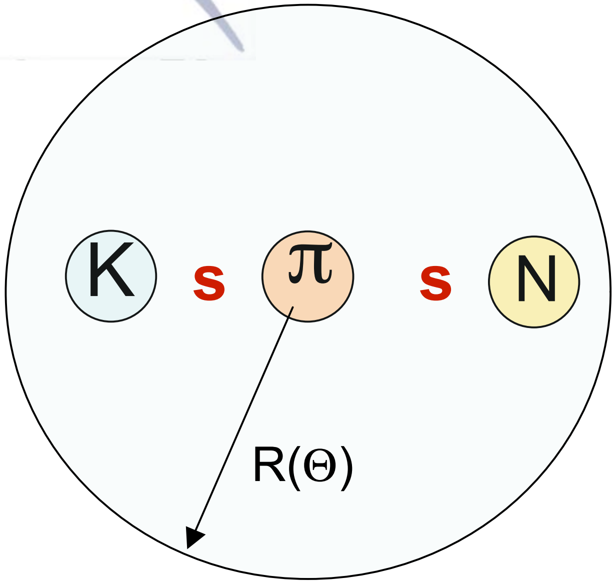
TABLE I: Spin, parity and isospin of two particle subsystems.

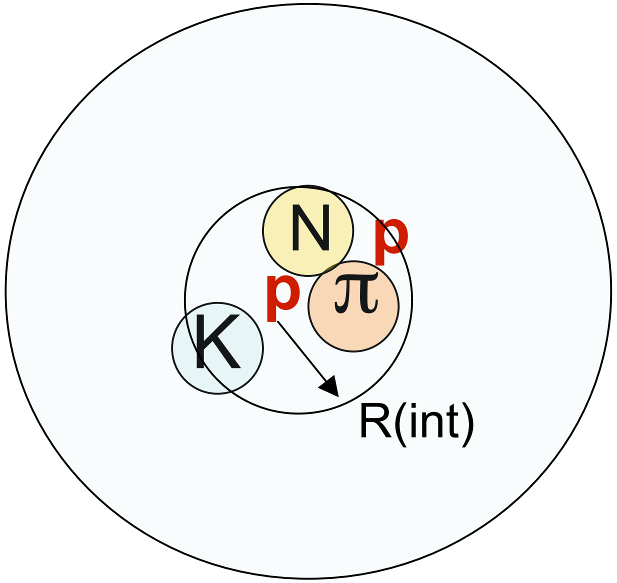
	Θ^+ $(K\pi N)$	πN	KN	$K\pi$
$J\pi$	$1/2^+$	$1/2^-$	$1/2^-$	0^+
I	0	1/2	1	1/2

- Kπ int. may have ambiguity
  - So strong to make Kπ bound state

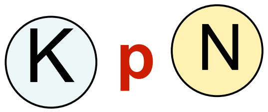
X (new scaler particle)

Width of Θ^+ in $K\pi N$ conjecture





Decay



s to p wave transition

in a interaction length

$$(R(int)/R(\Theta))^6$$

Radius of Θ⁺ (and X)

Asymptotic wave function (π)

$$\phi_{out}(r) = N\frac{1}{r}exp\left(-\frac{\sqrt{2\mu E_B}}{\hbar c}r\right)$$

$$< r^2 >\sim \int r^2\phi^2_{out}(r)4\pi r^2 dr = \left(\frac{(\hbar c)^2}{4\mu E_B}\right)$$

E_B=30 MeV   15 MeV

r~ 2 fm   r~ 3 fm

Extended object

Only in low q transfer reaction

Width ~ 1 MeV ~300 $(1/3)^6$

New hypothetical particle X: $K\pi$ bound state

- $K\pi$ interaction may be strong enough to make a bound state: New particle X
- $0^- + 0^- \rightarrow 0^+$ scaler particle
- Binding energy less than 30 MeV
  – If deeper than 30 MeV Θ^+ decays into N and X
  – Probably a few MeV bound
  – Very extended object

X (Why missed)

- Lowest order decay mode **X ! K$\gamma\gamma$**
  - No strong decay $M_X < M_K + M_\pi$
  - No $X \rightarrow K \gamma$ decay
    - ($0^+ \rightarrow 0^- + 1^-$ L non cons.)
  - No $X \rightarrow K e^+e^-$
    - (vec. curr. vs axial charge ($0^+ \rightarrow 0^-$)
- No such decay mode is listed in PDG
- No experimental searches ever made (Probably)

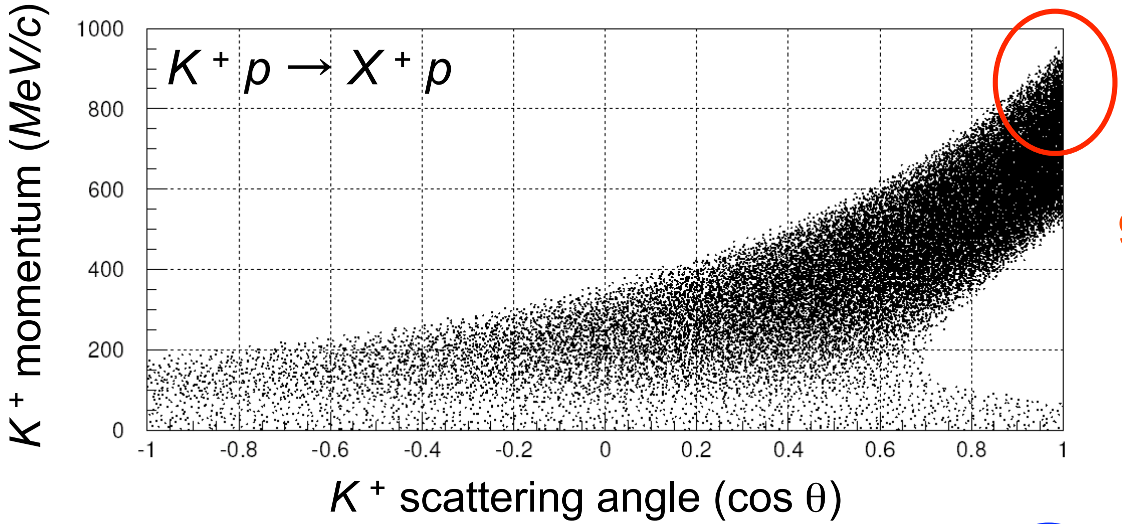
- If it exists.
  - Hard to believe but possibility is there.

How to measure (KEK-PS-E548)

- $p(K^{-+}, X^{-+})p$, X! K γ γ
  - Measure Kaon momentum in coincidence with γ rays
- BG process: $p(K^{-+}, K^{-+} \pi^0)$, π^0 ! γ γ
- X particle gives highest P_K
- Measure invariant mass of K and two γ's
  - Dedicated detector system
- Study of $K\pi$ final state interaction

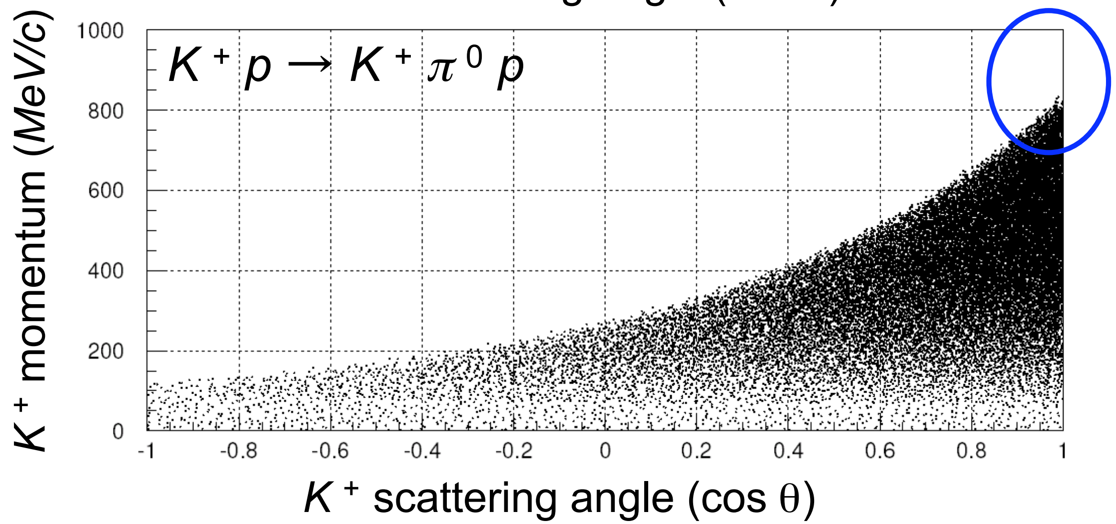
K^+ momentum (P_K=1 GeV/c)

Signal



Max
950 *MeV/c*

Background



Max
830 *MeV/c*

Experimental condition (E548)

- K^+ beam from K2 beam line at KEK-PS
  - P_K=1.2 GeV/c
  - 50k for 3×10^{12}ppp
- Target: 20cm thick H_2O and 20 cm thick CH_2
- Trigger
  - (K^+, K^+) X NaI(>5 MeV)
  - Rate ~ 500 ev/spill
- KURAMA spectrometer
- NaI
- Data taking ~10 shifts
- Analysis almost done
- Current results are subtle.