Dense $\bar{K}$ nuclei and their excited states

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   - K^-p-$\bar{K}^0n$ mixing
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Multi-quark hadrons, four, five and more?,
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Introduction

Studies of deeply bound kaonic nuclei by Akaishi & Yamazaki

- phenomenological $\bar{K}N$ potential
  1. free KN scattering data
  2. X-ray data of kaonic hydrogen atom
  3. binding energy and width of $\Lambda(1405)$

Strongly attractive.

$$V^{\bar{K}N}_{I=0}$$

- Analysis of $^{8}BeK^{-}$ with $\alpha\alpha K^{-}$ model ⇒

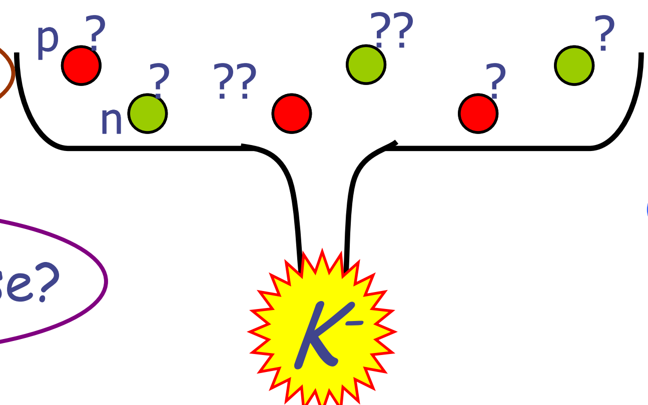
Binding energy of K^{-} = 113 MeV
Central density = $5\rho_0$

Kaonic nucleus

K⁻ deeply bound?

Highly dense?

Peculiar structure?



What kind of structure does A-nucleons + K⁻ system favor?

Formalism

Kaonic nuclei ...
- unknown structure
- peculiar structure ex) isovector deformation

⇨ ☆ Method : Antisymmetrized Molecular Dynamics

no assumption on clusters, shape, etc.

$V^{\bar{K}N}_{I=0}$ plays an essential role in kaonic nuclei.

Improving

- $K^- p / \bar{K}^0 n$ mixing

K^--proton ⇄ *I=0 $\bar{K}$N int.* ⇄ $\bar{K}^0$-neutron

- Angular momentum & isospin projections

Wave function

Essence of $K^- p / \overline{K}^0 n$ mixing

$$|N\rangle = a|\text{proton}\rangle + b|\text{neutron}\rangle$$

$$|K\rangle = x|K^-\rangle + y|\overline{K^0}\rangle$$

Nucleon's wave function

$$|\varphi_\iota\rangle = \sum_{\alpha=1}^{Nn} C_\alpha^i \exp\left[-\upsilon\left(\mathbf{r} - \frac{\mathbf{Z}_\alpha^i}{\sqrt{\upsilon}}\right)^2\right]|\sigma_\alpha^i \tau_\alpha^i\rangle$$

Superposition of Gaussian wave packets

$$|\tau_\alpha^i\rangle = \left(\frac{1}{2} + \gamma_\alpha^\iota\right)|p\rangle + \left(\frac{1}{2} - \gamma_\alpha^\iota\right)|n\rangle$$

p-n mixing

Total wave function

$$|\Phi\rangle = \det[|\varphi_\iota\rangle] \otimes |\varphi_K\rangle$$

$$|\Phi^\pm\rangle = |\Phi\rangle \pm |P\Phi\rangle$$

Charge projection

$$\ldots d\alpha \exp\left[-i\alpha\left(\hat{T}_Z - M\right)\right]|\Phi^\pm\rangle$$

Anti-kaon's wave function

$$|\varphi_K\rangle = \sum_{\alpha=1}^{Nk} C_\alpha^K \exp\left[-\upsilon\left(\mathbf{r} - \frac{\mathbf{Z}_\alpha^K}{\sqrt{\upsilon}}\right)^2\right]|\tau_\alpha^K\rangle$$

Superposition of Gaussian wave packets

$\overline{K}^0$-K^- mixing

Use $|P_M \Phi^\pm\rangle$ as a trial function

J & T projections (VBP)

$$\left|\Phi^{\pm}\right\rangle \Longrightarrow \left|P^{J}_{MK}P^{T}_{TzTz'}\Phi^{\pm}\right\rangle$$

: Eigen state of angular momentum J and isospin T

$$\left|P^{J}_{MK}P^{T}_{TzTz'}\Phi^{\pm}\right\rangle = \int d\Omega_{Ang}\; D^{J*}_{MK}(\Omega_{Ang})\,\hat{R}_{Ang}(\Omega_{Ang}) \times \int d\Omega_{iso}\; D^{T*}_{TzTz'}(\Omega_{iso})\,\hat{R}_{iso}(\Omega_{iso})\left|\Phi^{\pm}\right\rangle$$

J projection

T projection

$$\hat{R}_{Ang}(\Omega) = \exp\left[-i\alpha\hat{J}_z\right]\exp\left[-i\beta\hat{J}_y\right]\exp\left[-i\gamma\hat{J}_z\right]$$

$$\hat{R}_{iso}(\Omega) = \exp\left[-i\alpha\hat{T}_z\right]\exp\left[-i\beta\hat{T}_y\right]\exp\left[-i\gamma\hat{T}_z\right]$$

Calculate various expectation values with $\left|P^{J}_{MK}P^{T}_{TzTz'}\Phi^{\pm}\right\rangle$.

Formalism

1. Hamiltonian $\hat{H} = \hat{T} + \hat{V}_{NN} + \hat{V}_{KN} + \hat{V}_{Coulomb} - \hat{T}_G$

2. Variational parameters $\left\{X_\alpha^i\right\} = \left\{C_\alpha^i,\ \mathbf{Z}_\alpha^i,\ \gamma_\alpha^i,\ C_\alpha^{\mathrm{K}},\ \mathbf{Z}_\alpha^{\mathrm{K}},\ \gamma_\alpha^{\mathrm{K}}\right\}$
   are determined by Frictional cooling eq. with constraint.

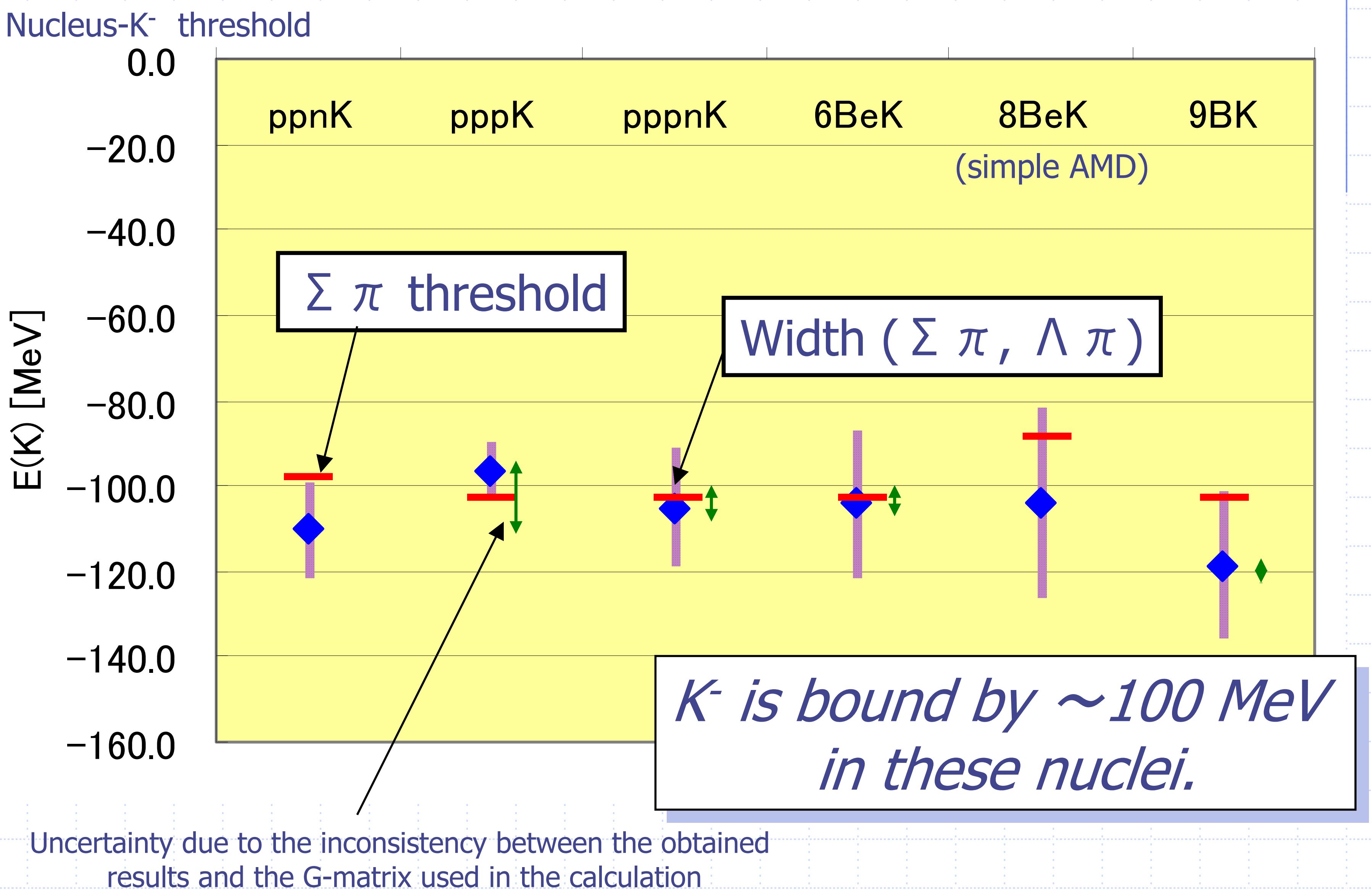
3. G-matrix method ⇨ Effective interaction $\hat{V}_{NN}$, $\hat{V}_{KN}$
   bare NN int = Tamagaki potential (OPEG)
   bare KN int = AY potential

given density and starting energy of $\bar{K}$
→ G-matrix

AMD calculation
→ density and starting energy of $\bar{K}$

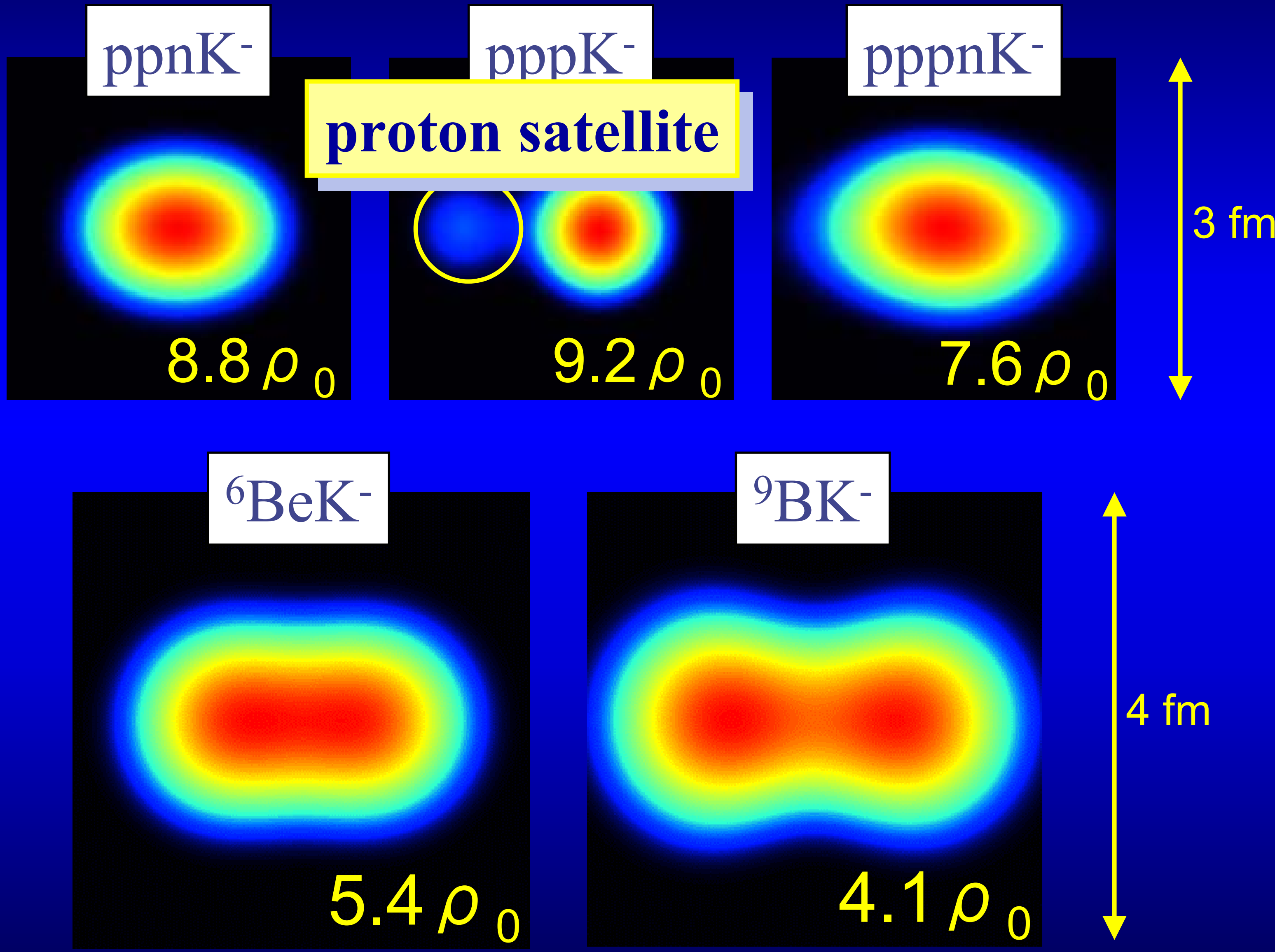
Repeat until getting consistency

Binding energy of K^- and Decay-width

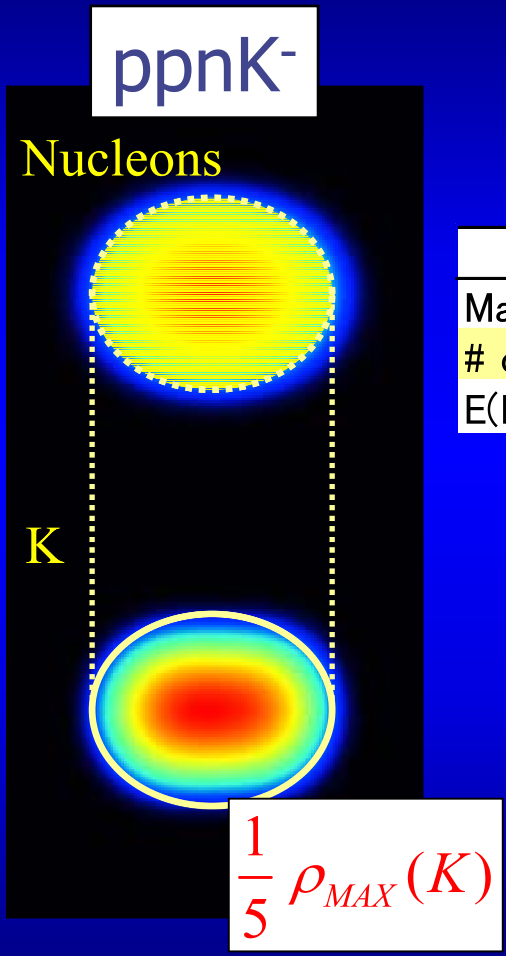


K^- is bound by ~100 MeV in these nuclei.

Nucleon density distribution



Number of nucleons near K⁻ meson



one center like

two center like

	ppnK	pppK	pppnK	6BeK	9BK
Max Kdens	0.67	1.48	0.62	0.34	0.35
# of nucleons	1.67	1.14	1.78	2.55	2.53
E(K)	110.3	96.7	105.0	104.2	117.0

strange structure

Single K⁻ meson can interact with limited numbers of nucleons?

→ *Saturation of E(K)*

Excited state of ppnK$^-$

total B.E.

29 MeV

$J^\pi = \frac{1}{2}^+, T = 1$

Γ = 95 MeV

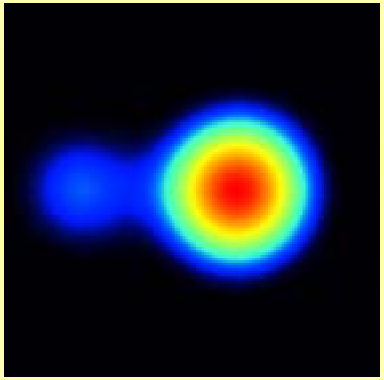
R_{rms} = 1.20 fm

80 MeV

$J^\pi = \frac{3}{2}^-, T = 1$

Γ = 128 MeV

R_{rms} = 0.84 fm



Isobaric analog state of pppK$^-$

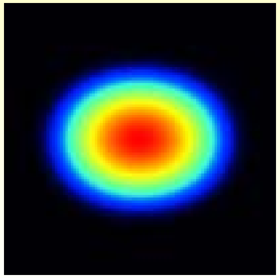
103 MeV

118 MeV

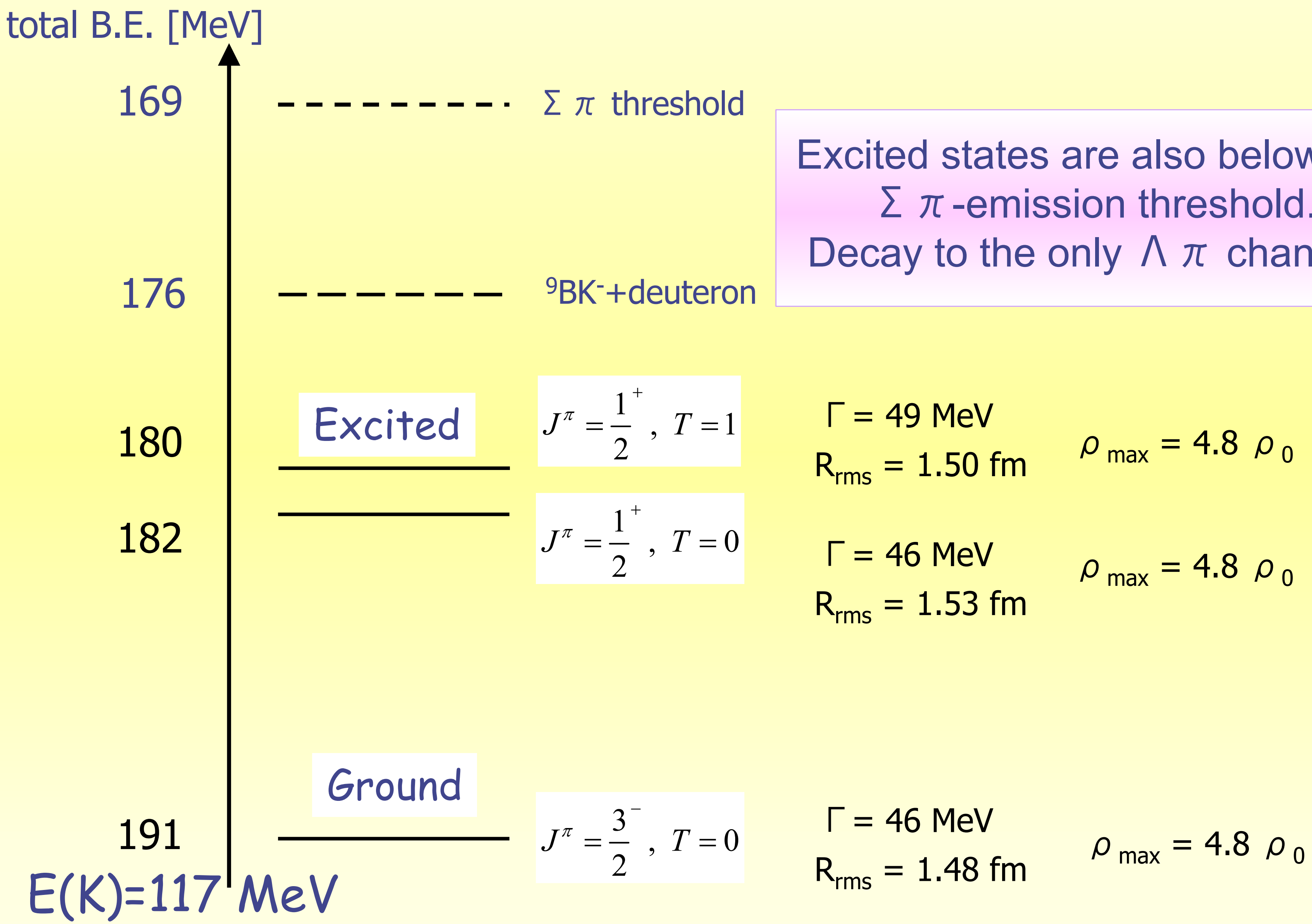
$J^\pi = \frac{1}{2}^+, T = 0$

Γ = 21 MeV

R_{rms} = 0.72 fm



Ground and Excited states of $^{11}CK^{-}$



Excited states are also below the $\Sigma\pi$-emission threshold.
Decay to the only $\Lambda\pi$ channel.

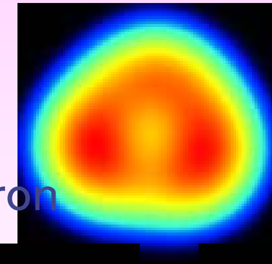
Structure of $^{11}CK^-$

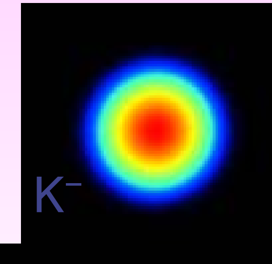
•Ground
191 MeV

$$J^\pi = \frac{3}{2}^-, T = 0$$

Nucleons

Kaon



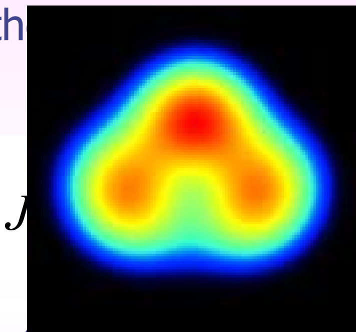


4 fm

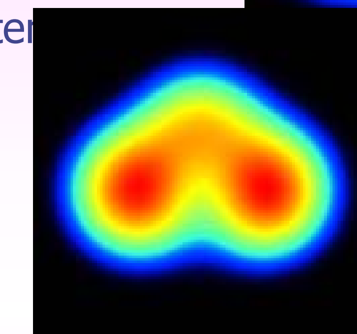
Three clusters are attracted by a kaon
being at th ster

•Excited
182 MeV

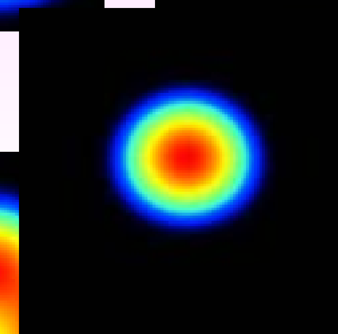
Proton

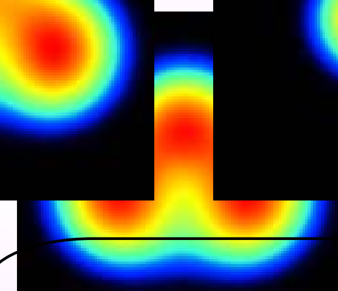


Neutron



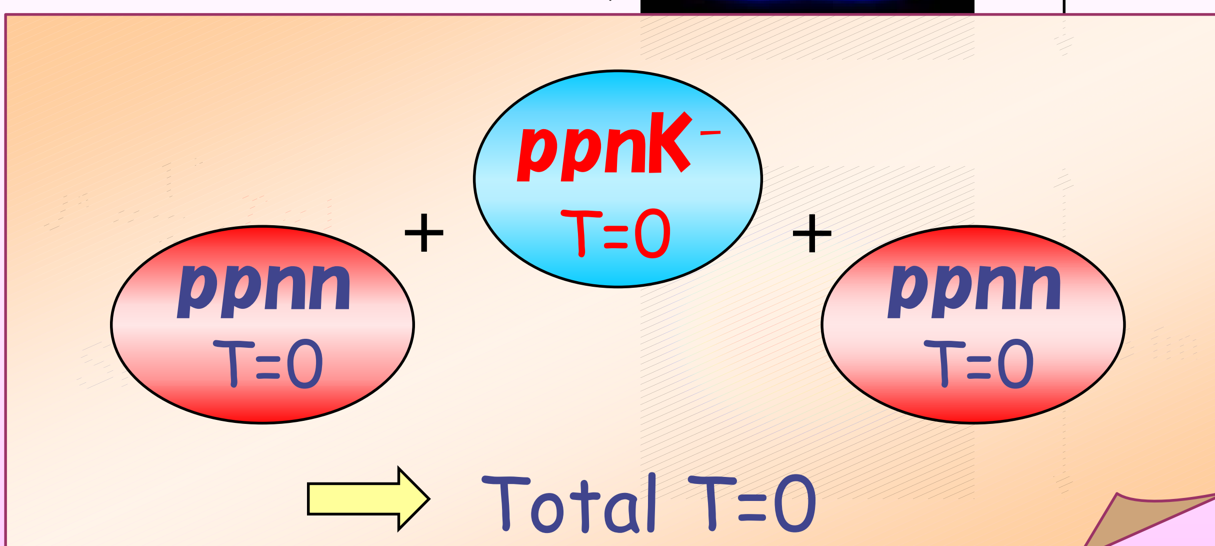
K⁻





Cluster-like

•Excited
180 MeV



Summary

- We have improved AMD so that we can treat $K^-p/\bar{K}^0n$ mixing and perform J & T projections.

- Results:

	E(K) [MeV]	width [MeV]	Max ρ [fm^-3]	Rrms [fm]
ppnK−	110.3	21.2	1.50	0.72
pppK−	96.7	12.5	1.56	0.81
pppnK−	105.0	25.9	1.29	0.97
6BeK−	104.2	33.3	0.91	1.17
9BK−	118.5	33.0	0.71	1.45
11CK−	117.4	46.0	0.81	1.48

In the ground state of kaonic nuclei, K^- is deeply bound by ～100 MeV and forms highly dense state.

Saturation of E(K) is related to the number of nucleons with which a K^- can interact.

- Excited states
  - $ppnK^-$ $J^\pi=3/2^-$, T=1 : Isobaric analog state of the ground state of $pppK^-$
    38 MeV above the ground state, Γ is very large to be 128 MeV.

  - $^{11}CK^-$ Two excited states as well as the ground state are below the Σπ threshold.
    - $J^\pi=1/2^+$, T=1 : shell-like structure
    - $J^\pi=1/2^+$, T=0 : cluster-like structure
      $^4He(T=0) + ppnK^-(T=0) + {}^4He(T=0)$ configuration.