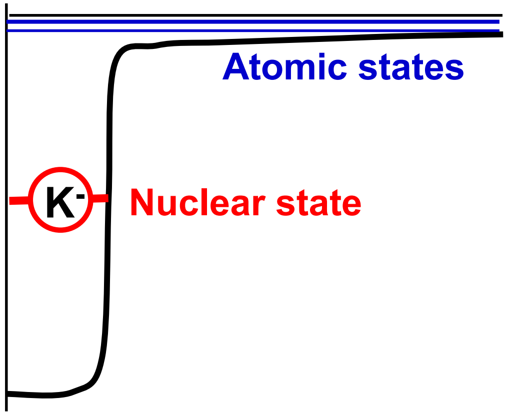
$\bar{K}$-Nucleus Bound Systems

A new paradigm in Nuclear Physics



Yoshinori AKAISHI
Akinobu DOTE
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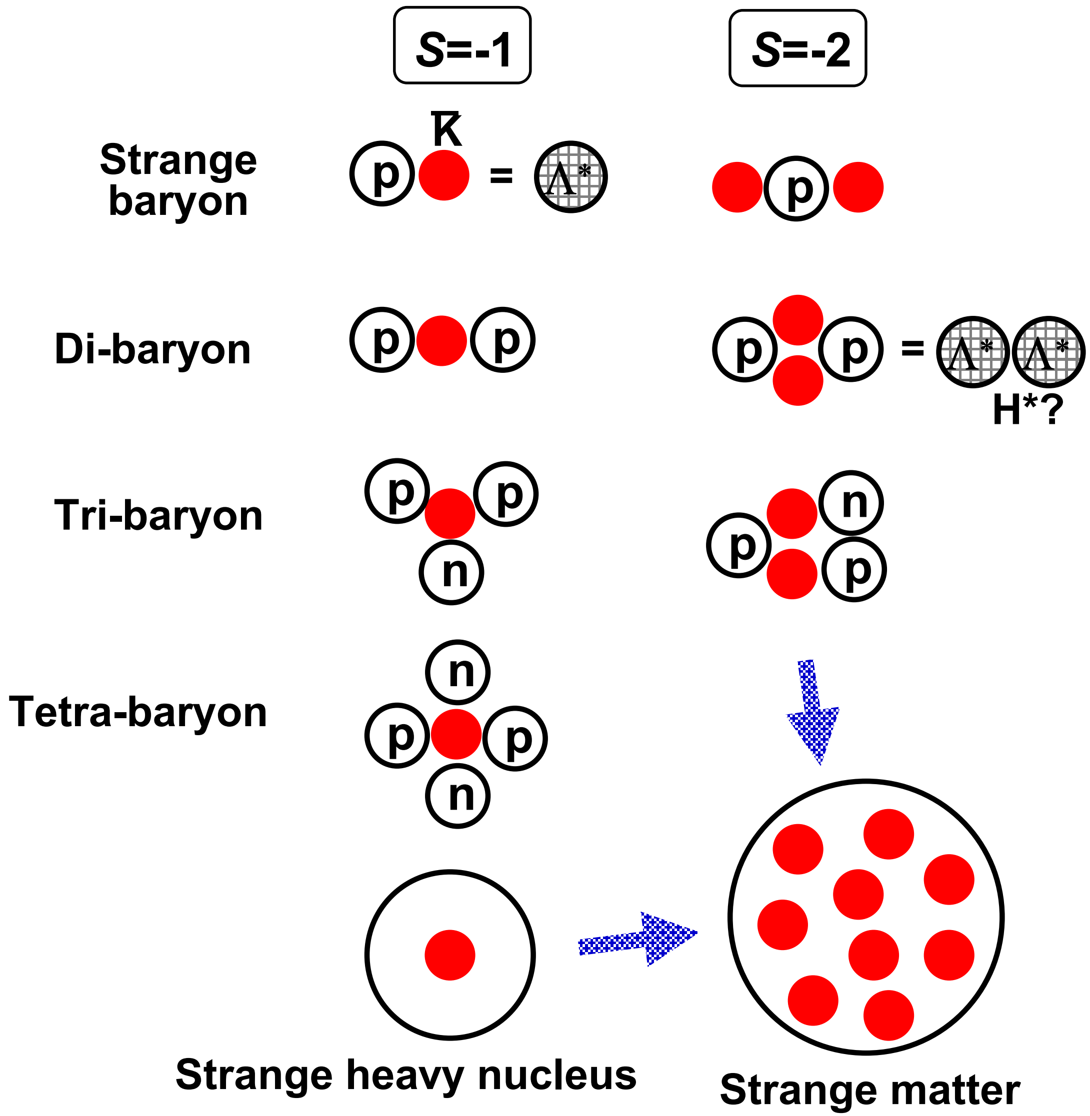
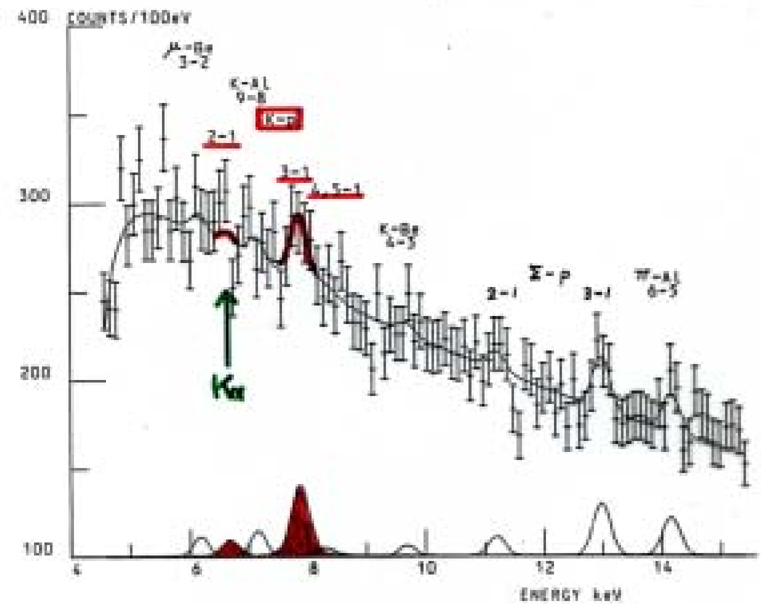
Institute of Particle and Nuclear Studies, KEK

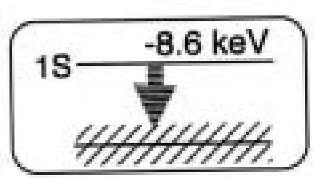
Few-Body $\bar{K}N$ Systems



Kaonic Hydrogen X-Rays

P.M. Bird et al., Nucl. Phys. A404 (1983) 482.





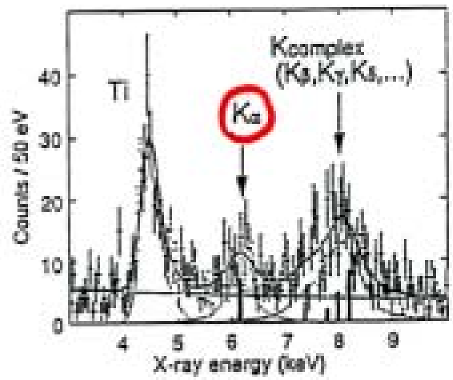
Downward shift

$(-323 \pm 63 \pm 11) + i(407 \pm 208 \pm 100)$ eV

DEAR @ DAΦNE

K^-p atom

M. Iwasaki et al., Phys. Rev. Lett. **78** (1997) 3067.
T.M. Ito et al., Phys. Rev. C **58** (1998) 2366.



$\varepsilon + \frac{i}{2}\Gamma = 2\alpha^3 \mu a_{K^-p}$

$a_{K^-p} = (-0.78 \pm 0.15 \pm 0.03) + i(0.49 \pm 0.25 \pm 0.12)$ fm

$a_{K^-p} = (-0.66 \pm 0.05) + i(0.64 \pm 0.04)$ fm   Martin

$a_{K^-p} = \frac{1}{2}a^{T=0} + \frac{1}{2}a^{T=1}$

$\bar{K}N$ scattering length

$a^{T=0} = (-1.70 \pm 0.07) + i(0.68 \pm 0.04)$ fm

$a^{T=1} = (\ \ 0.37 \pm 0.09) + i(0.60 \pm 0.07)$ fm

A.D. Martin,
Nucl. Phys. B179 (81) 33.

$a_0 = \frac{1}{4}a^{T=0} + \frac{3}{4}a^{T=1}$
$= -0.15 + i\,0.62$ fm

$\bar{K}$-nucleus optical potential

$$U^{opt}(r_K) = -\frac{2\pi\hbar^2}{\mu_K}\left(1 + \frac{m_K}{M_N}\right) a\,\rho(r_K)$$

$\Rightarrow +19 - i\,80$ MeV at $r_K = 0$

Repulsive!

$\bar{K}N$ interaction

$$V^{T}_{\bar{K}N}(r) = V^{T}_{D}\exp(-(r/0.66)^2)$$

$$V^{T}_{\bar{K}N,\pi\Sigma}(r) = V^{T}_{C_1}\exp(-(r/0.66)^2)$$

$$V^{T}_{\bar{K}N,\pi\Lambda}(r) = V^{T}_{C_2}\exp(-(r/0.66)^2)$$

$$V^{T}_{\pi\Sigma}(r) = V^{T}_{\pi\Lambda} = 0$$

$V^{T=0}_{D} =$ -436 MeV

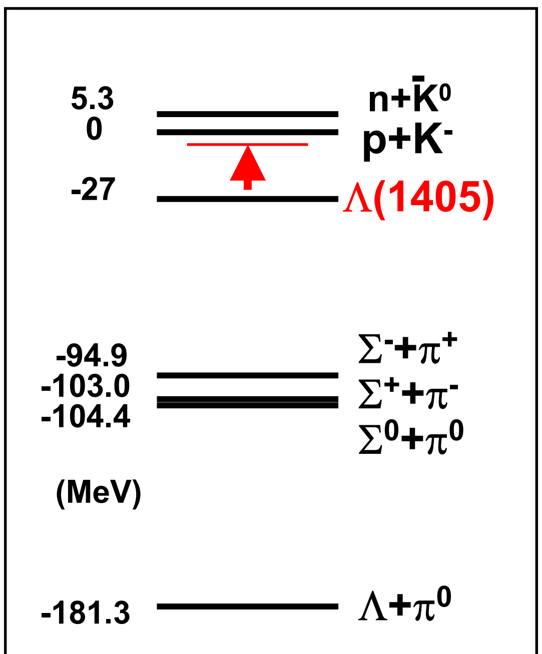
$V^{T=0}_{C_1} =$ -412 MeV

$V^{T=0}_{C_2} =$ none

$V^{T=1}_{D} =$ -62 MeV

$V^{T=1}_{C_1} =$ -285 MeV

$V^{T=1}_{C_2} =$ -285 MeV



Martin (1981)

$$a^{T=0} = (-1.70 \pm 0.07) + i(0.68 \pm 0.04)\ \text{fm}$$

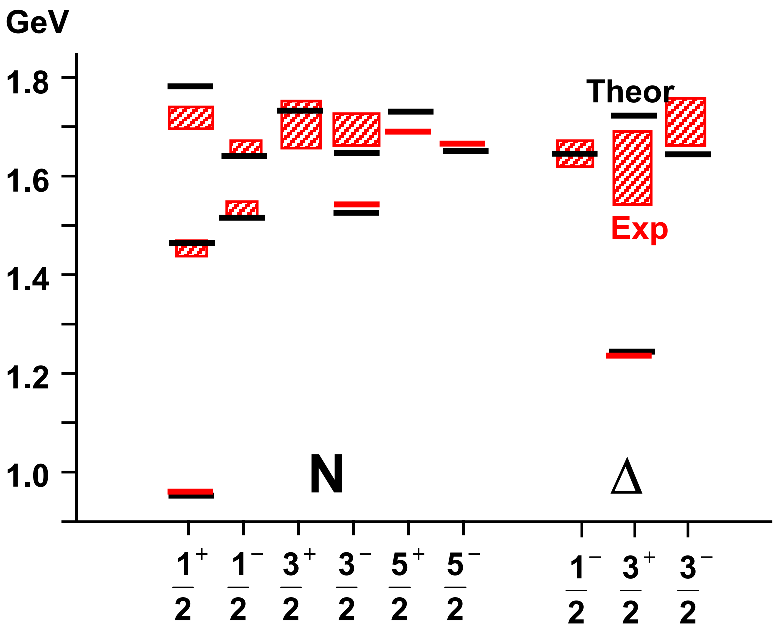
$$a^{T=1} = 0.37 + i\,0.60\ \text{fm}$$

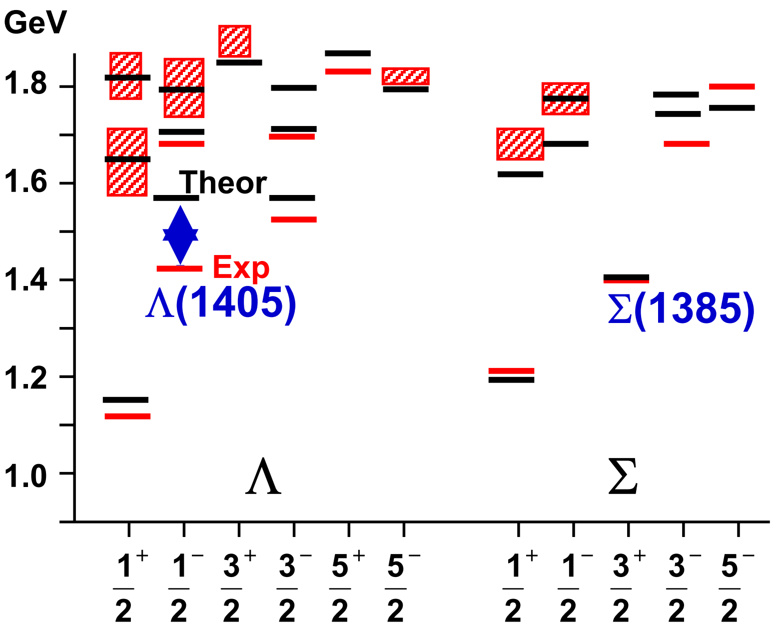
KpX Iwasaki et al. (1997)

$$a_{K^-p} = (-0.78 \pm 0.15 \pm 0.03) + i(0.49 \pm 0.25 \pm 0.12)\ \text{fm}$$

A Chiral Constituent-Quark Model

L.Ya. Glozman, W. Plessas, K. Varga & R.F. Wagenbrunn,
Phys. Rev. D 58 (1998) 094030.





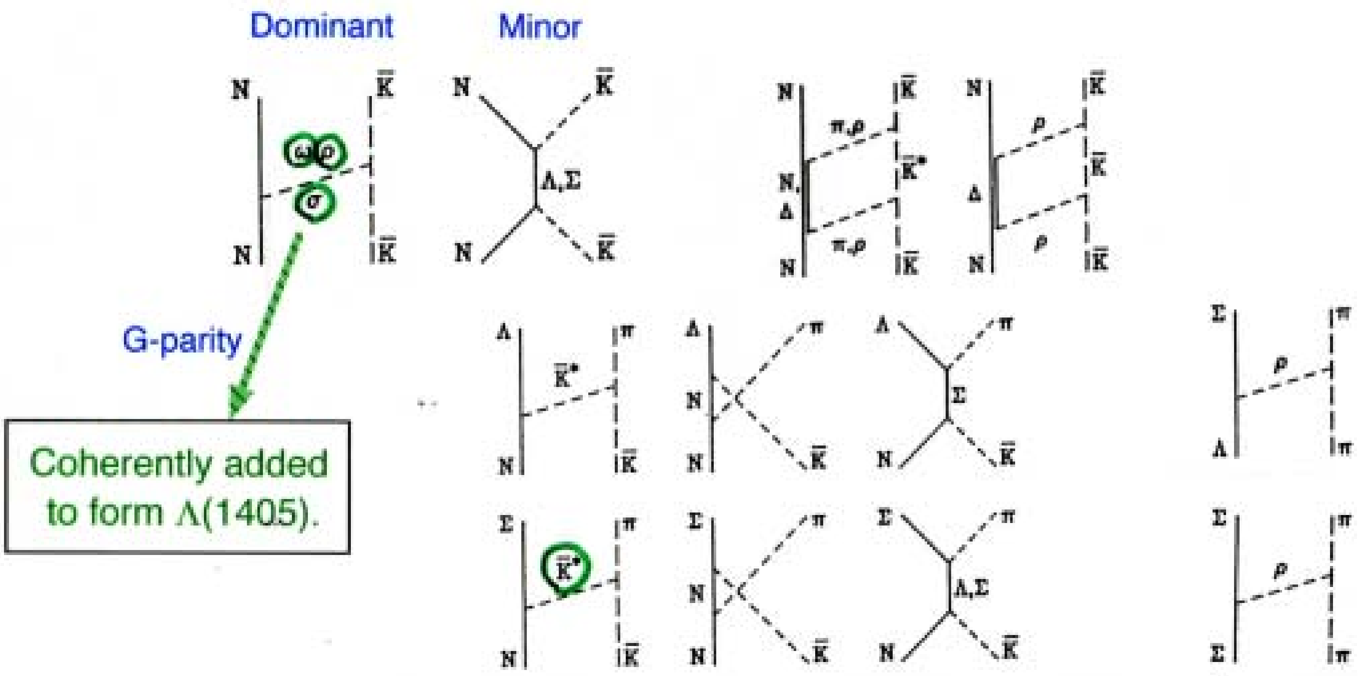
Lattice QCD quenched to 3Q
H. Suganuma et al.

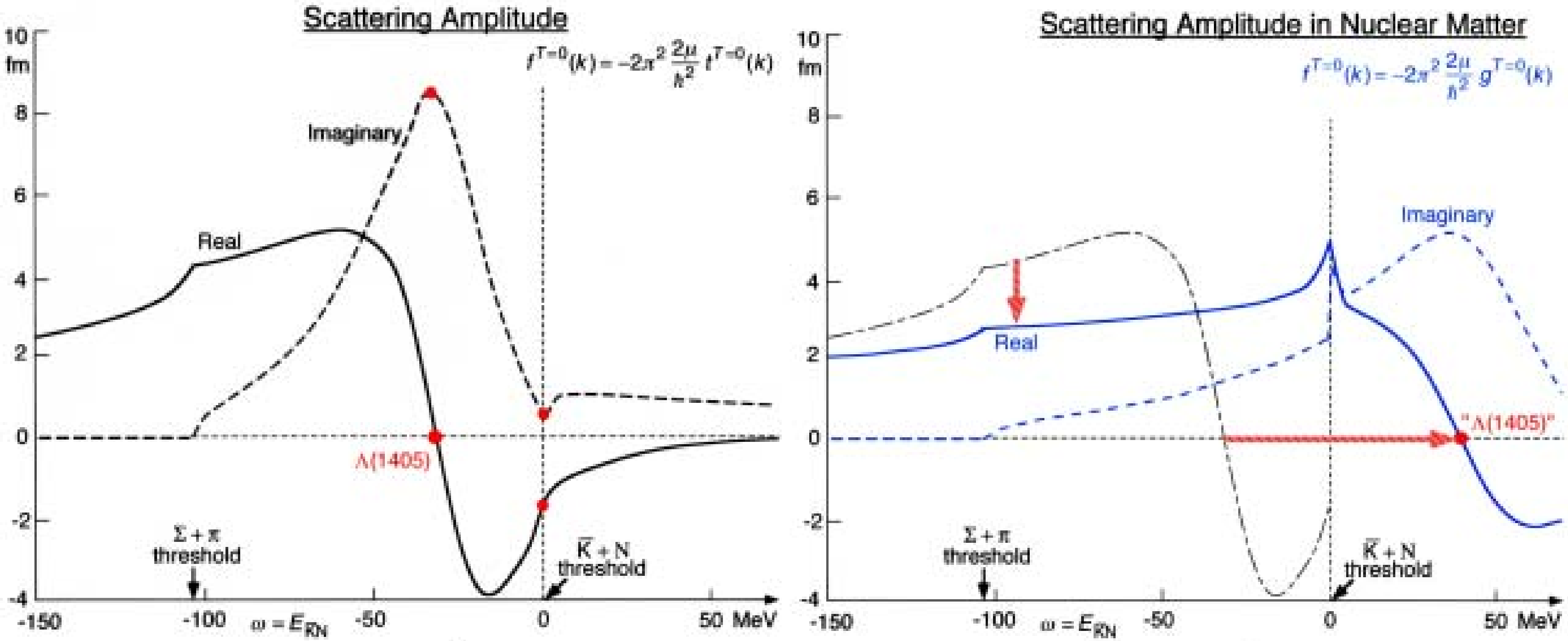
$M(3Q, 1/2^-) \approx 1.7$ GeV

Jülich $\bar{K}N$ Quasi-potential

A. Müller-Groeling, K. Holinde & J. Speth, Nucl. Phys. **A513** (1990) 557.

$p_{\bar{K}}^{\text{lab.}} = 60 \sim 300\ \text{MeV}/c$





Scattering Amplitude
10 fm
8
6
4
2
0
-2
-4
$f^{T=0}(k) = -2\pi^2 \frac{2\mu}{\hbar^2} t^{T=0}(k)$
Imaginary
Real
Λ(1405)
Σ + π threshold
$\bar{K}$ + N threshold
-150
-100
$\omega = E_{\bar{K}N}$
-50
0
50 MeV
Scattering Amplitude in Nuclear Matter
$f^{T=0}(k) = -2\pi^2 \frac{2\mu}{\hbar^2} g^{T=0}(k)$
Imaginary
Real
"Λ(1405)"

Optical potential

$$U^{\text{opt}}(r) = \frac{V_0 + iW_0}{1 + \exp\{(r - R_0)/a_s\}}, \quad V_0 + iW_0 = \frac{1}{4}(g^{T=0} + 3g^{T=1})\rho_0$$

K⁻ atom

No Pauli exclusion

$$V_0 + iW_0 = +37 - i78\ \text{MeV}$$ for *t*-matrix: $$t = v + v\frac{1}{e_0}t$$

$$V_0 + iW_0 = -134 - i65\ \text{MeV}$$ for *g*-matrix: $$g = v + v\frac{Q}{e}g$$

$\bar{K}$ nucleus

$$V_0 + iW_0 = -118 - i11\ \text{MeV}$$ for *E*= -110 MeV

J. Schaffner-Bielich, V. Koch & M. Effenberger, Nucl. Phys. A669 (2000) 153.

A. Ramos & E. Oset, Nucl. Phys. A671 (2000) 481.

A. Cieply, E Friedman, A. Gal & J. Mares, Nucl. Phys. A696 (2001) 173.

Shallow optical potential $V_0+iW_0= -50 - i\,60$ MeV

Deep optical potential $V_0+iW_0= -120 - i10$ MeV

Y. Akaishi & T. Yamazaki, Phys. Rev. C65 (2002) 044005.

N. Kaiser, P.B. Siegel & W. Weise, Nucl. Phys. A594 (1995) 325.

Chiral SU(3) Dynamics

N. Kaiser, P.B. Siegel and W. Weise, Nucl. Phys. **A594** (1995) 325.

T. Waas , N. Kaiser and W. Weise, Phys. Lett. **B365** (1995) 12.

Lagrangian

SU(3) baryon field

$$L_{int}^{(1)} = \frac{i}{8f^2} \mathrm{tr}\left(\bar{B}[[\phi, \partial_0 \phi], B]\right), \qquad L^{(2)}$$

SU(3) meson field

Pseudo-potential

$$v_{ij}(k,k') = \frac{C_{ij}}{f_\pi^2} \beta_i \beta_j g_i(k^2) g_j(k'^2)$$

$f_\pi = 94.5\,\mathrm{MeV}$

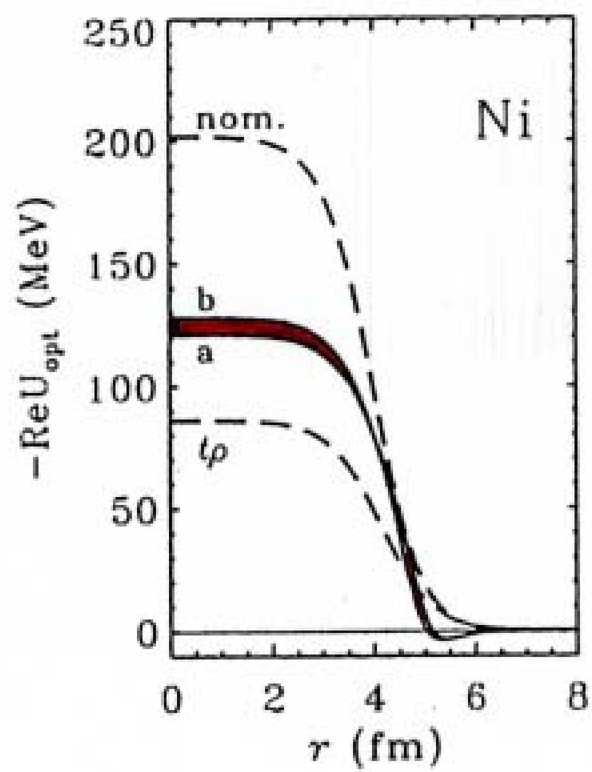
Pseudoscalar meson decay constant

$$g_j(k) = \frac{1}{1+\left(k/\alpha_j\right)^2} \qquad \beta_i = \sqrt{\frac{1}{2\omega_i}\frac{M_i}{E_i}}$$

Flux normalization

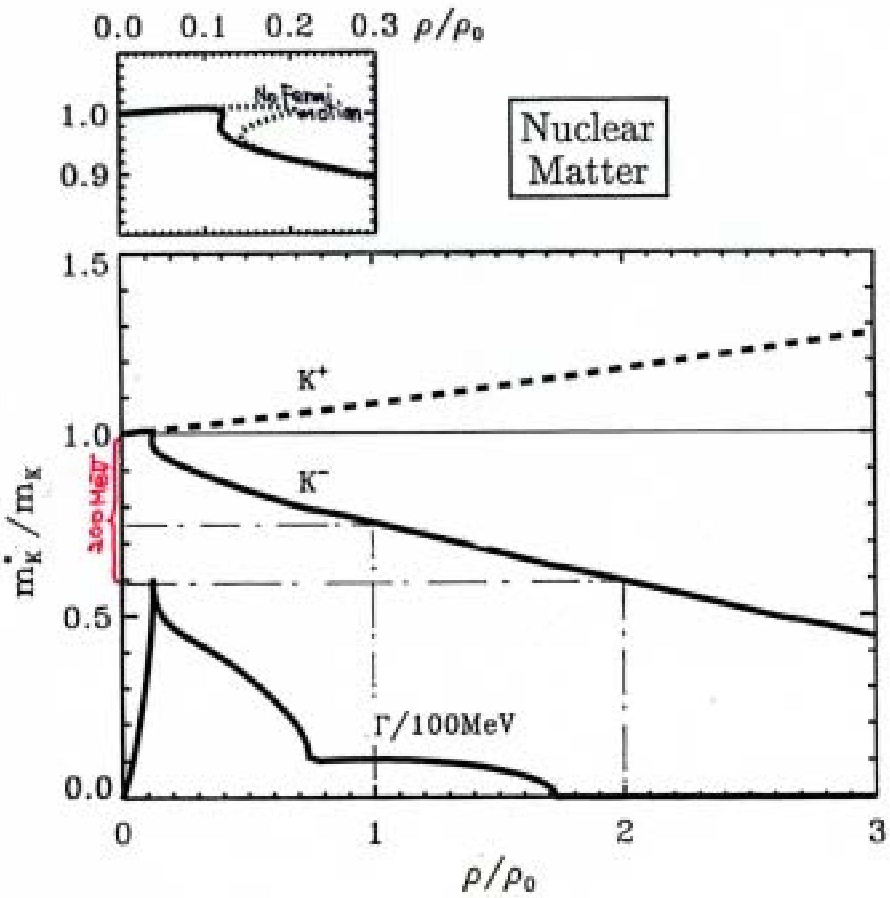
$\alpha_{K^-p} = \alpha_{\bar{K}^0 n} = 757.8\,\mathrm{MeV}, \quad \alpha_{\pi^0\Lambda} = 300\,\mathrm{MeV}$

$\alpha_{\pi^+\Sigma^-} = \alpha_{\pi^0\Sigma^0} = \alpha_{\pi^-\Sigma^+} = 448.1\,\mathrm{MeV}$



Chiral SU(3) Dynamics

T. Waas, N. Kaiser and W. Weise, Phys. Lett. **B379** (1996) 34.



Chiral symmetry

$$\begin{cases} T_0 = 3\frac{m_K}{2f^2} \\ T_1 = \frac{m_K}{2f^2} \end{cases} \text{ for } K^-N$$

$$3a_1 - a_0 = 2(b_0 + 3b_1) = 0$$

$$\begin{cases} T_{1/2} = 2\frac{m_\pi}{2f^2} \\ T_{3/2} = -\frac{m_\pi}{2f^2} \end{cases} \text{ for } \pi N$$

$$2a_{3/2} + a_{1/2} = 2b_0 = 0$$

isoscalar

$$2\omega U = -T\rho$$

$$T^{thr.}_{K^-p} = -T^{thr.}_{K^+p} = \frac{m_K}{f^2}$$

$$T^{thr.}_{K^-n} = -T^{thr.}_{K^+n} = \frac{m_K}{2f^2}$$

$$T^{thr.}_{\pi^-p} = -T^{thr.}_{\pi^-n} = \frac{m_\pi}{2f^2}$$

Tomozawa-Weinberg

Variational calculation of ppK$^-$

Hamiltonian

$$H = -\hbar^2\left[\sum_{(ij)}\frac{1}{2}\left(\frac{1}{M_i}+\frac{1}{M_j}\right)\left\{\frac{\partial^2}{\partial r_{ij}^2}+\frac{2}{r_{ij}}\frac{\partial}{\partial r_{ij}}\right\}+\sum_k\frac{1}{M_k}\cos\theta_{(ijk)}\frac{\partial}{\partial r_{ik}}\frac{\partial}{\partial r_{kj}}\right]$$

$$+V_{pp}(r_{12})+V_{pK}(r_{23})+V_{pK}(r_{31})$$

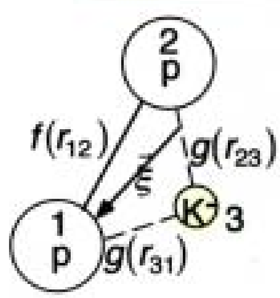
Variational wave function

$$\Psi = f(r_{12})g(r_{23})g(r_{31})$$

Euler equation

$$\delta\langle\Psi|H-\lambda|\Psi\rangle = 0$$

$$\left[-\frac{\hbar^2}{2\mu_{pK}}\frac{d^2}{dr^2}+V_{pK}(r)+U_{pK}^{av.}(r)\right]r\bar{g}(r)=\lambda\, r\bar{g}(r)$$



Two-body wave function in the system

$$\bar{g}(r)=\sqrt{S(r)}g(r)$$

Off-shell transformation

$$S(r)=\int d\vec{\xi}\,\left|g(r_{31})f(r_{12})\right|^2_{r_{23}=r}$$

Nuclear $\bar{K}NN$ bound states

$K^- \otimes nn$

$$2\left\{ v^{T=1} \right\}$$

***S* = 0**

T = 3/2 Unbound

$K^- \otimes d$

$$2\left\{ \frac{1}{4} v^{T=0} + \frac{3}{4} v^{T=1} \right\}$$

***S* = 1**

T = 1/2 Above the Λ^*+n threshold

$K^- \otimes pp$

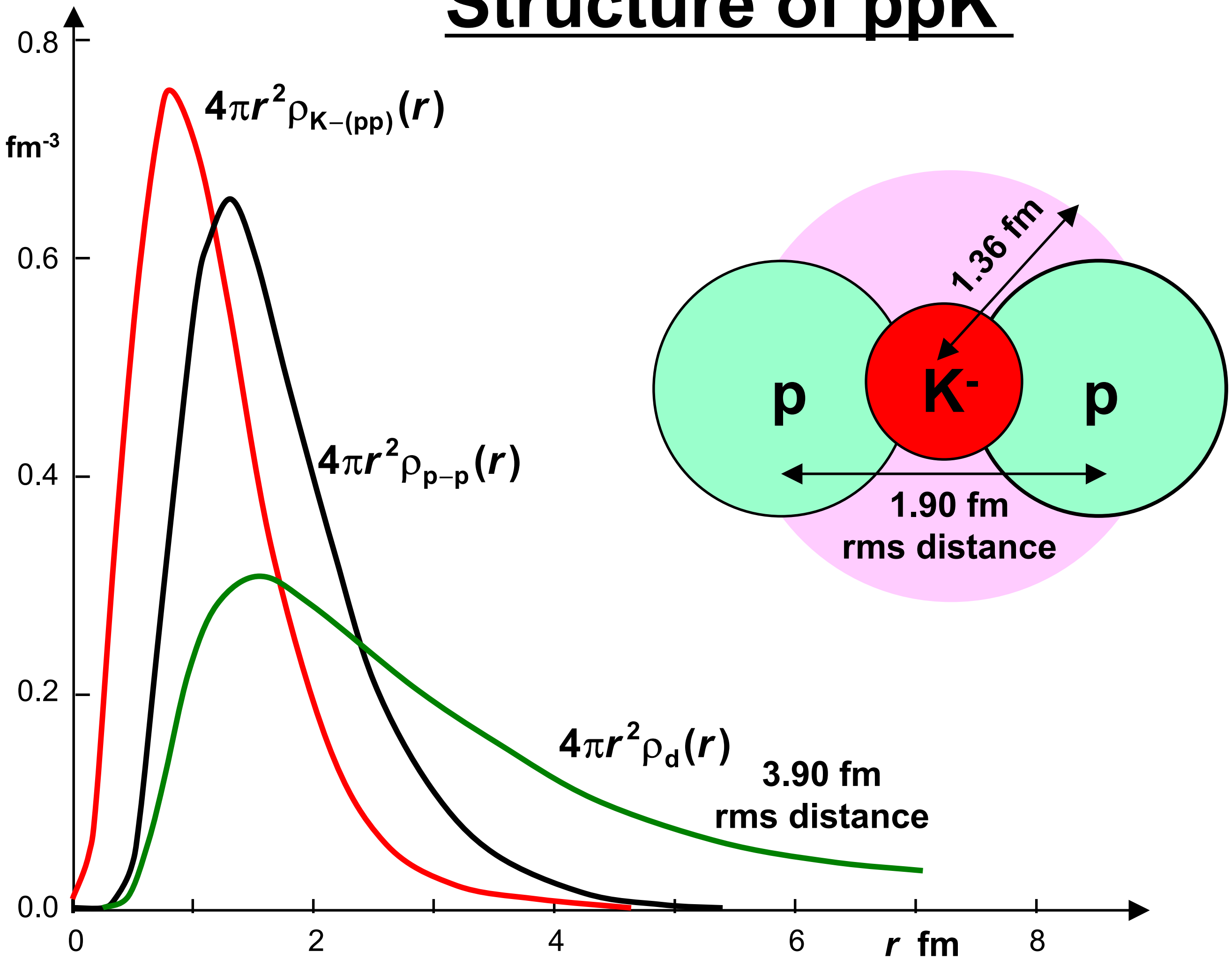
$$2\left\{ \frac{3}{4} v^{T=0} + \frac{1}{4} v^{T=1} \right\}$$

***S* = 0**

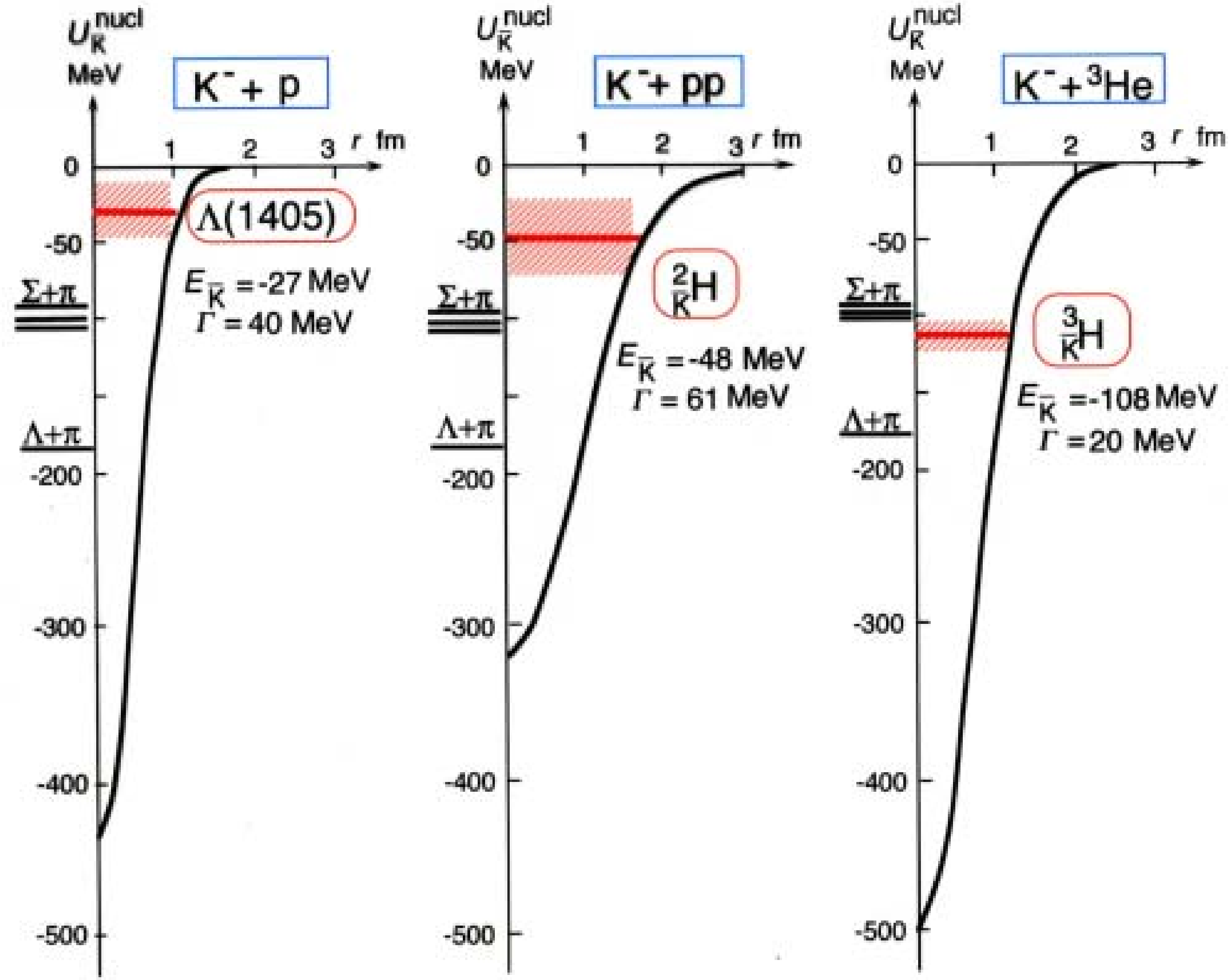
T = 1/2 **E = -48 MeV Γ = 61 MeV**

$V_{NN}(^1S_0) \to V_{NN}(^3S_1)$	-64 MeV	69 MeV
$M_N \to 1.5\, M_N$	-76 MeV	75 MeV
Both	-98 MeV	82 MeV

Structure of ppK$^-$



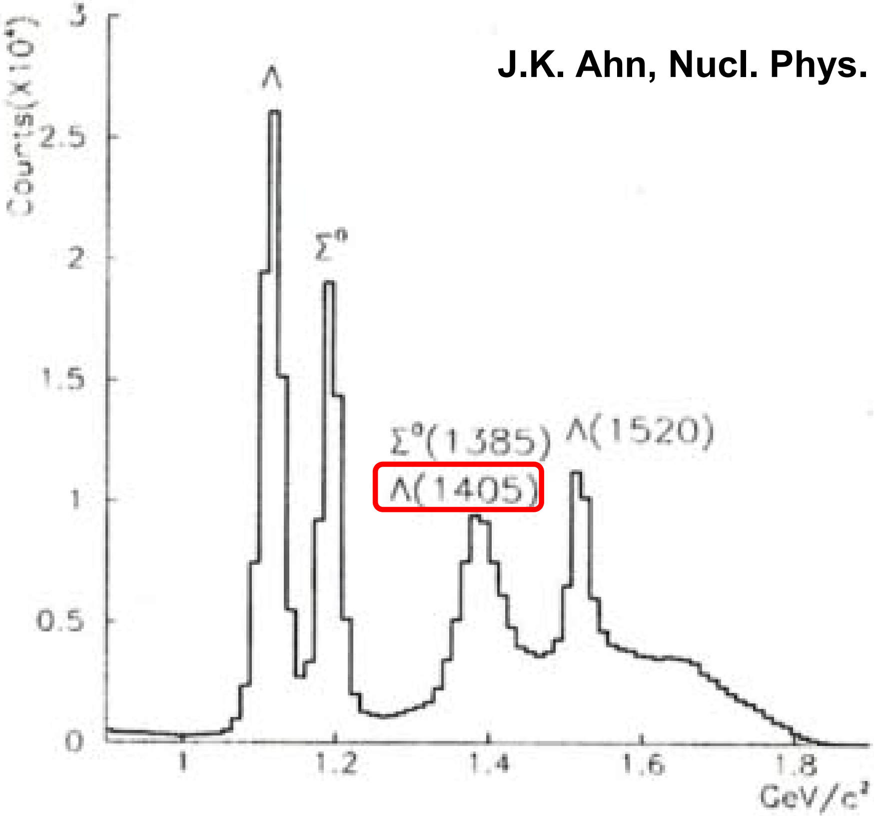
T. Yamazaki & Y. Akaishi, Phys. Lett. B535 (2002) 70.



K⁻+ p
Λ(1405)
E_K̄ = -27 MeV
Γ = 40 MeV
K⁻+ pp
²_K̄H
E_K̄ = -48 MeV
Γ = 61 MeV
K⁻+³He
³_K̄H
E_K̄ = -108 MeV
Γ = 20 MeV
Σ+π
Λ+π
U_K̄^nucl MeV
r fm

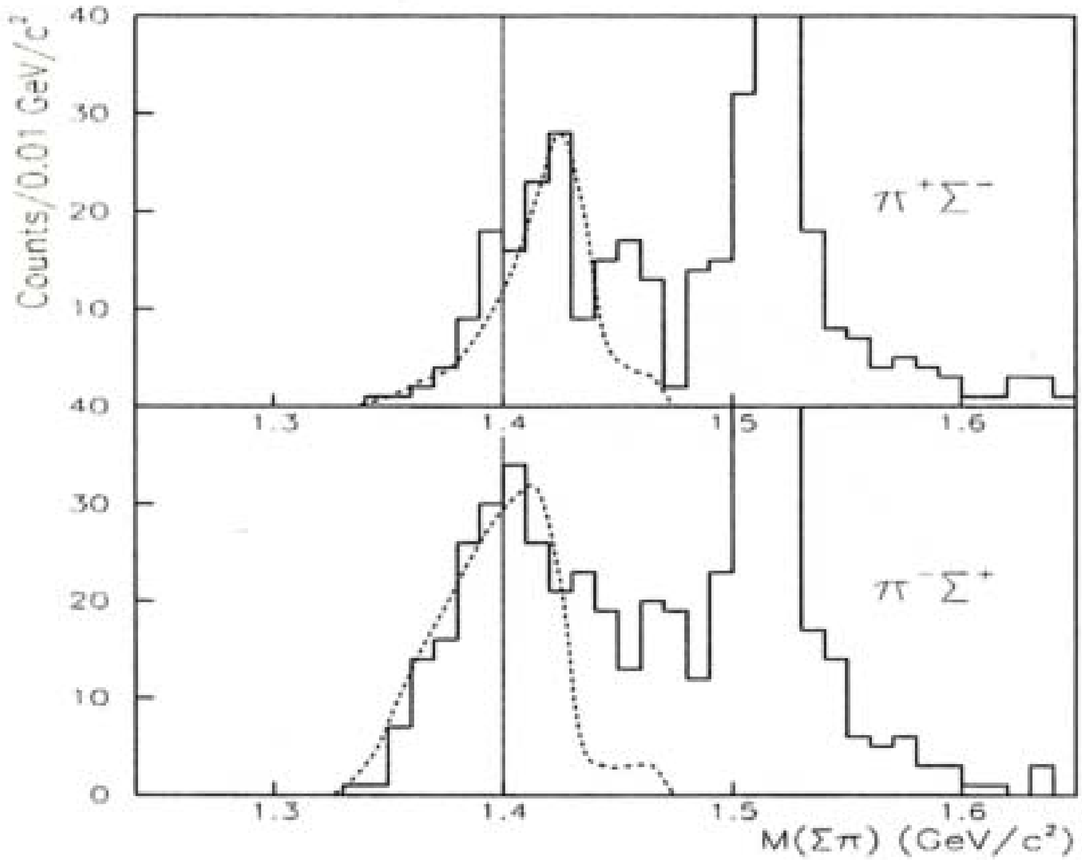
(γ, K^+) at SPring - 8

J.K. Ahn, Nucl. Phys. A721 (2003) 715c



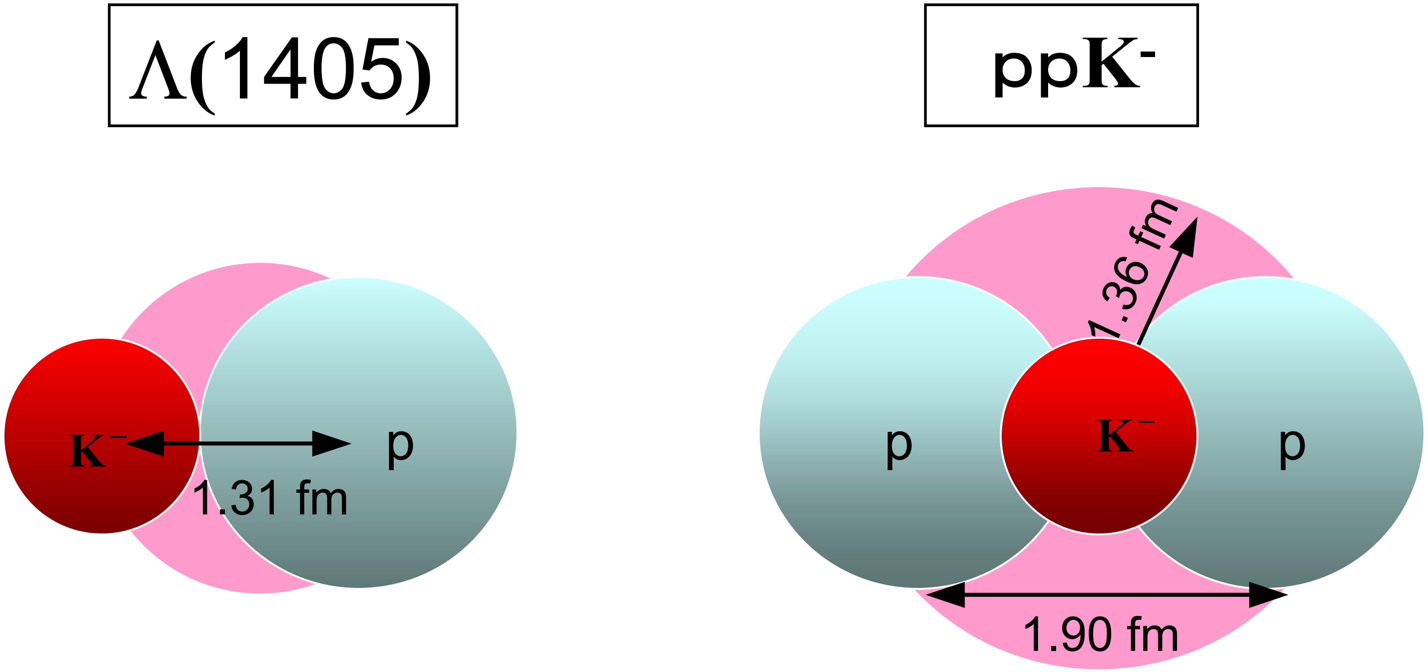
On the Λ(1405)

J.K. Ahn, Nucl. Phys. A721 (2003) 715c

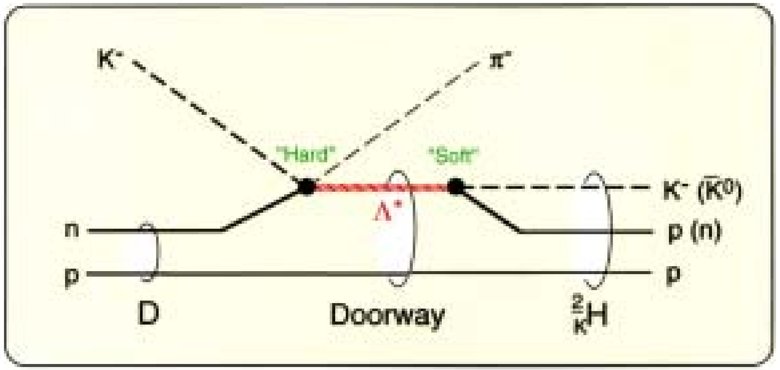


J.C. Nacher, E. Oset, H. Toki & A. Ramos, Phys. Lett. B455 (1999) 55.

M.F.M. Lutz & E.E. Kolomeitsev, Nucl. Phys. A700 (2002) 193.


Λ(1405)
ppK-
K−
p
1.31 fm
p
K−
p
1.36 fm
1.90 fm

$D(K^-, \pi^-)\,^{2}_{K}H$ reaction through $\Lambda(1405)$ as a doorway state



$$\left.\frac{d^2\sigma}{dE_\pi d\Omega_\pi}\right|_{\rm fwd} = \alpha(k_\pi)\left.\frac{d^2\sigma^{\rm elem}_{\Lambda^*}}{dE_\pi d\Omega^{(0)}_\pi}\right|_{\rm fwd} \frac{1}{(\tilde{E}-E_{\Lambda^* p})^2+\frac{1}{4}\Gamma^2_{\Lambda^*}}|V_{\rm soft}|^2$$

$$\times\left(-\frac{1}{\pi}\right){\rm Im}\left[\iint d\vec{r}\,d\vec{r}\,'\,\tilde{f}^*(\vec{r})\left\langle\vec{r}\left|\frac{1}{E-H_{K^-(pp)}+i\varepsilon}\right|\vec{r}\,'\right\rangle\tilde{f}(\vec{r}\,')\right]$$

$$\alpha(k_\pi) = \left\{1-\frac{E^{(0)}_\pi}{E^{(0)}_{\Lambda^*}}\frac{k_K-k^{(0)}_\pi}{k^{(0)}_\pi}\right\}\frac{k_\pi}{k^{(0)}_\pi}$$

$$\tilde{f}(\vec{r}) = \exp\left(i2\frac{M_p}{M_{\Lambda^*}+M_p}(\vec{k}_K-\vec{k}_\pi)\vec{r}\right)\frac{1}{\sqrt{\rho_{\Lambda^*}(0)}}2^3\,\psi_{(pp)}(2\vec{r})\,\psi_D(2\vec{r})$$

$$\tilde{E} = E_K - E_\pi + M_n c^2 - M_{\Lambda^*}c^2 - B(n) - \frac{\hbar^2}{2(M_{\Lambda^*}+M_p)}(k_K-k_\pi)^2$$

$$E = E_K - E_\pi - m_K c^2 - \frac{\hbar^2}{2(m_K+M_D)}(k_K-k_\pi)^2$$

$$V_{\rm soft} \equiv \langle\Lambda^*|V_{\bar{K}N}|\Lambda^*\rangle = -138 - i20\ {\rm MeV}, \qquad \rho_{\Lambda^*}(0) = 0.45\ {\rm fm}^{-3}$$

Production of Λ(1405) in bubble chamber

$K^- + p \to \Lambda(1405) + (\pi\pi)^0$ $p_K = 1.15$ GeV/c

M.H. Alston, L.W. Alvarez, P. Eberhard, M.L. Good,
W. Graziano, H.K. Ticho, & S.G. Wojcicki,
Phys. Rev. Lett. **6** (1961) 698.

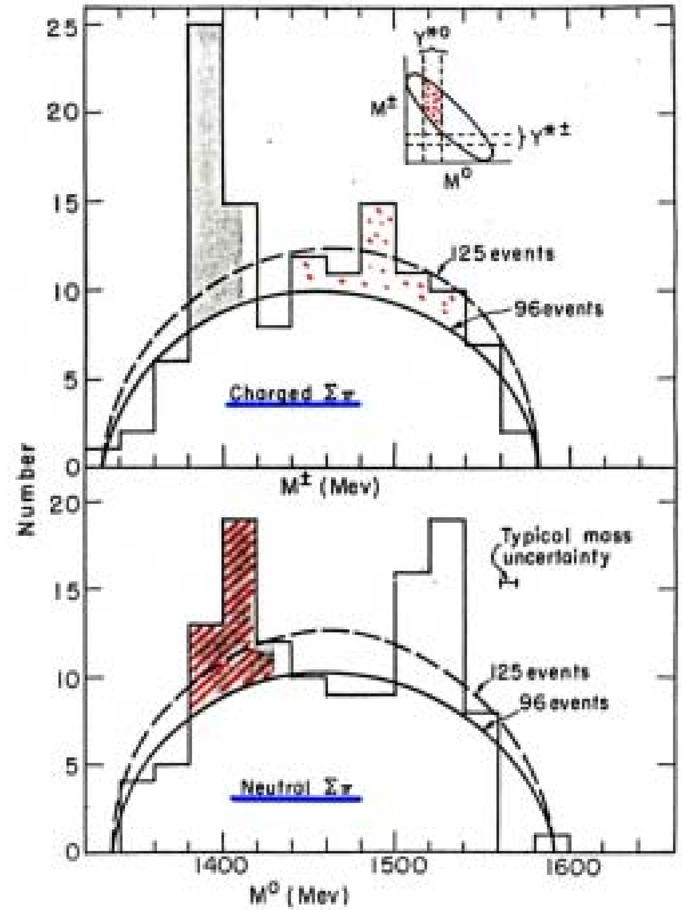
$K^- + p \to \Lambda(1405) + \pi^0$ $p_K = 0.76 \sim 1.15$ GeV/c

$\sigma = 0.1 \sim 0.2$ mb

P. Bastien, M. Ferro-Luzzi & A.H. Rosenfeld,
Phys. Rev. Lett. **6** (1961) 702.

$K^- + p \to \Sigma^+ + \pi^- + \pi^0$
$\to \Sigma^- + \pi^+ + \pi^0$

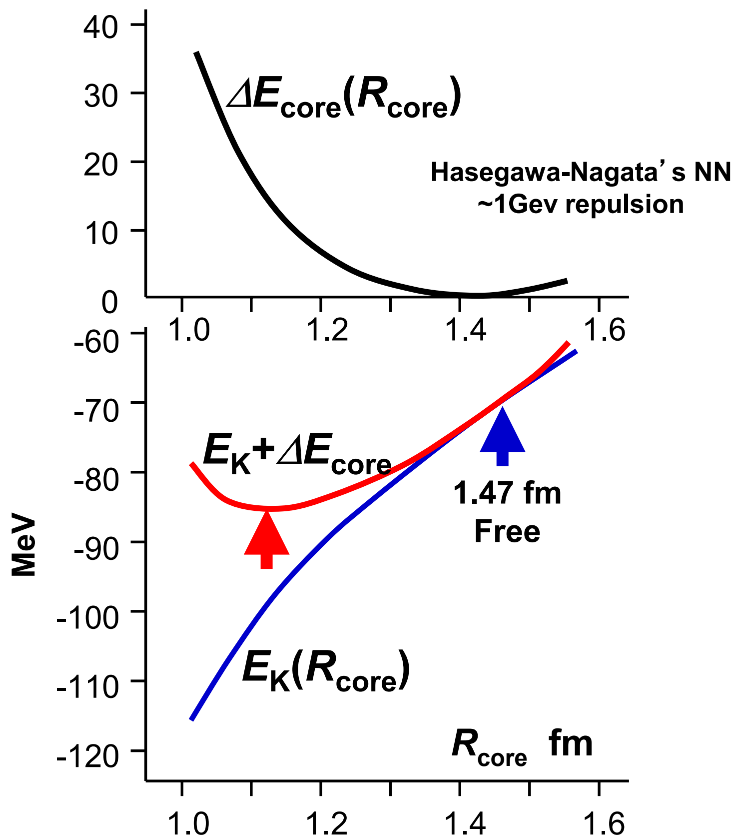
D(K⁻, π⁻) "K⁻pp"
~ 6 μb/sr
Exp. is feasible.

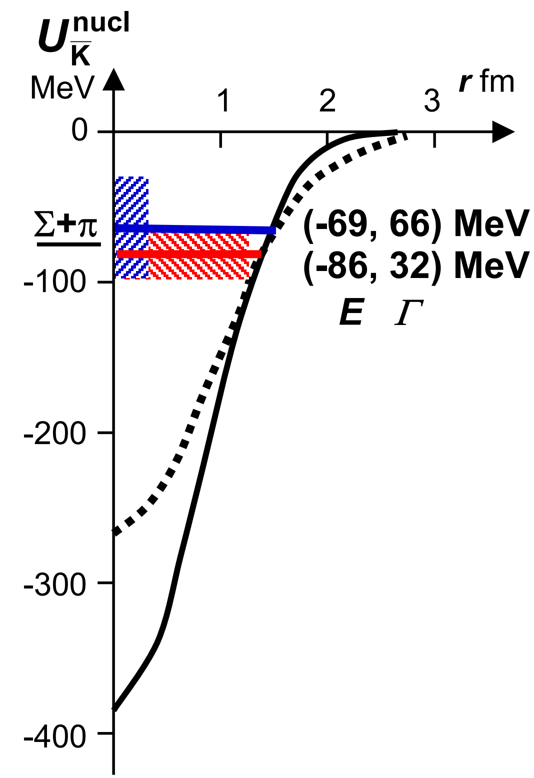


Nuclear $^{4}_{\bar{K}}H$ bound state

$$[K^- \otimes {}^4He]_{T=1/2}$$

$$v^{T=0} + 3v^{T=1}$$





Nuclear $^{3}_{\bar{K}}H$ bound state

$$[K^{-}\otimes{}^{3}He + \bar{K}^{0}\otimes{}^{3}H]$$

$$3\left\{\frac{1}{6}v^{T=0} + \frac{5}{6}v^{T=1}\right\}$$

$T=1$: $E_{0s} = -21$ MeV $\Gamma_{0s} = 95$ MeV

rms r.=1.20 fm

$$3\left\{\frac{1}{2}v^{T=0} + \frac{1}{2}v^{T=1}\right\}$$

$T=0$: $E_{0s} = -108$ MeV $\Gamma_{0s} = 20$ MeV

Narrow !

rms r.=0.97 fm

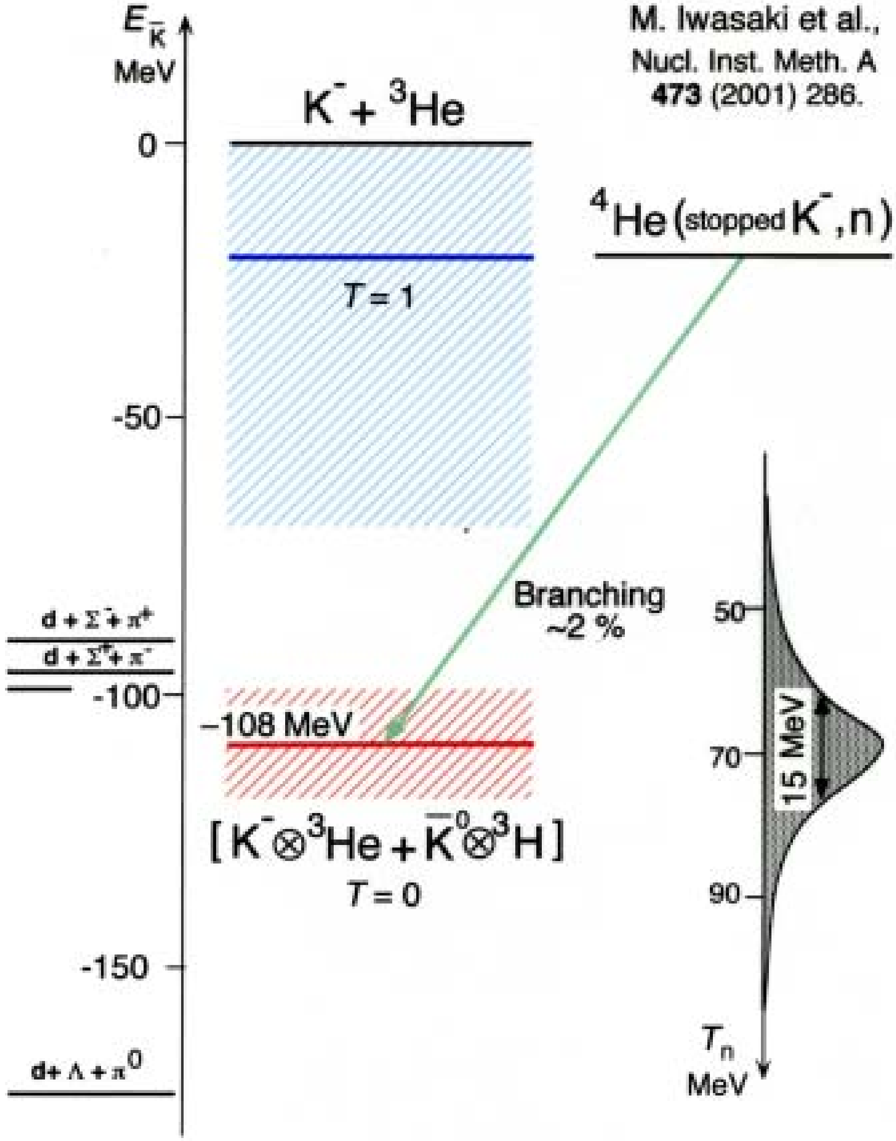
$K^{-}\otimes{}^{4}He$ $4\left\{\frac{1}{4}v^{T=0} + \frac{3}{4}v^{T=1}\right\}$

1.5	1
1	2
T=0 int. Attraction	T=1 int. Width

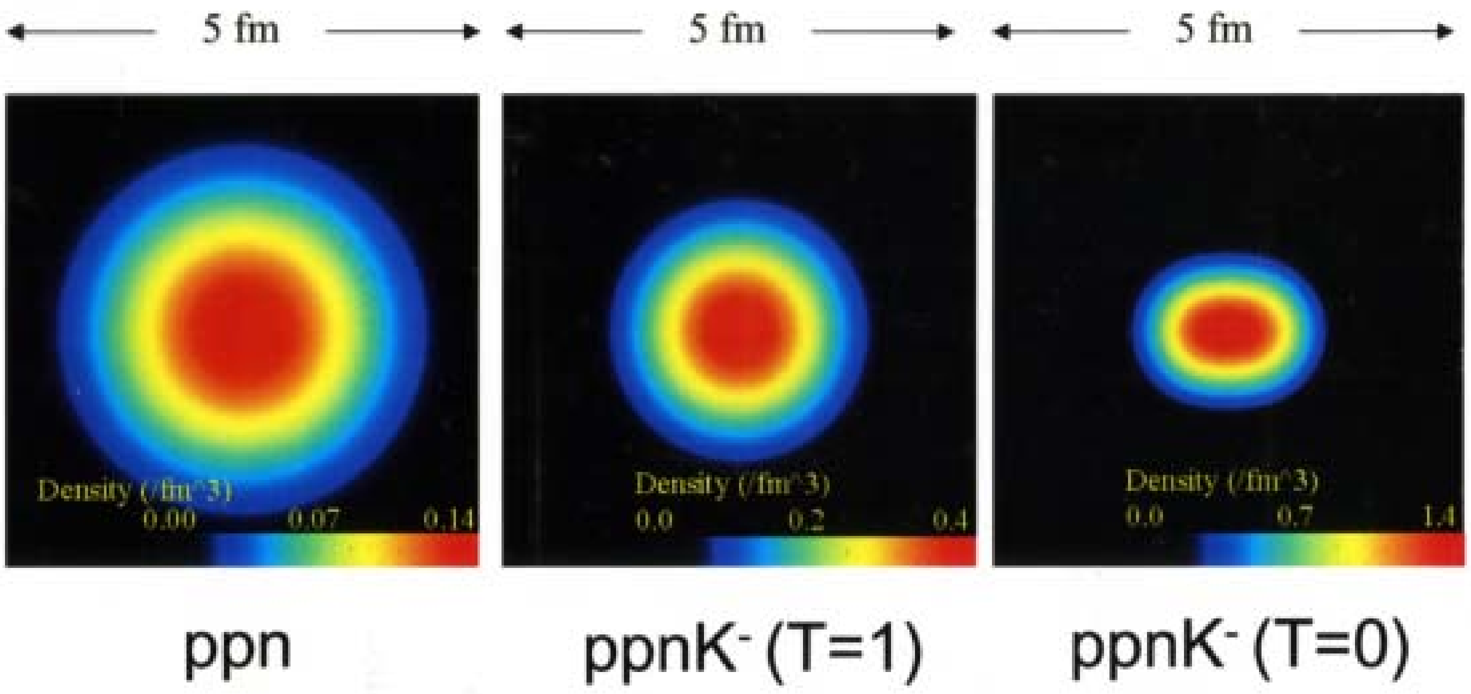
How to excite :

$$^{4}He(_{\text{stopped}}K^{-},n)\ ^{3}_{\bar{K}}H$$

M. Iwasaki, K. Itahashi, H. Outa, T. Yamazaki

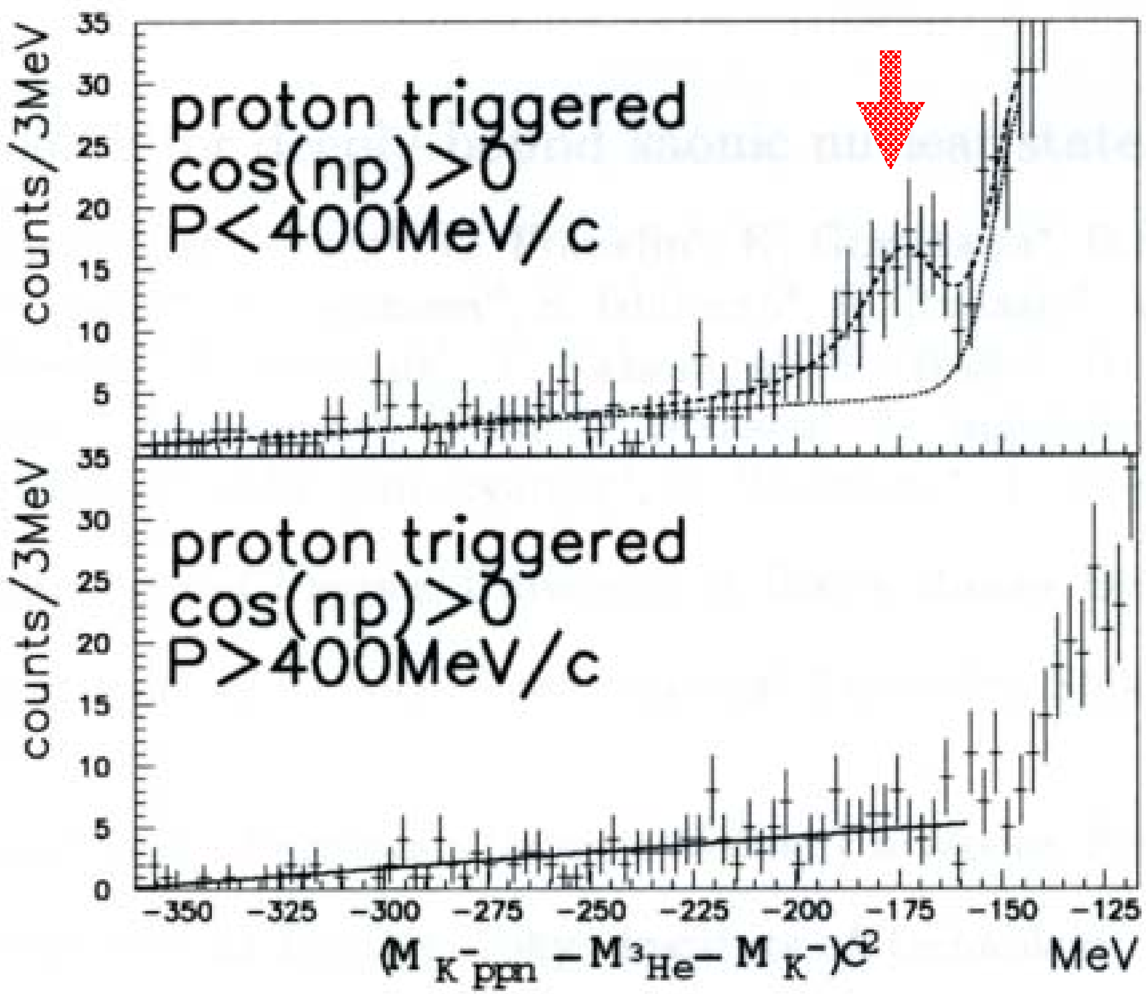


$E_{\bar{K}}$ MeV
M. Iwasaki et al.,
Nucl. Inst. Meth. A
473 (2001) 286.
$K^- + {}^3He$
0
^4He(stopped K^-, n)
T = 1
-50
Branching
~2 %
d + Σ⁻ + π⁺
d + Σ⁺ + π⁻
-100
−108 MeV
[$K^- \otimes {}^3He + \bar{K}^0 \otimes {}^3H$]
T = 0
-150
d+ Λ + π⁰
50
70
90
15 MeV
T_n
MeV


5 fm
5 fm
5 fm
Density (/fm^3)
0.00
0.07
0.14
Density (/fm^3)
0.0
0.2
0.4
Density (/fm^3)
0.0
0.7
1.4
ppn
ppnK- (T=1)
ppnK- (T=0)

Evidence for $ppnK^-$

from ^4He(stopped K^-,n)



T. Suzuki
H. Bhang
G. Franklin
K. Gomikawa
R.S. Hayano
T. Hayashi
K. Ishikawa
S. Ishimoto
K. Itahashi
M. Iwasaki
T. Katayama
Y. Kondo
Y. Matsuda
T. Nakamura
S. Okada
H. Outa
B. Quinn
M. Sato
M. Shindo
H. So
P. Strasser
T. Sugimoto
K. Suzuki
S. Suzuki
D. Tomono
A.M. Vinodkumar
E. Widmann
T. Yamazaki
T. Yoneyama

K^-ppn

$v_{\bar{K}N} \to f\, v_{\bar{K}N}$

(unit in MeV)

f	$\Lambda(1405)$ fit	K^-ppn	E_K	B_{Kppn}	Γ^{π}	$\hbar\omega$
1.00	S	S	-108 -i10	116	20	44
1.00	K-G	K-G	-119 -i10	127	20	44
1.31	S	S	-164 -i 5	172	9	50
1.17	K-G	K-G	-164 -i 6	172	11	46

S : Schroedinger

K-G : Klein-Gordon

Γ_{KNN}= 12 MeV

$$\hbar\omega = \frac{\hbar^2}{M} a$$

$$\rho(r) = \rho(0)\, \exp(-\frac{3}{2} a r^2)$$

$$\bar{\rho} = \sqrt{\frac{1}{8}}\rho(0), \qquad \rho(0) = 3\left(\frac{3a}{2\pi}\right)^{3/2}$$

M. Iwasaki et al. B_{Kppn}=173$\pm$4 MeV

Γ < 25 MeV

M ~ 3137 MeV/c^2

$ppnK^-$

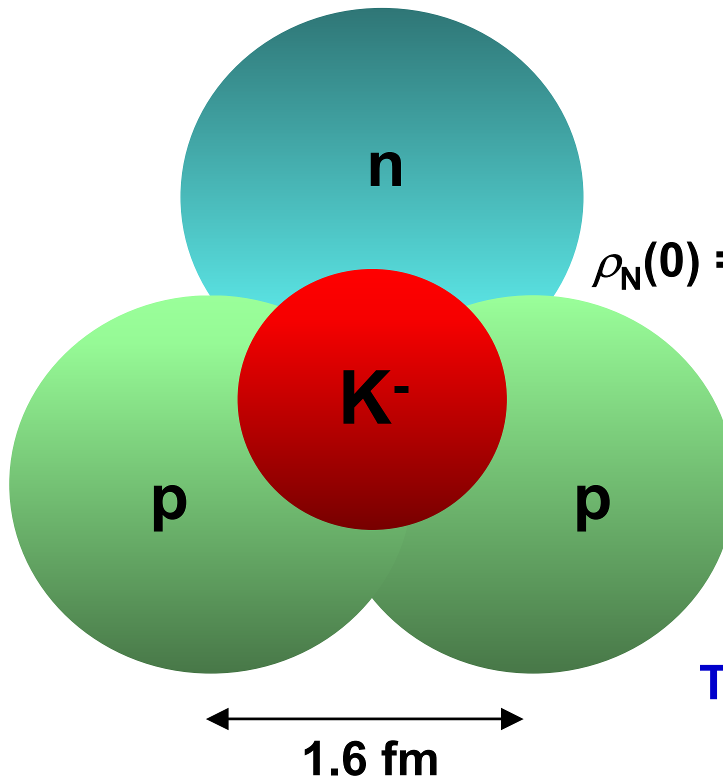
$\Delta B \sim 50$ MeV

Chiral restoration?

m_K/f^2

udd
$\bar{u}s$
uud   uud

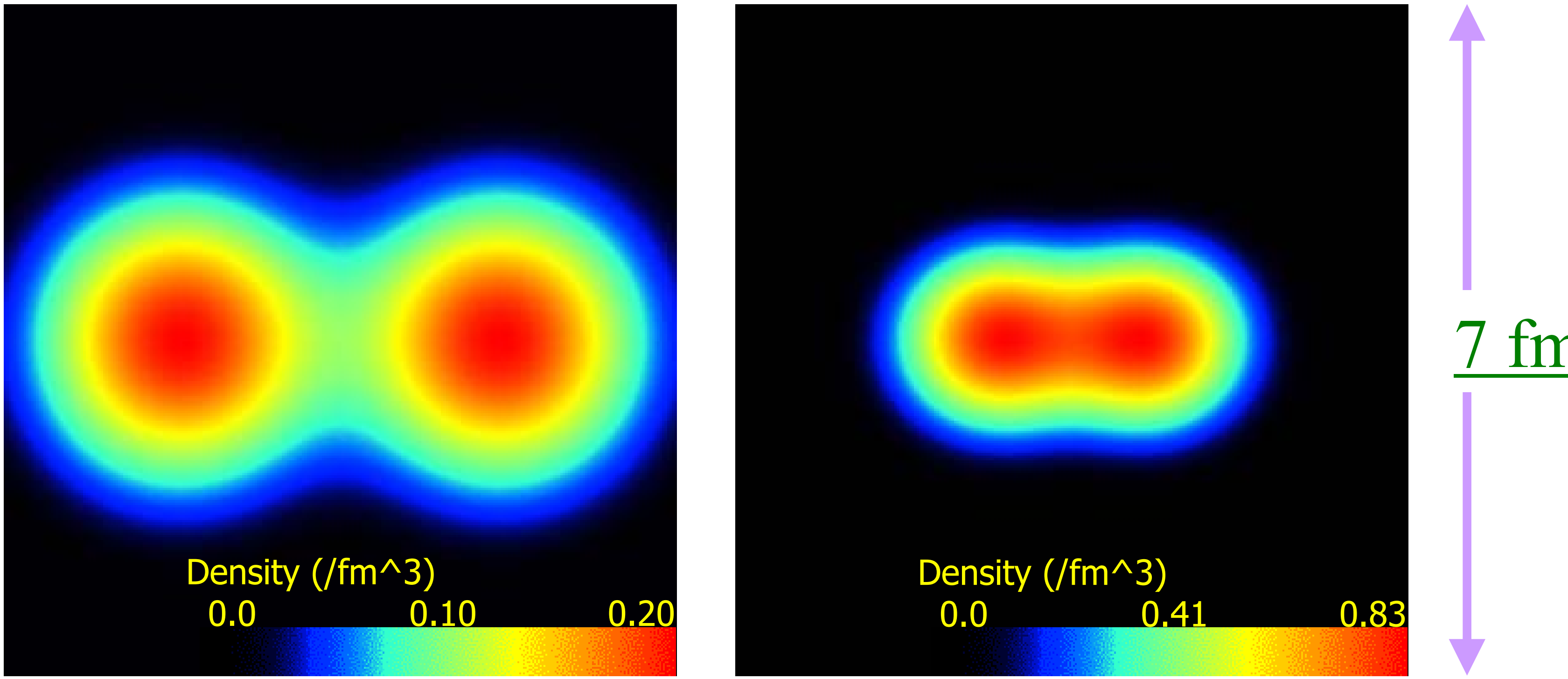
11 or 9 quarks?



$\rho_N(0) = 6.8\ \rho_0$

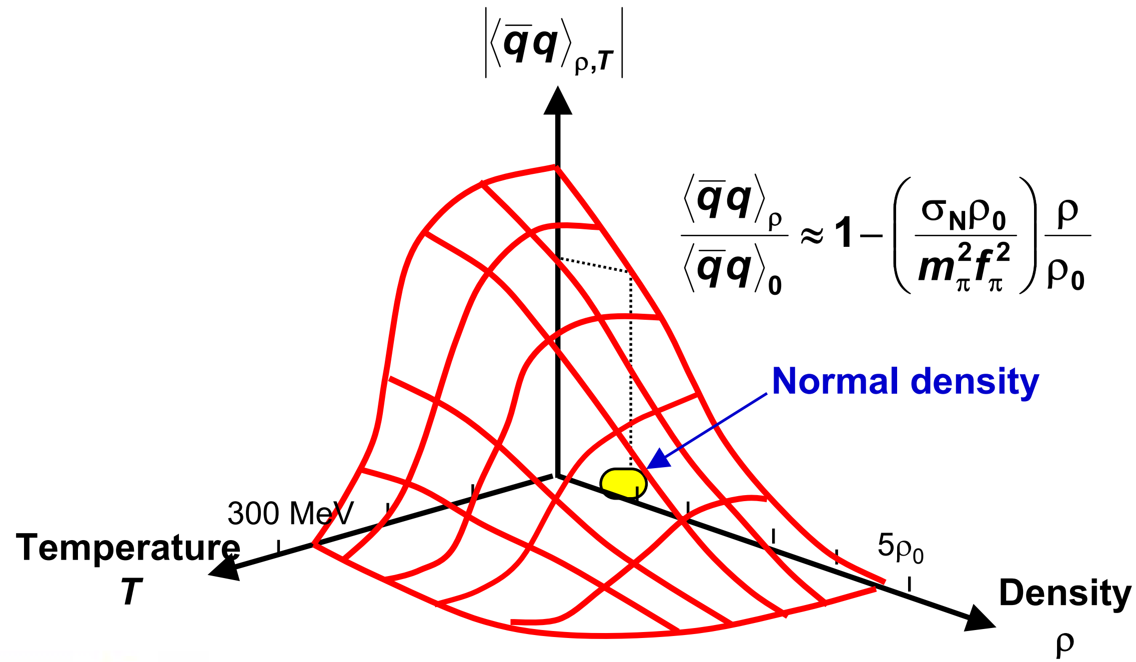
Tri-baryon?

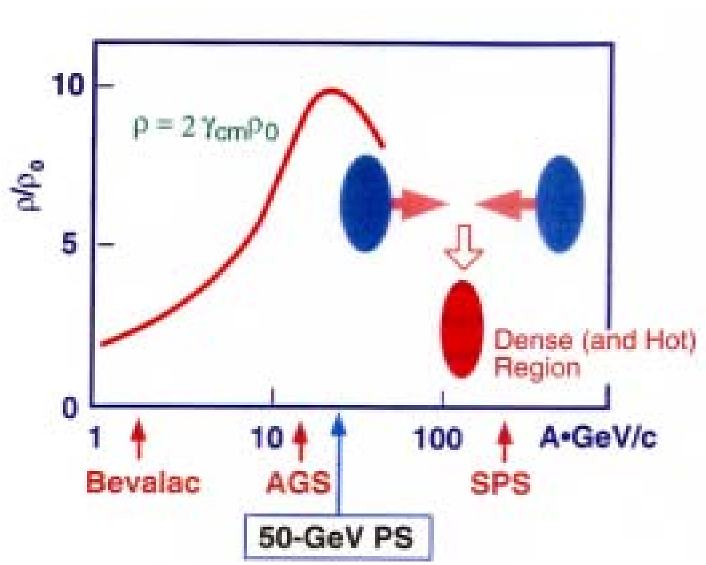
^{8}Be $\quad$ $^{8}BeK^{-}$



Dense & Cold

AMD calculation by Dote et al.

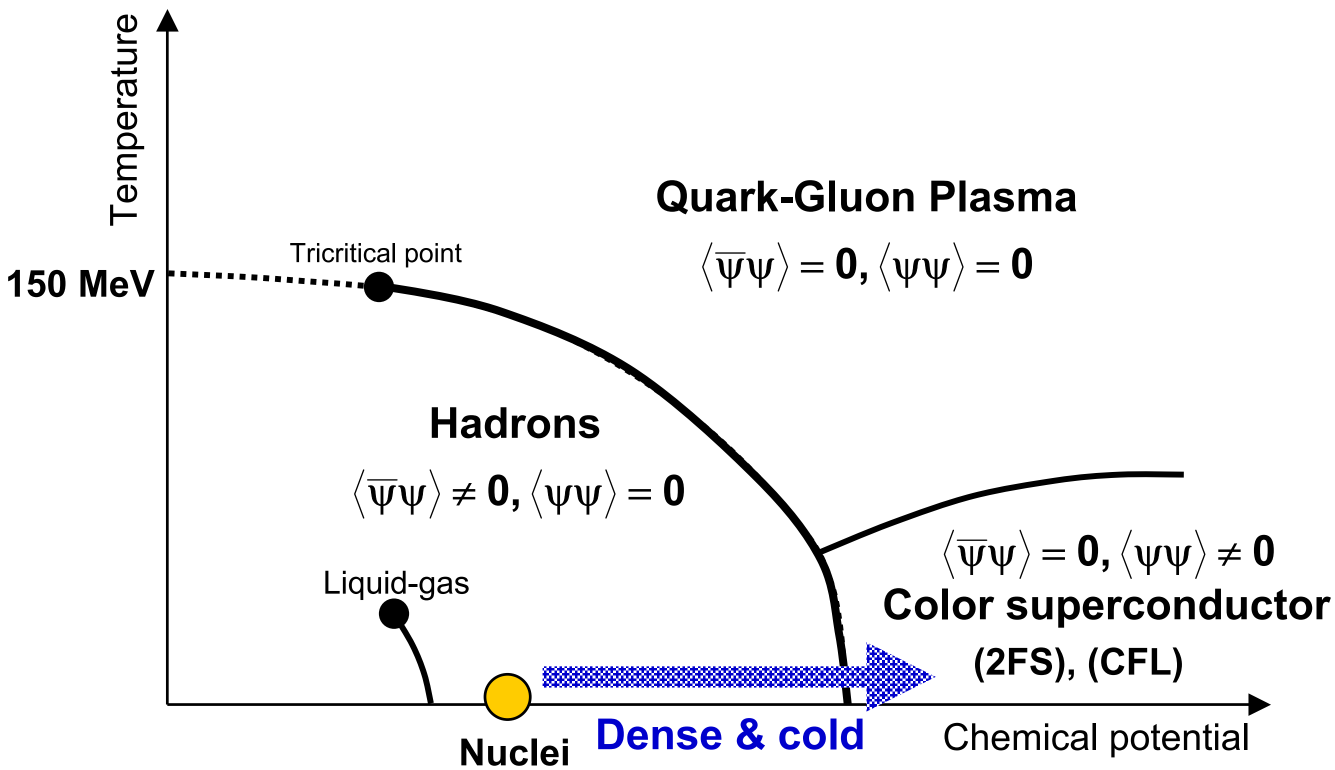




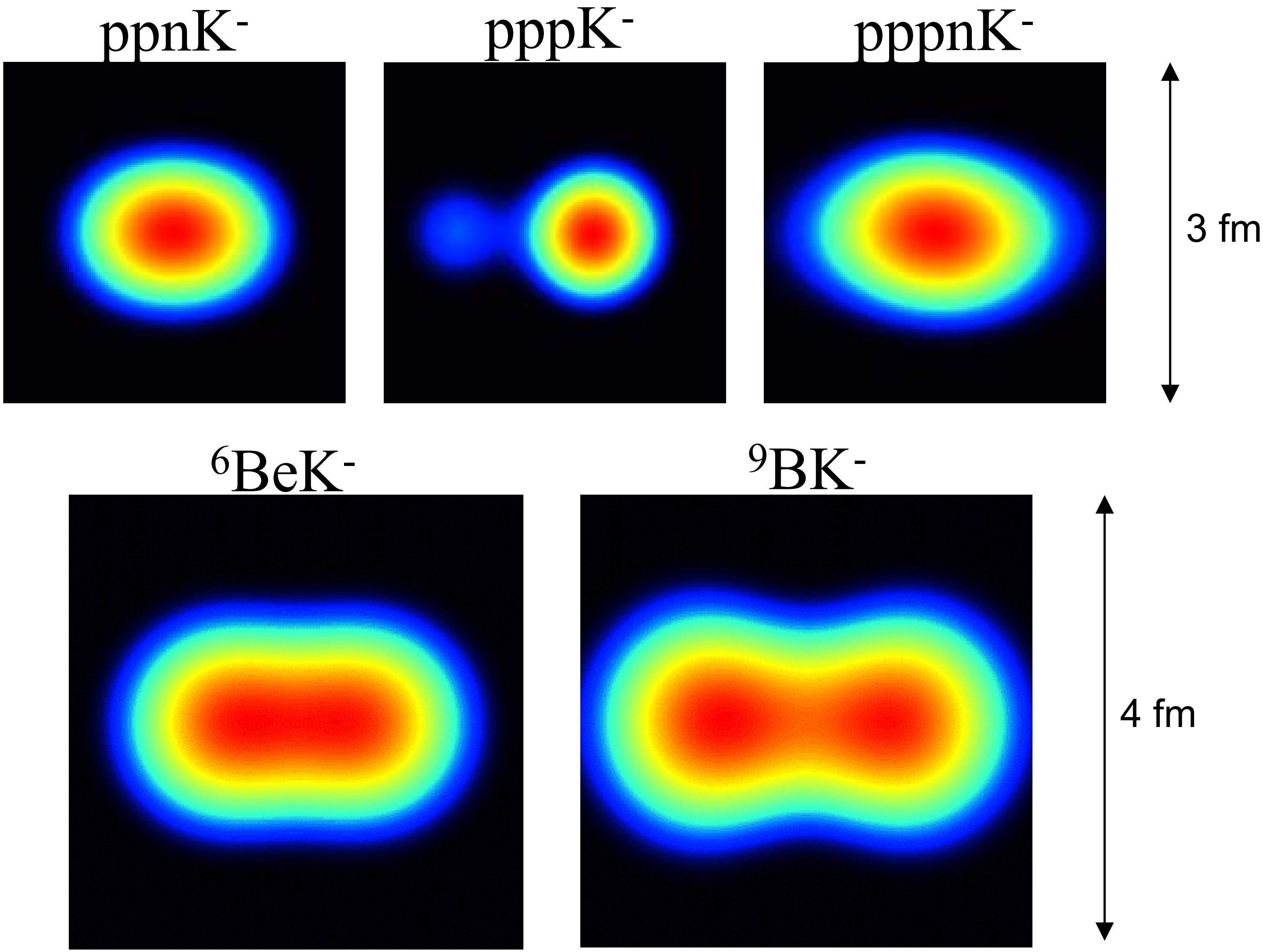
T. Hatsuda & T. Kunihiro,
Phys. Rev. Lett. 55 (1985) 158.

W. Weise, Nucl. Phys. A443 (1993) 59c.

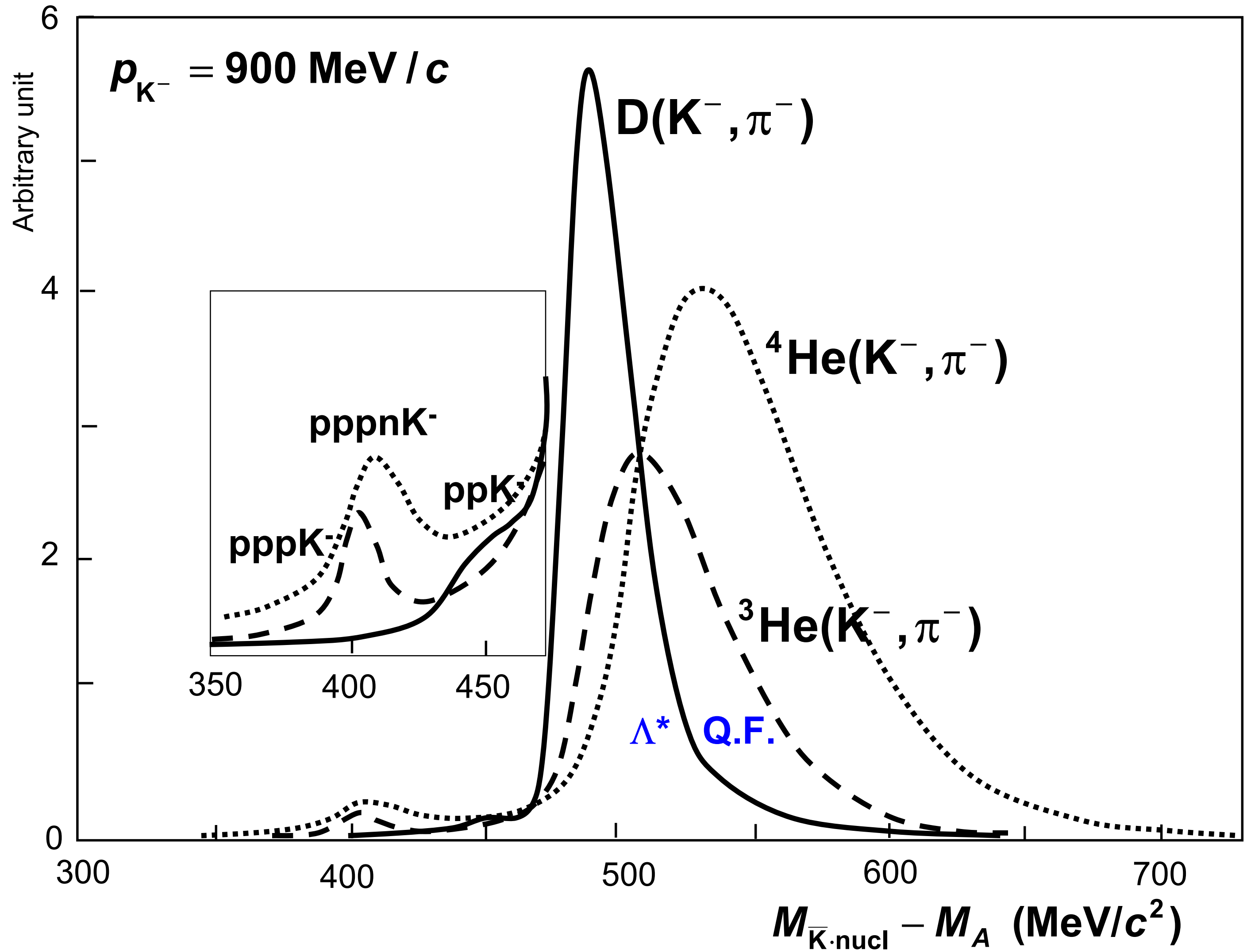
Phase Diagram



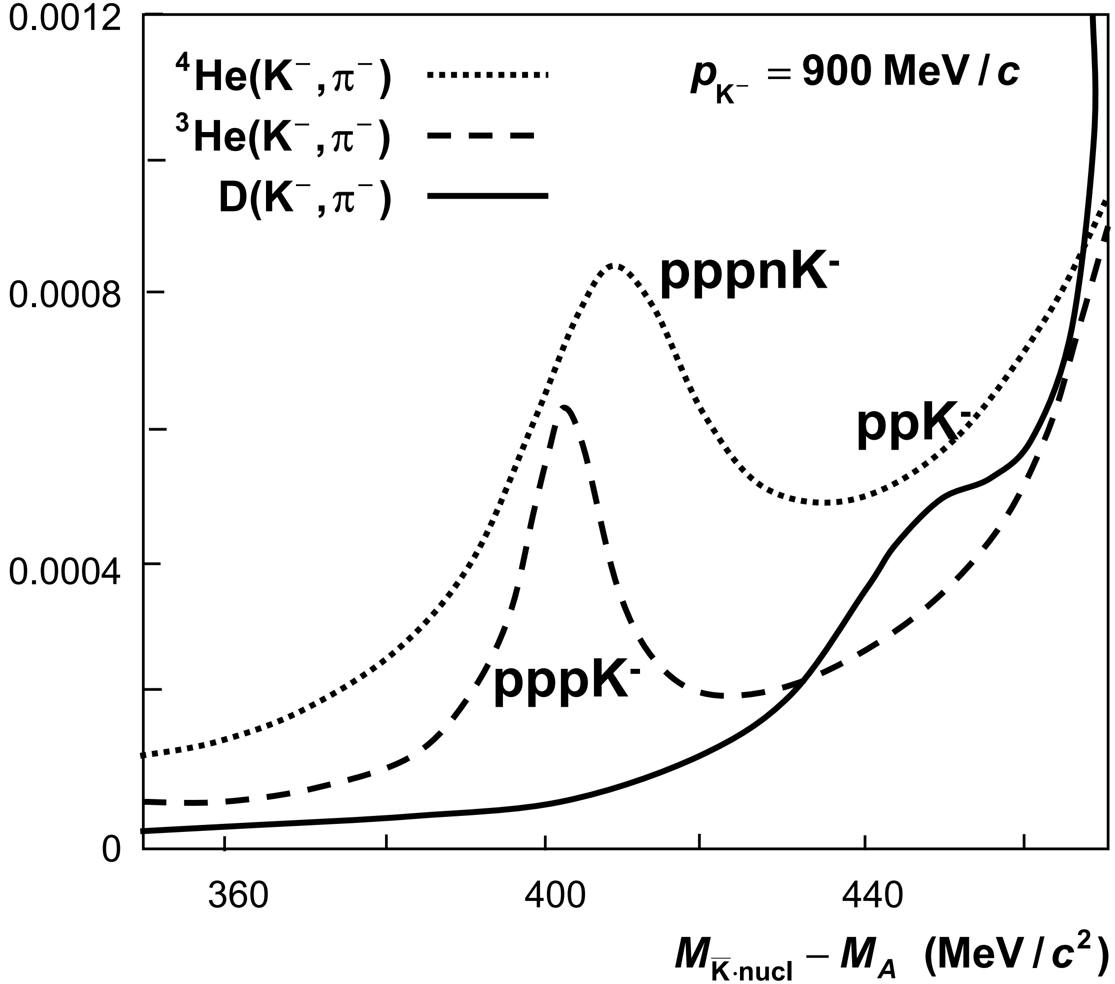
Nucleon density distribution



Spectral Function

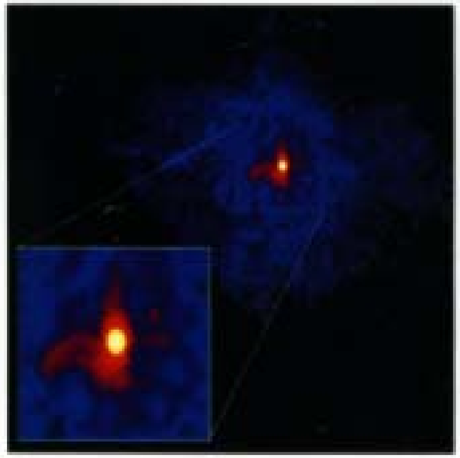


Spectral Function



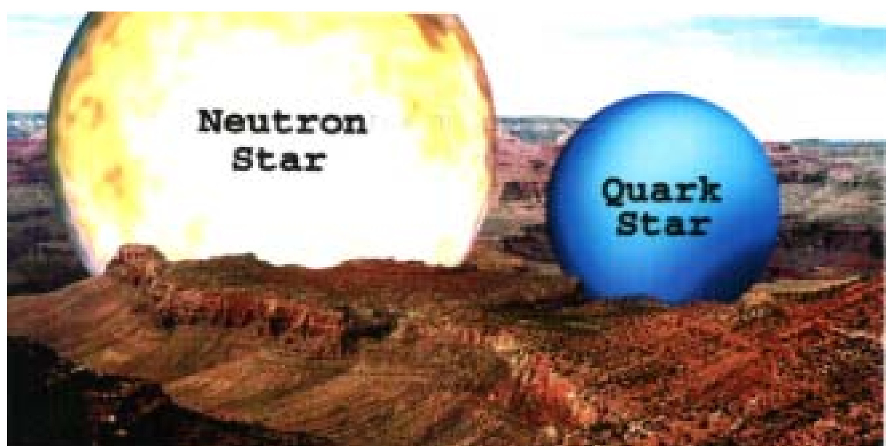
NASA's Chandra X-ray

A.D. 1181

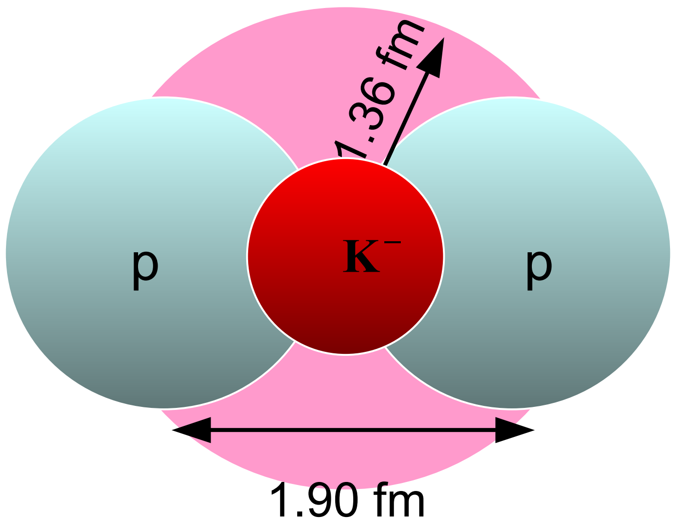


3C58

RX J1856

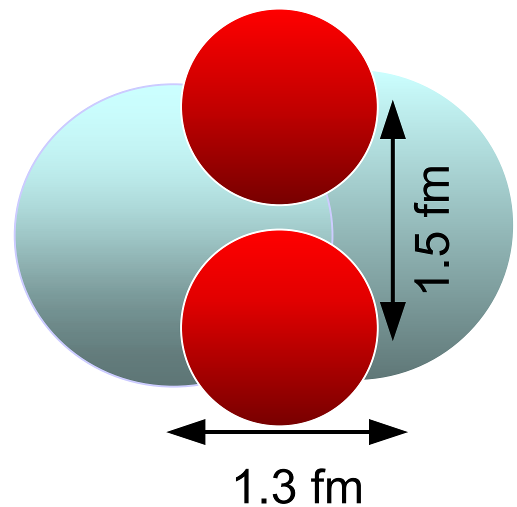


ppK^-



Strange deuteron?

$ppK^- K^-$



$\bar{u}s$

uud uud

$\bar{u}s$

uuddss

Jaffe's H* di-baryon?

Concluding Remarks

Nuclear $\bar{K}$ bound state

$\bar{K}$ behaves as a "contractor".

Mini strange matter

A new means to investigate
Hadron dynamics in dense&cold matter

Chiral restoration?
Color superconductivity?
Kaon condensation?
Strange hadronic/quark matter?

Few-body $\bar{K}$ nuclear systems would provide experimental data of fundamental importance for strangeness and hadron physics.