NP04, Tokai, 8/2004

A. Gal
HU, Jerusale

- Brief overview of SNP04 7/2004 at Osaka
- Brief review of $S=-2$ physics
- Extrapolation to Strange Hadronic Matter

WHY study hypernuclei ?

YN and YY interactions are not (and will not be) fully available from free-space measurements; unified BB phenomenology.

Studying hypernuclei illuminates strange matter at medium and (occasionally) high density; connection to QCD properties.

Connection to other strange hadrons in matter:

K^-, ...

hyperonic excitations: $\Lambda(1405)$, $\Lambda(1520)$, ...

hidden strangeness: φ, f_0, ...

Connection to strange quark matter, strangelets, neutron stars, hyperstars .... but where is the H dibaryon ???

HYPONUCLEI $(S=+1)$? Θ^+ nuclei

- New facilities
  - Jlab $^{A}Z(e,e'K^{+})\,^{A}_{\Lambda}(Z-1)$ Hashimoto
    $^{12}_{\Lambda}B$ spectroscopy; resolution below 1 MeV
  - DAΦNE, Finuda detector, Marcello ✓
    new results from K^{-}_{stop} on Li, C, Al, V,
    1.4 MeV FWHM. Σ^{-}, K^{-} signals ?
- S=-2 hypernuclei
  - extension of E373 - $^{6}_{\Lambda\Lambda}He$ Nakazawa ✓
    few more emulsion events

    Theory: Nemura (A=4,5,6) ✓
    Yamamoto, Rijken, Lanskoy ✓, Fujiwara ✓

    Ξ^{-} hypernuclei as a gateway, Nagae
- PANDA experiment at new GSI saito
  $(\bar{p}p \to \Xi\bar{\Xi})$

- Sensational Physics
  - Θ^+ : $\frac{1}{2}^+$ or $\frac{1}{2}^-$? Toki (Hiyama)

    Oka - instanton contribution vs. H dibaryon

    Vicente-Vacas Θ^+ bound states?

    (K^+,π^+), (π^-,K^-) experiments to look for HYPONUCLEI

    (A. Goldhaber 1979 ?)

    (Imai, Hosaka; at NP04)
  - K^- bound states ???

    Suzuki $^4He(K^-_{st},p)$ Iwasaki

    theory: Dote, Gal

    ~ 200 MeV binding

    excited ΣNN configuration ?

    Kishimoto $^{16}O(K^-,n)$ $\begin{matrix}90\\130\end{matrix}$? MeV bound

1 Review

ΛΛ Hypernuclei

[1998 INT Workshop
by G. Franklin]

Stopped Ξ^- emulsion experiments

- Measure ΛΛ ground state via $\Lambda \to p\pi^-$ decay mode (only possible in light hypernuclei)
- Low K flux requirements (but need good K/π ratio)
- 3 reconstructed events identified in 30 years.
- 3 more recently observed ΛΛ hypernucli
  - nonmesonic decays
  - species and binding not determined
- ΛΛ Hypernuclei exist, $\Delta B_{\Lambda\Lambda}$ probably positive, but...

$K^- p \to K^+ \Xi^-$

$\Xi^- p \to \Lambda\Lambda$

extra ΛΛ binding $\langle V \rangle_M^{{}^1S_0}$

	#K⁻	stops	$B_{\Lambda\Lambda}$ (MeV)	$\Delta B_{\Lambda\Lambda}$ (MeV)
Danysz *et al.* 1963 $\boxed{{}^{10}_{\Lambda\Lambda}Be} \to {}^{9}_{\Lambda}Be + p + \pi^-$ $\quad \to \alpha + \alpha + p + \pi^-$	10^5	~2	17.7±0.4	4.3±0.4
'old' Prowse 1966 $\boxed{{}^{6}_{\Lambda\Lambda}He} \to {}^{5}_{\Lambda}He + p + \pi^-$ $\quad \to \alpha + p + \pi^-$	10^6	~30	10.9±0.8	4.7 ± 1.0
Aoki *et al.* 1990 ${}^{10}_{\Lambda\Lambda}Be \to {}^{10}_{\Lambda}B + \pi^-$ $\quad \to {}^{3}He + \alpha + p + n + n$	10^9	80	8.5±0.7	−4.9 ± 0.7
OR: ${}^{14}_{\Lambda\Lambda}C^* + n \to \boxed{{}^{13}_{\Lambda\Lambda}B} + p + n$ $\quad \to {}^{13}_{\Lambda}C + \pi^-$ $\quad\quad \to {}^{3}He + \alpha + \alpha + n + n$			27.5±0.7	4.8 ± 0.7

$$\Delta B_{\Lambda\Lambda} \underset{\text{def.}}{=} B_{\Lambda\Lambda} - 2B_{\Lambda}$$

Observation of a $^{6}_{\Lambda\Lambda}$He Double-Hypernucleus

KEK - E373 , PRL (in press) 19.11.01

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Takahashi et al.   PRL (2001)

(Dated: September 19, 2001)

Abstract

A double-hyperfragment event has been found in a hybrid-emulsion experiment. It is identified uniquely as the sequential decay of ${}_{\Lambda\Lambda}^{6}\mathrm{He}$ emitted from a Ξ^- hyperon nuclear capture at rest. The mass of ${}_{\Lambda\Lambda}^{6}\mathrm{He}$ and the Λ-Λ interaction energy $\Delta B_{\Lambda\Lambda}$ have been measured for the first time devoid of the ambiguities due to the possibilities of excited states. The value of $\Delta B_{\Lambda\Lambda}$ is $1.01 \pm 0.20\,^{+0.18}_{-0.11}$ MeV. This demonstrates the Λ-Λ interaction is weakly attractive.

PACS numbers: 21.80.+a, 21.10.Dr, 25.80.Pw, 27.20.+n

'old' event gave $\Delta B_{\Lambda\Lambda} = 4.7 \pm 0.6$ MeV

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2B_{\Lambda} \sim \langle V_{\Lambda\Lambda} \rangle$$

KEK E373
Nakazawa ......

$K^- p \rightarrow K^+ \Xi^-$ in emulsion

Takahashi et al PRL 87 (2001)

Double-hypernucleus Event "Nagara"

NOTE: This is the preliminary result of the analysis Ⓐ $\Xi^- + {}^{12}C \rightarrow {}^4He + {}^3H + {}^{6}_{\Lambda\Lambda}He$

Event Description

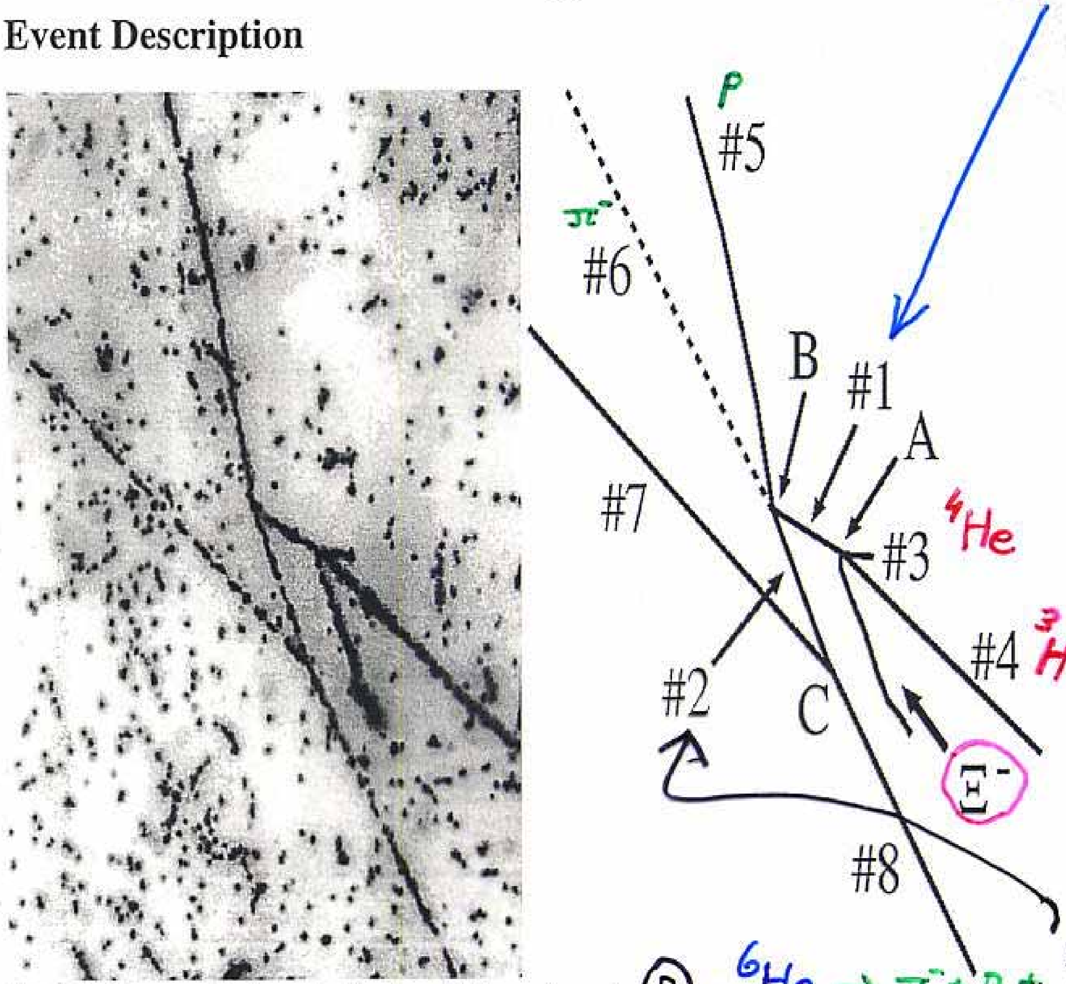


Figure 1: Picture and schematic drawing of "Nagara" event.

Ⓑ ${}^{6}_{\Lambda\Lambda}He \rightarrow \pi^- + p + {}^{5}_{\Lambda}He$

The picture and the schematic drawing of the event is shown in Figure 1. This event was found by Y.Iwata at Gifu University and named "Nagara". A Xi- hyperon came to rest at point A, from which 3 charged particles (track#1, #3, #4) were emitted. One of them decayed to 3 charged particles (track#2, #5, #6) at point B. The particle of track#2 decayed again to 2 charged particles (track#7, #8) at point C.

The event was detected in the most downstream plate (#12) of the emulsion module. The particle of track#7 left the emulsion stack and entered the downstream SciFi-Block detector (D-Block). Unfortunately track#5 ended in the base (50 micron thick acrylic film). The particle of track#8 was scattered by about 90 degree in plate#10 and stopped in plate#11. The particle of track#6 was identified as pi-.

Ⓒ ${}^{5}_{\Lambda}He \rightarrow p + d + 2n$, or other sequences

["old" event: $\Delta B_{\Lambda\Lambda} \approx 4.7 \pm 0.6$ MeV] $\Delta B_{\Lambda\Lambda} = 0.81 \pm 0.15$ MeV

final (PRL) $1.01 \pm 0.20 {}^{+0.18}_{-0.11}$ MeV

Strangeness −2

The H dibaryon ?

H: {uuddss}

$\underset{\sim}{1}_f , \underbrace{0^+ ; 0}$

holds also for ΛΛ

(particularly stable due to $\sum_{i<j} (\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j)\,\delta(\vec{r}_{ij})$ OGE

Jaffe 1977)

$$\to \sqrt{\tfrac{4}{5}}\,\underset{\sim}{8}_c \otimes \underset{\sim}{8}_c + \sqrt{\tfrac{1}{5}}\,\underbrace{\underset{\sim}{1}_c \otimes \underset{\sim}{1}_c}$$

$$\sqrt{\tfrac{1}{8}}\,\Lambda\Lambda + \sqrt{\tfrac{4}{8}}\,\Xi N + \sqrt{\tfrac{3}{8}}\,\Sigma\Sigma$$

if H exists, why $^{\;\;6}_{\Lambda\Lambda}\mathrm{He} \not\to H + {}^4\mathrm{He}$?

[range of calculations: $B_H \sim 80$ to -100 MeV.]

	6q "inside"	BB "outside"
H	attraction	repulsion
ΛΛ	repulsion	attraction

How effective is this barrier for stopping ΛΛ → H from tunneling?

AGS dedicated exp's, 813/836

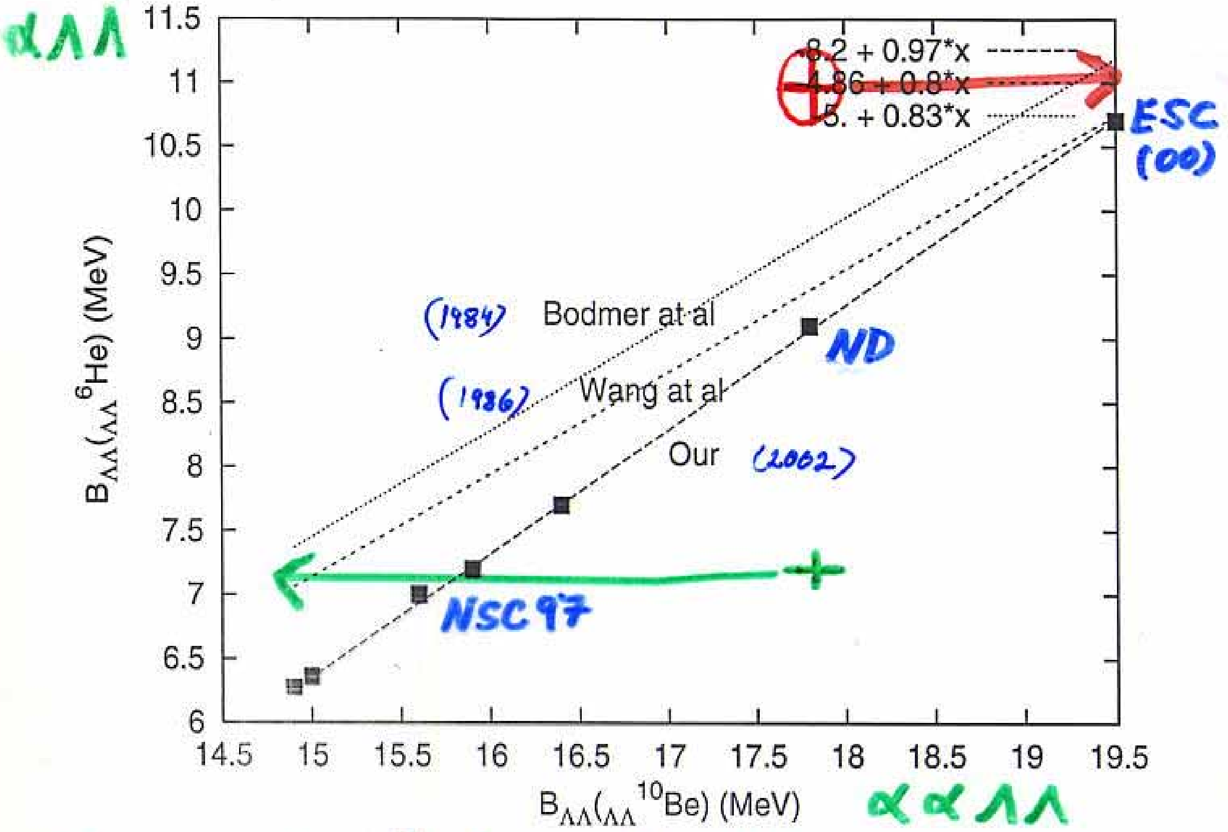
$\Xi^- d \to H n$

$K^- \, {}^3\mathrm{He} \to K^+ H n$

(suggested by Aerts + Dover)

deeply bound H ruled out by E836 (PRL 1997)

Consistency of $_{\Lambda\Lambda}^{6}$He and $_{\Lambda\Lambda}^{10}$Be



3 and 4-body calculations

- 'old' $_{\Lambda\Lambda}^{6}$He event (1966)
- 'new' $_{\Lambda\Lambda}^{6}$He event (2001)

$\Delta B_{\Lambda\Lambda} = $ 4.7±0.6 / 1.0±0.3 MeV

'Our' = Filikhin and Gal, PRC 65 (2002) 041001
NPA 707 (2002) 491

⇆ add ±3 MeV to $B_{\Lambda\Lambda}(_{\Lambda\Lambda}^{10}Be)$ due to $^{8}Be(2^{+})$

Nijmegen potential models (one-boson-exchange)

$(\Lambda\Lambda)_{^1S_0}$

hard core D (1977) attraction 1 - 5 MeV
F (1979) repulsion

soft core (attractive)

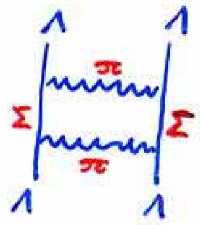
NSC 89

NSC 97
Λ-binding ✓ } versions
spin dependence ✓ } e, f
$\lesssim$ 1 MeV

ESC00 ~ 5 MeV

why ΛΛ interaction is expected weak ?

1. no one-pion exchange - - - - - -



2. quark-model motivated couplings

$$\frac{g^2_{\sigma\Lambda\Lambda}}{g^2_{\sigma NN}} \sim \frac{g^2_{\omega\Lambda\Lambda}}{g^2_{\omega NN}} \sim \left(\frac{2}{3}\right)^2 \quad \left(\begin{matrix}\text{non-s}\\ \text{quarks}\end{matrix}\right)$$

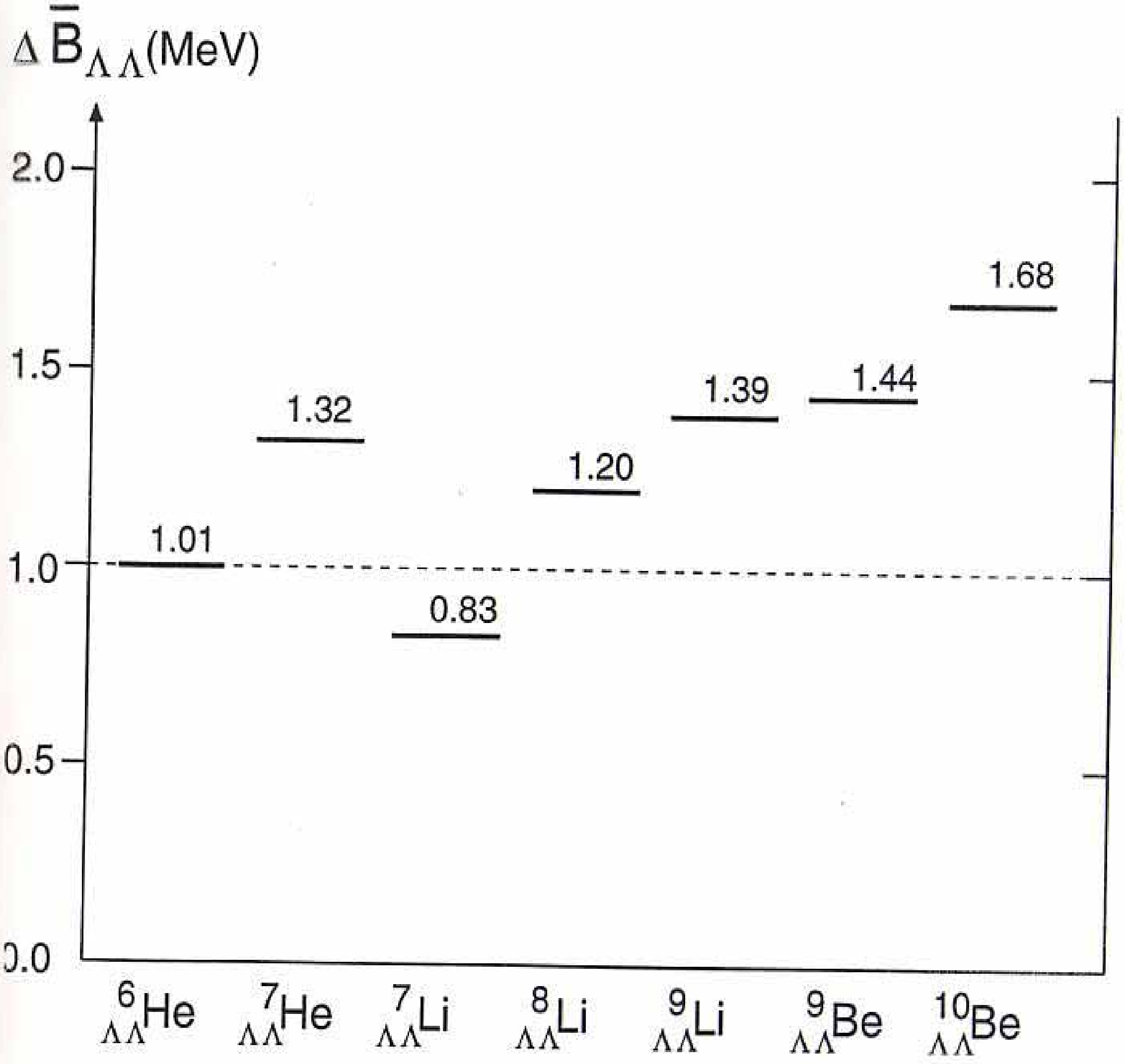
$$\therefore |V_{\Lambda\Lambda}| \lesssim \frac{1}{2} |V_{NN}|$$

$$|V_{\Lambda\Lambda}| < |V_{\Lambda N}| < |V_{NN}|.$$

but earlier ΛΛ hyp. data indicated $|V_{\Lambda N}| < |V_{\Lambda\Lambda}| \lesssim |V_{NN}|$

Hiyama et al. PRC 66 (2002)

024007



$\alpha X \Lambda\Lambda$ cluster model

$^{6}_{\Lambda\Lambda}$He mostly

New calculations incorporate

(i) $\Lambda N - \Sigma N$ coupling (evident from A=4 Λ hypernuclei)

(ii) $\Lambda\Lambda - \Xi N - \Sigma\Sigma$ coupling

Carr, Afnan, Gibson (1997)

Afnan, Gibson (PRC 2003)

* Myint, Shinmura, Akaishi (EPJ A 2003)

Filikhin, Gal, Suslov (PRC 2003)

Vidaña, Ramos, Polls (PRC2004) $\Sigma\Sigma$ is important!

Lanskoy, Yamamoto (PRC 2003) $^{5}_{\Lambda\Lambda}$He

effects are small, 0.2–0.3 MeV, except for *
(about double) (and except for A=5)

Yamada (PRC 2004)

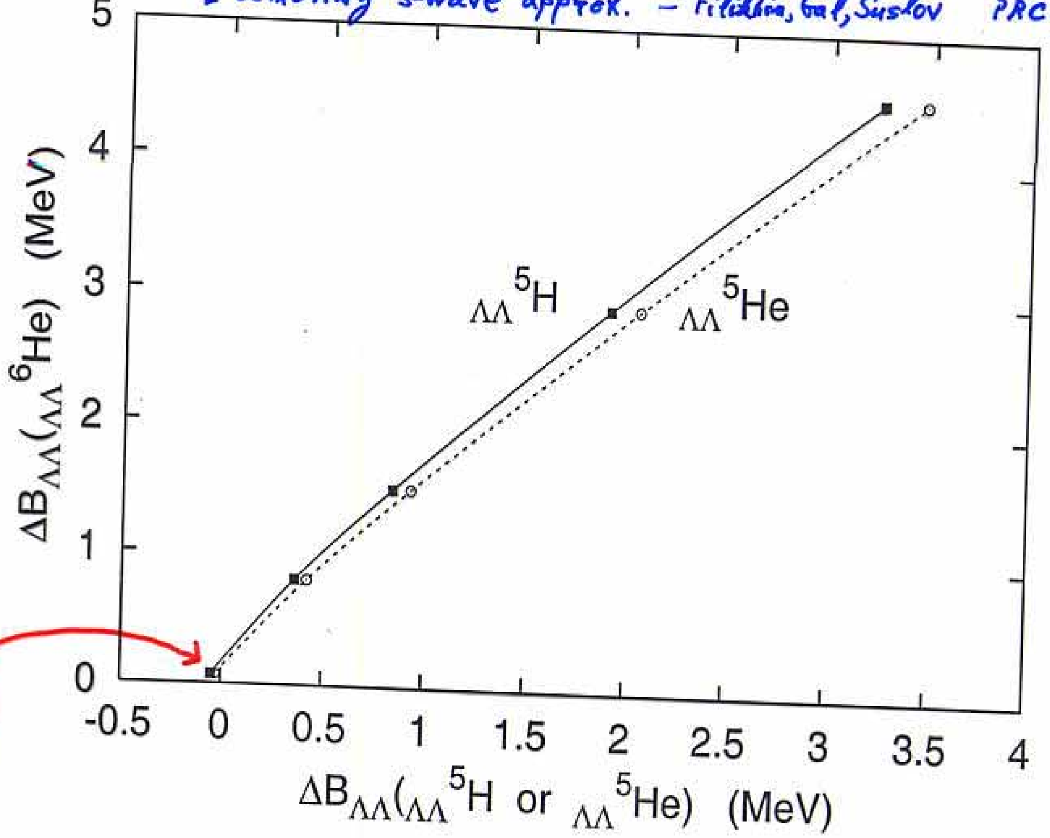
(iii) rearrangement effects in ^{4}He

Kohno, ~~et al~~ Fujiwara, Akaishi (PRC 2003) huge !?

(i)+(ii) Nemura et al. (2004)

$^{6}_{\Lambda\Lambda}He = \Lambda\Lambda\alpha$ Filikhin and Gal, Faddeev calcs. PRC NPA (2002)

[removing s-wave approx. – Filikhin, Gal, Suslov PRC (2008)]



$V_{\Lambda\Lambda}=0$

$^{5}_{\Lambda\Lambda}H$: $\Lambda\,\underbrace{\Lambda\;{}^{3}H}_{{}^{4}_{\Lambda}H \text{ is reproduced}}$

1^{+} —— 1.1

0^{+} —— 0

MeV

$^{4}_{\Lambda}Z$

$^{5}_{\Lambda\Lambda}He$: $\Lambda\,\underbrace{\Lambda\;{}^{3}He}_{{}^{4}_{\Lambda}He \text{ is reproduced}}$

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda} - 2\left(\frac{3}{4}B_{\Lambda}(1^{+}) + \frac{1}{4}B_{\Lambda}(0^{+})\right),$$

yet $^{5}_{\Lambda\Lambda}Z$ is stable against $^{5}_{\Lambda\Lambda}Z \to \Lambda + {}^{4}_{\Lambda}Z$

AGS - E906

$K^- + {}^{9}Be \rightarrow K^+ + {}_{\Lambda\Lambda}X \left({}_{\Lambda}U + {}_{\Lambda}V \right)$

${}_{\Lambda\Lambda}Y \rightarrow \underline{\underline{\pi^-}} + {}_{\Lambda}Z$

$\hookrightarrow \underline{\underline{\pi^-}} + V$

looking for pairs
of decay pions
in addition to those
from ${}_{\Lambda}U + {}_{\Lambda}V$ decays

Production of ${}^{4}_{\Lambda\Lambda}H$ Hypernuclei

J. K. Ahn[13], S. Ajimura[10], H. Akikawa[7], B. Bassalleck[9], A. Berdoz[2], D. Carman[2], R. E. Chrien[1], C. A. Davis[8,14], P. Eugenio[2], H. Fischer[3], G. B. Franklin[2], J. Franz[3], T. Fukuda[15], L. Gan[4], H. Hotchi[12], A. Ichikawa[7], K. Imai[7], S. H. Kahana[1], P. Khaustov[2], T. Kishimoto[10], P. Koran[2], H. Kohri[10], A. Kourepin[6], K. Kubota[12], M. Landry[8], M. May[1], C. Meyer[2], Z. Meziani[11], S. Minami[10], T. Miyachi[12], T. Nagae[5], J. Nakano[12], H. Outa[5], K. Paschke[2], P. Pile[1], M. Prokhabatilov[6], B. P. Quinn[2], V. Rasin[6], A. Rusek[1], H. Schmitt[3], R. A. Schumacher[2], M. Sekimoto[5], K. Shileev[6] Y. Shimizu[10], R. Sutter[1], T. Tamagawa[12], L. Tang[4], K. Tanida[12], K. Yamamoto[7], L. Yuan[4]

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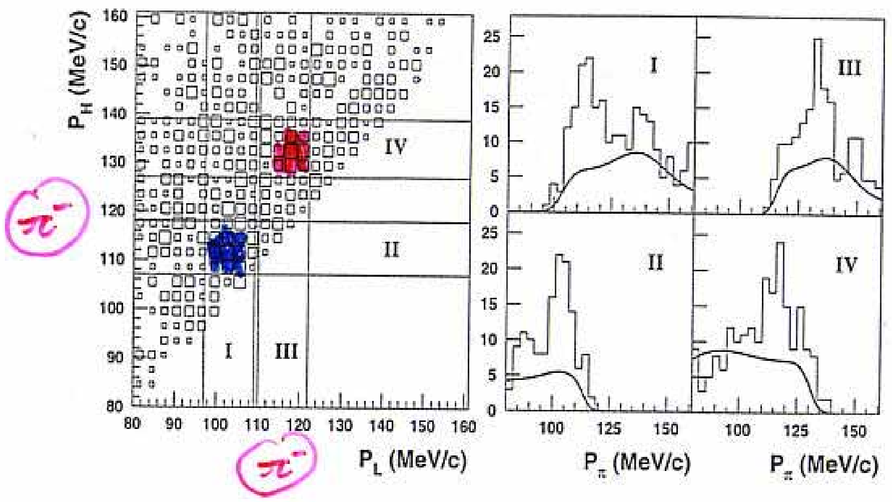
(Received: PRL ? ✓)
87 (2001)



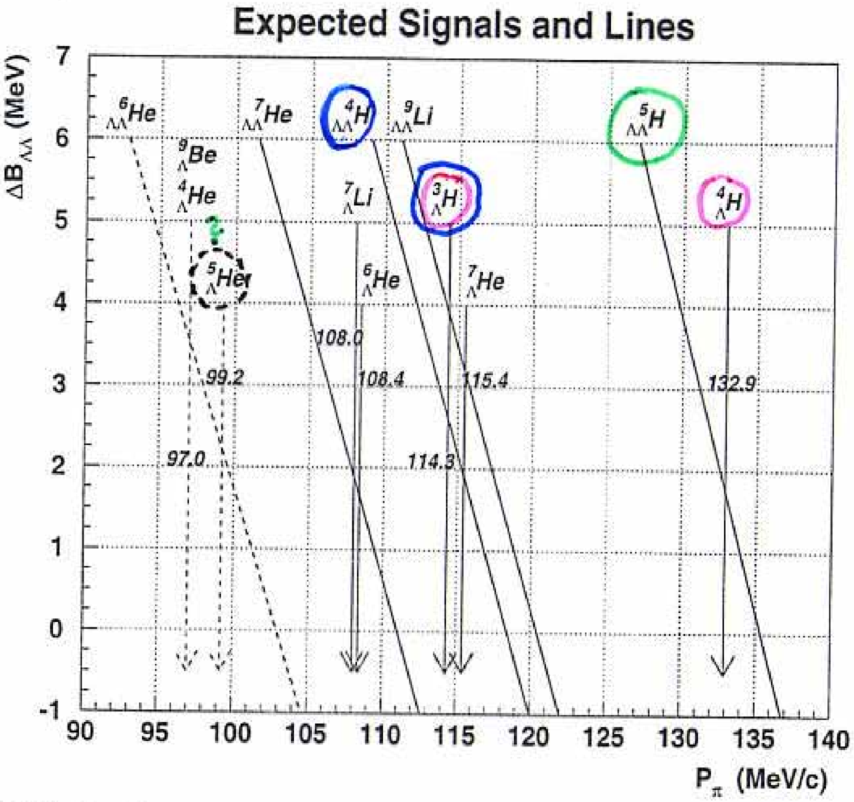


FIG. 3. The characteristic π momenta of the singly and doubly strange hyperfragments expected to be produced in this experiment. Dashed lines represent 3-body decay; the inclined lines show the dependence of the pion momenta on the assumed $\Lambda\Lambda$ pairing energy. This figure was adopted from Reference [2] and modified.

~~${}_{\Lambda\Lambda}^{4}H \to \pi^- + {}_{\Lambda}^{4}He$~~ ${}_{\Lambda\Lambda}^{4}H \to \pi^- + {}_{\Lambda}^{4}He^{*} \longrightarrow p + {}_{\Lambda}^{3}H$

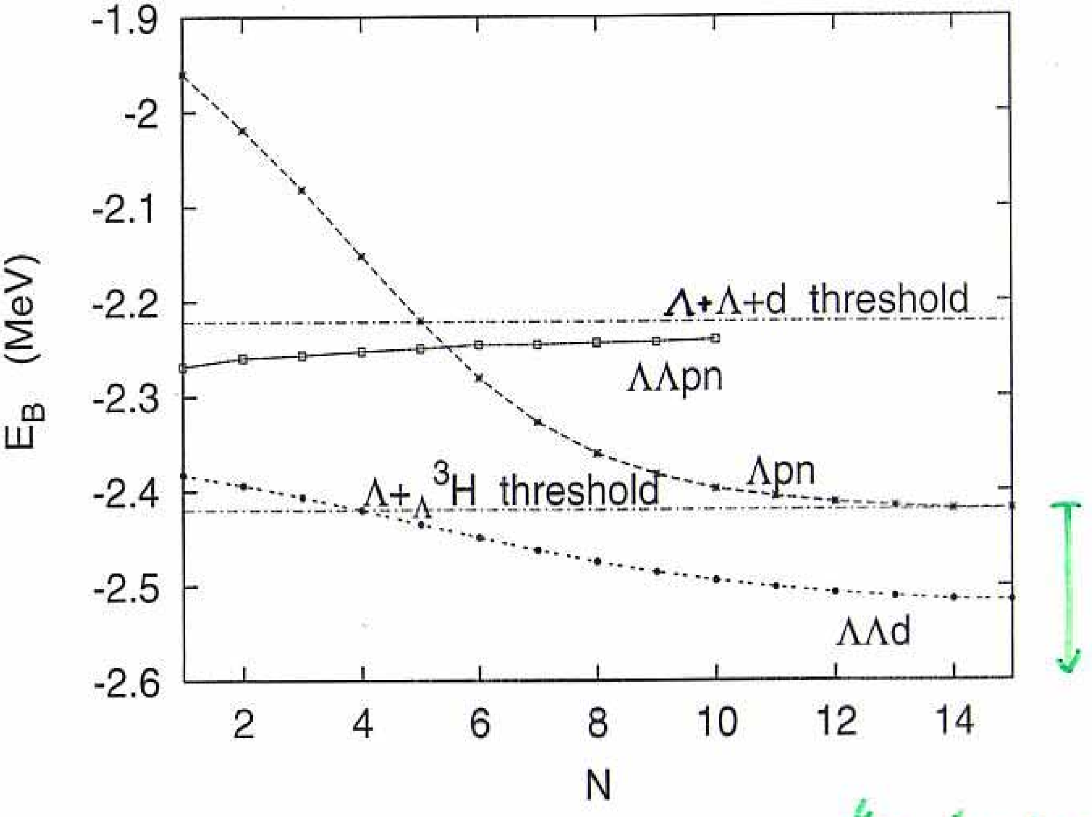
$\hookrightarrow \pi^- + {}^{3}He$

(${}_{\Lambda\Lambda}^{5}H \to \pi^- + {}_{\Lambda}^{5}He$ no signif. trace)

$\Delta B_{\Lambda\Lambda} \sim 1$ MeV for ${}_{\Lambda\Lambda}^{6}He$ is incompatible with ${}_{\Lambda\Lambda}^{4}H$ groundstate!

(Nemura)

Filikhin and Gal, PRL 89 (2002)



$^{4}_{\Lambda\Lambda}H$ binding

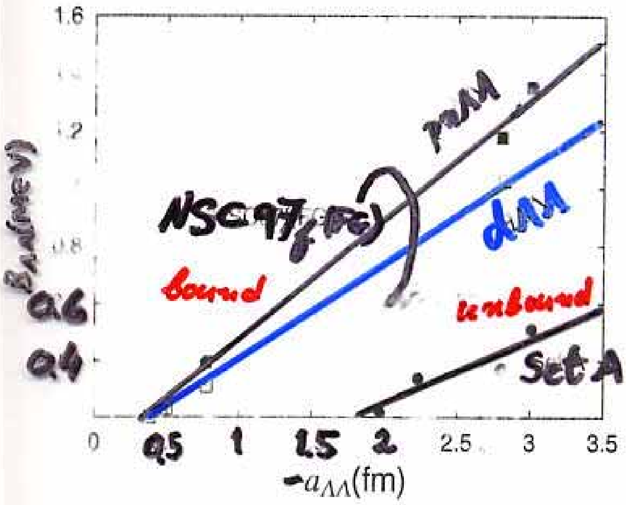
4-body calc.

Increasing $V_{\Lambda\Lambda}$ does not bind $^{4}_{\Lambda\Lambda}H$!

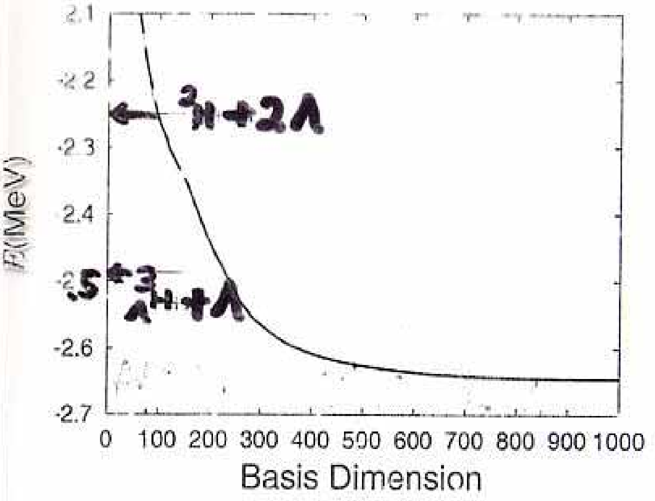
How come Λpn is bound, but ΛΛpn is not ?

Nemura, Akaishi, Myint, PRC 67 (2003)

Stochastic variational search for ${}^{4}_{\Lambda\Lambda}H$



Calculated $B_{\Lambda\Lambda}({}^{4}_{\Lambda\Lambda}H)$ as a function of the scattering length, $a_{\Lambda\Lambda}$. The solid squares were obtained using the [illegible] ΛN potential and the solid circles by the Set A potential. The open squares are the result of the $d\Lambda\Lambda$ three-body model, taken from Ref. [1]. The straight lines were drawn only for the sake of a guide to the reader.



[illegible] energy [illegible] of ${}_{\Lambda\Lambda}$H as a function of the basis dimension, K. The interactions are taken from Ref. [1], spin-[illegible] NSC97f(FG) ΛN, and [illegible] deduced from the recent [illegible]perimental $B_{\Lambda\Lambda}({}_{\Lambda\Lambda}He)$. The converged energy is clearly [illegible]wer than the ${}^{3}_{\Lambda}H+\Lambda$ threshold.

ough the convergence of the energy is rather slow, the

	$\langle T_c\rangle$	$\langle V_{NN}\rangle$	E_c	$\sqrt{\langle r^2$
${}^{2}H$	18.74	−20.99	[illegible]	3.85
${}^{3}_{\Lambda}H^{*}$	19.09	−21.20	[illegible]	[illegible]
${}^{3}_{\Lambda}H$	20.70	−22.30	−1.59	3.54
${}^{4}_{\Lambda\Lambda}H(a_{\Lambda\Lambda}=-0.77\text{fm})$	22.28	−23.17	−0.88	3.34
${}^{4}_{\Lambda\Lambda}H(a_{\Lambda\Lambda}=-2.8\text{fm})$	24.73	−24.55	0.18	3.08

TABLE I: Energy expectation values of kinetic (T tential (V_{NN}) terms, and the sum of these energies (the pn subsystem, in units of MeV. The rms [illegible] a proton and a neutron, or between a nucleon and a Λ listed, in units of fm. The spin-triplet pn and NSC ΛN potentials, taken from Ref. [1], were used.

	$B_{\Lambda}({}^{3}_{\Lambda}H)$	$B_{\Lambda}({}^{4}_{\Lambda}H)$	$B_{\Lambda}({}^{4}_{\Lambda}H^{*})$
NSC97f(FG)	0.24	2.69	1.99
Set A	0.18	2.24	1.14
Experiment	0.13 ± 0.05	2.04 ± 0.04	1.00 ± 0.0

TABLE II: Λ separation energies, given in units of M $A = 3,4$ single-Λ hypernuclei. The Minnesota NN p was used.

other at the point where $a_{\Lambda\Lambda} = 0$ fm. This [illegible] a the polarization of the pn subsystem is small, an the $d\Lambda\Lambda$ model is a good approximation if the teraction is very weak. The polarization of the de subsystem grows as the strength of the ΛΛ inter increases. Table I lists the energy expectation val the proton and neutron subsystem in each (hype cleus, and also the root-mean square distances be a p and an n, or between a nucleon and a Λ. Here the kinetic energy of the pn subsystem, which is d by $T_c = (p_1 - p_2)^2/4m_N$. The table shows that t fluence of the Λ particle upon the internal struct the pn subsystem becomes large as the Λ particle close to the nucleon. Especially in the case of a st attractive ΛΛ potential, the change in the internal e [illegible] or of the rms distance $\sqrt{\langle r^2_{NN}\rangle}$ is significan

As can be seen in Fig. 2, the $B_{\Lambda\Lambda}$ value is sensit the choice of the ΛN potential. For the purpose o dicting whether ${}^{4}_{\Lambda\Lambda}H$ exists as a particle-stable b state, the ΛN potential has to be examined car Table II compares the B_{Λ} values of $A = 3,4$ h nuclei. The calculated B_{Λ} value of the $A = 4$ s using NSC97f(FG) is larger than that using Set

Summary and Outlook

(i) $S=-2$ is the frontier of experimentation in Strangeness Nuclear Physics

a. $\Lambda\Lambda$ hypernuclei

(relevance to H dibaryon)

b. Ξ hypernuclei

(relevance to Strange Hadronic Matter)

(ii) Facilities :

AGS - uncertain future

Ξ^- atom search is feasible!

Japan Hadron Facility $\gtrsim$ 2006

50 GeV hadron machine

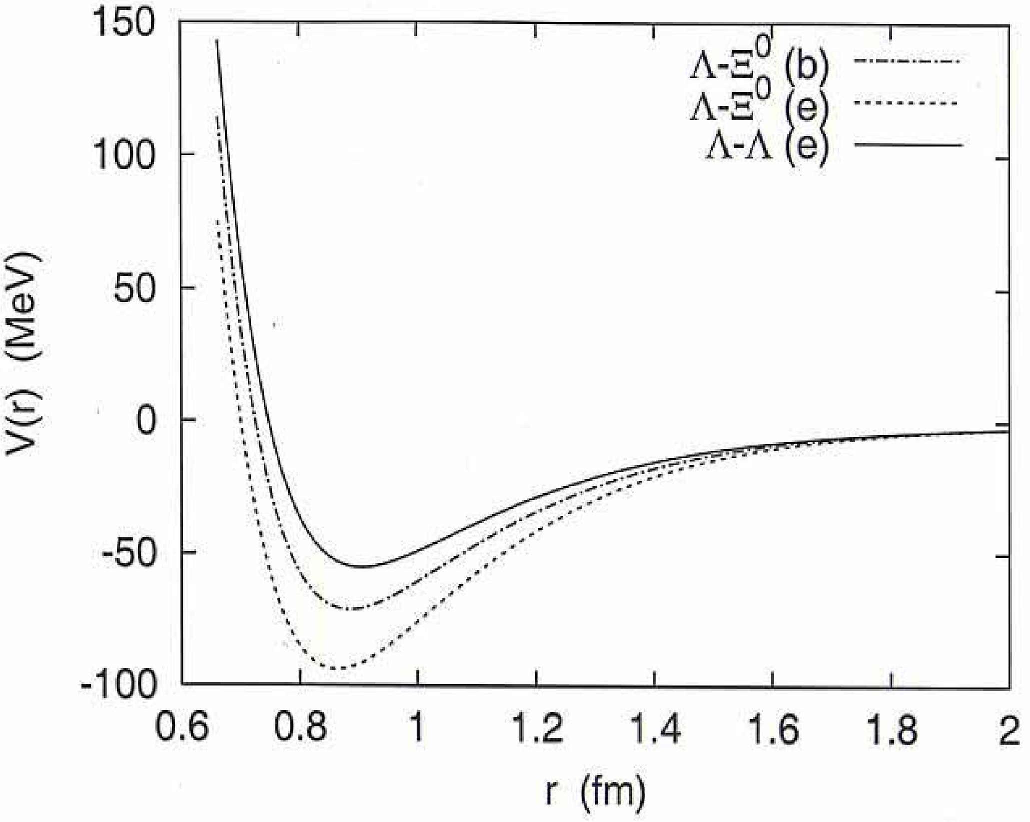
High Energy Storage Ring (GSI) - $\bar{p}$ beam

Pochodzalla et al. : $\bar{p}p \to \Xi^- \Xi^+$

(3 GeV/c) $\quad \Lsh\ \Xi^- p \to \Lambda\Lambda$

estimate 4000 $\Lambda\Lambda$ hyp. per month on ^{12}C target

(Kilian : $\bar{p}p \to \bar{K}^* K^*$, $\bar{K}^* N \to \Xi K$)



from $S=-2$ to $S=-3$

using NSC97

Faddeev Calculations

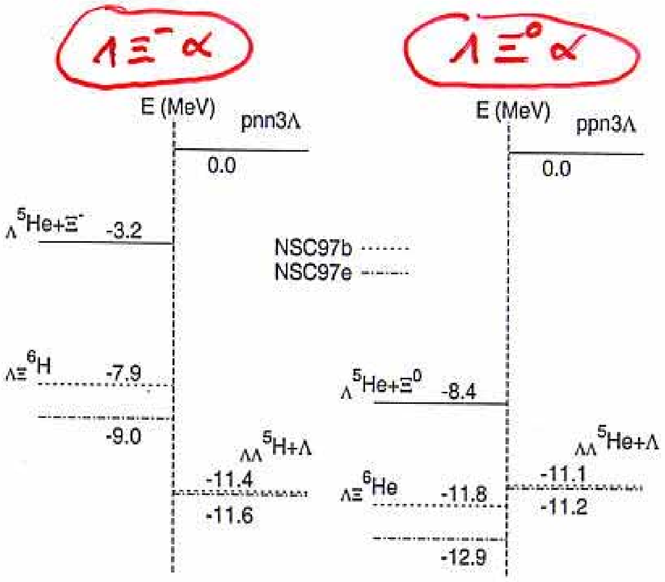


FIGURE 4. Calculated level scheme of $^{6}_{\Lambda\Xi}$H and $^{6}_{\Lambda\Xi}$He hypernuclei.

[18], does not resolve this incompatibility. Adding $^{13}_{\Lambda\Lambda}$B [9] as input does not alleviate it either, since the possibility of unobserved γ deexcitation cannot be dismissed also for this species, while on the theoretical side the analysis of $^{13}_{\Lambda\Lambda}$B in terms of a few-body cluster is more dubious than for the lighter $\Lambda\Lambda$ species.

Discarding past history of this emulsion experimentation for $\Lambda\Lambda$ hypernuclear events identified as heavier than $^{6}_{\Lambda\Lambda}$He, because of the ambiguities mentioned here, one remains with the very recent report from the KEK E373 experiment [14] which claims to have identified uniquely $^{6}_{\Lambda\Lambda}$He, with $\Delta B_{\Lambda\Lambda} \sim 1$ MeV. No particle-stable excited states are possible for this species or for its Λ hypernuclear core $^{5}_{\Lambda}$He, so this event - if confirmed - should be taken as the most directly relevant constraint on the $\Lambda\Lambda$ interaction.

Moreover, $^{6}_{\Lambda\Lambda}$He is also ideally suited for three-body cluster calculations such as the Faddeev equations here solved for the $\alpha\Lambda\Lambda$ system. Using *s*-wave soft-core $\Lambda\Lambda$ potentials that simulate several of the Nijmegen $\Lambda\Lambda$ interaction models, we have shown that model NSC97 is the only one capable of coming close to the observed binding, short by about 0.5 MeV of the new value [14]. In fact, we estimate the theoretical uncertainty of our Faddeev calculation for $^{6}_{\Lambda\Lambda}$He as bounded by 0.5 MeV, and such that the precisely calculated binding energy is *larger* by a fraction of this bound than the $\Delta B_{\Lambda\Lambda}$ values shown in Table 4. Taking into account such possible corrections would bring our calculated $\Delta B_{\Lambda\Lambda}$ values to within the error bars of the reported $\Delta B_{\Lambda\Lambda}$ value. There are two possible origins for this theoretical uncertainty, one is the restriction to *s*-waves in the partial-wave expansion of the Faddeev equations, excluding higher ℓ values; the other one is ignoring the off-diagonal $\Lambda\Lambda - \Xi N$ interaction which admixes Ξ components into the $^{6}_{\Lambda\Lambda}$He wavefunction. Both effects have been tested in several previous calculations and found small. For example, a recent work by Yamada and Nakamoto [37] using

$S=-3$

${}^{6}_{\Lambda\Xi}\mathrm{He}$ is particle stable $(\Lambda\Xi^0\alpha)$

${}^{6}_{\Lambda\Xi}\mathrm{H}$ is not particle stable $(\Lambda\Xi^-\alpha)$

$(m_{\Xi^-} > m_{\Xi^0}$ by $6.5\ \mathrm{MeV})$

Lightest $S=-3$ stable bound state;

requires Ω^- initiated reactions for production

$$\Omega^- + {}^{6}\mathrm{Li} \rightarrow {}^{6}_{\Lambda\Xi}\mathrm{He} + n$$

$$(\ \Xi^- + {}^{6}\mathrm{Li} \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + n\ )$$

Main assumptions:

1. $\Lambda\Xi$ from model NSC97 which is close to reproducing ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ 'new' $B_{\Lambda\Lambda}$.
2. $\Lambda\alpha$ is fitted to $B_{\Lambda}({}^{5}_{\Lambda}\mathrm{He})$.
3. $\Xi\alpha$ is normalized to Ξ-${}^{11}\mathrm{B}$ potential depth as deduced from E885 $K^- + {}^{12}\mathrm{C} \rightarrow K^+ + {}^{12}_{\Xi}\mathrm{Be}$.

Ξ-nucleus interaction is poorly known;

search for ${}^{A}_{\Xi}Z$ bound states $(\Gamma \lesssim 3\ \mathrm{MeV})$

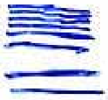
and look for Ξ^- X rays in Ξ^- atoms.

Introduction

From Hypernuclei to Multi-Strange Objects

ordinary nuclei

Λ-hyp.



$_{\Lambda}^{A}Z$

$$\left[\underbrace{(M_\Lambda - M_N)}_{\sim 176\ \text{MeV}} + (B_N - B_\Lambda) \gg \varepsilon_F = \frac{k_F^2}{2M_N} \approx 40\ \text{MeV} \right.$$

^{A}Z

$$_{\Lambda}^{A}Z \xrightarrow[\sim 10^{-10}\,\text{sec}]{}$$

$$\Lambda \to \begin{matrix} p\,\pi^- \\ n\,\pi^0 \end{matrix}$$

$$\Lambda N \to NN$$

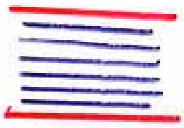
Add strangeness to nuclei: $_{\Lambda}^{A}Z$, $_{\Lambda\Lambda}^{A}Z$, ...

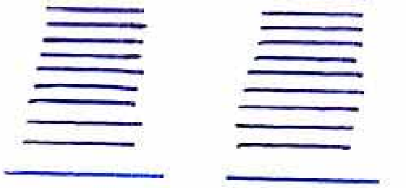
Strange Quark Matter

Chin, Kerman 1979

Witten } 1984
Farhi, Jaffe

$\varepsilon_F \simeq k_F \sim 300$ MeV





$$(M_\Lambda - M_N) \sim m_s - m_{u,d} \Big]$$

~ 150 MeV

s quarks

d u quarks

Q (charge) $-\frac{1}{3}$ $-\frac{1}{3}$ $+\frac{2}{3}$

Stable (?) Matter ???

$f_q \approx \frac{1}{2}(1 - f_s)$

$$f_q = \frac{Z}{A} \to A^{-2/3} \to 0, \quad f_s \equiv \frac{|S|}{A} \sim 0.5 - \underline{1.0}$$

3. Multi-Strange Objects -- Λ's and Ξ's

$$\Xi + N \rightarrow \Lambda + \Lambda \; + \underbrace{(\sim) 25 \; \text{MeV}}_{}$$

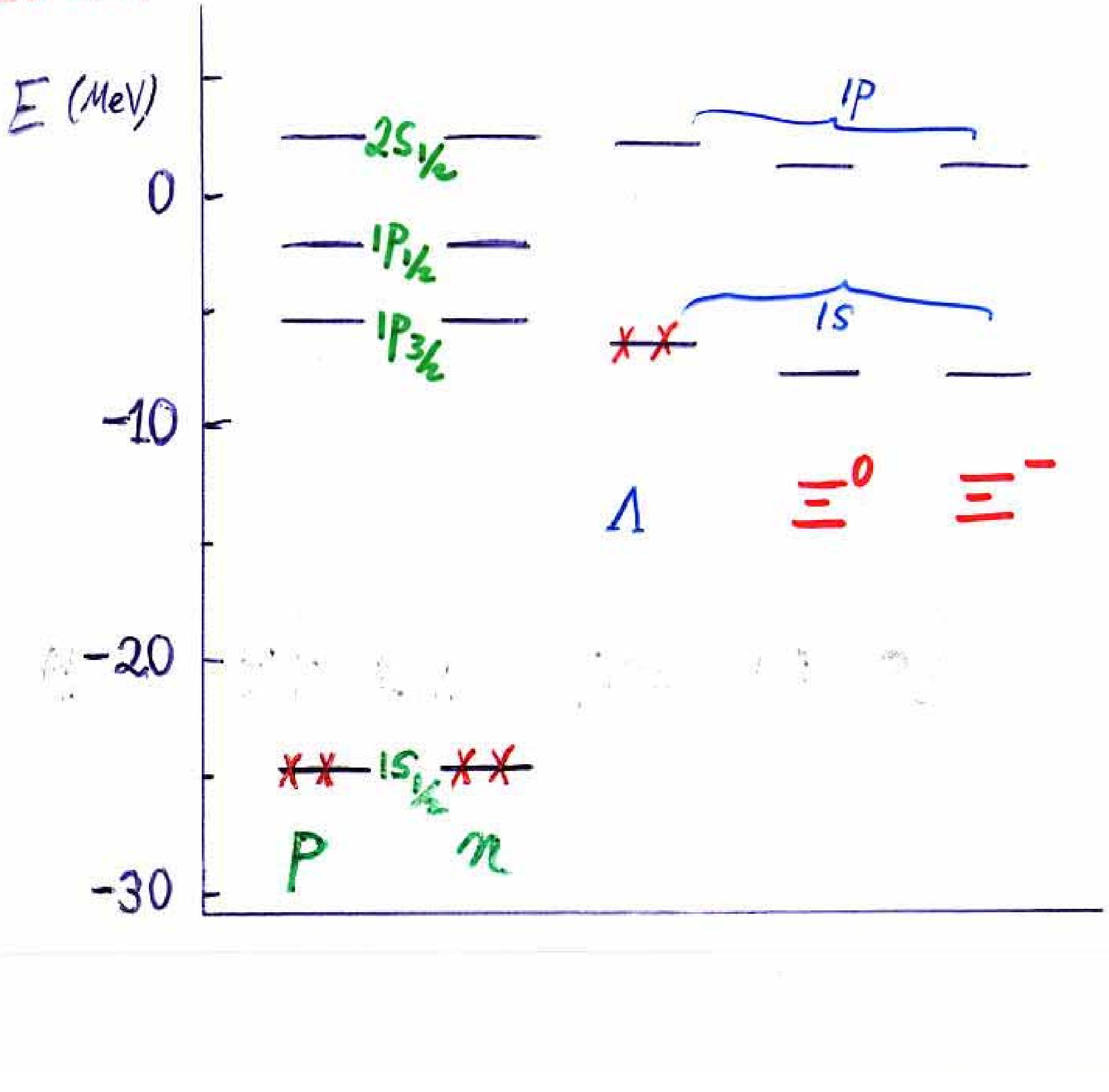
(σ+ω model)

overcome it
by Pauli blocking
of bound Λ's

Example : $pp\,nn\,\Lambda\Lambda\,\Xi^0\Xi^0\,\Xi^-\Xi^-$

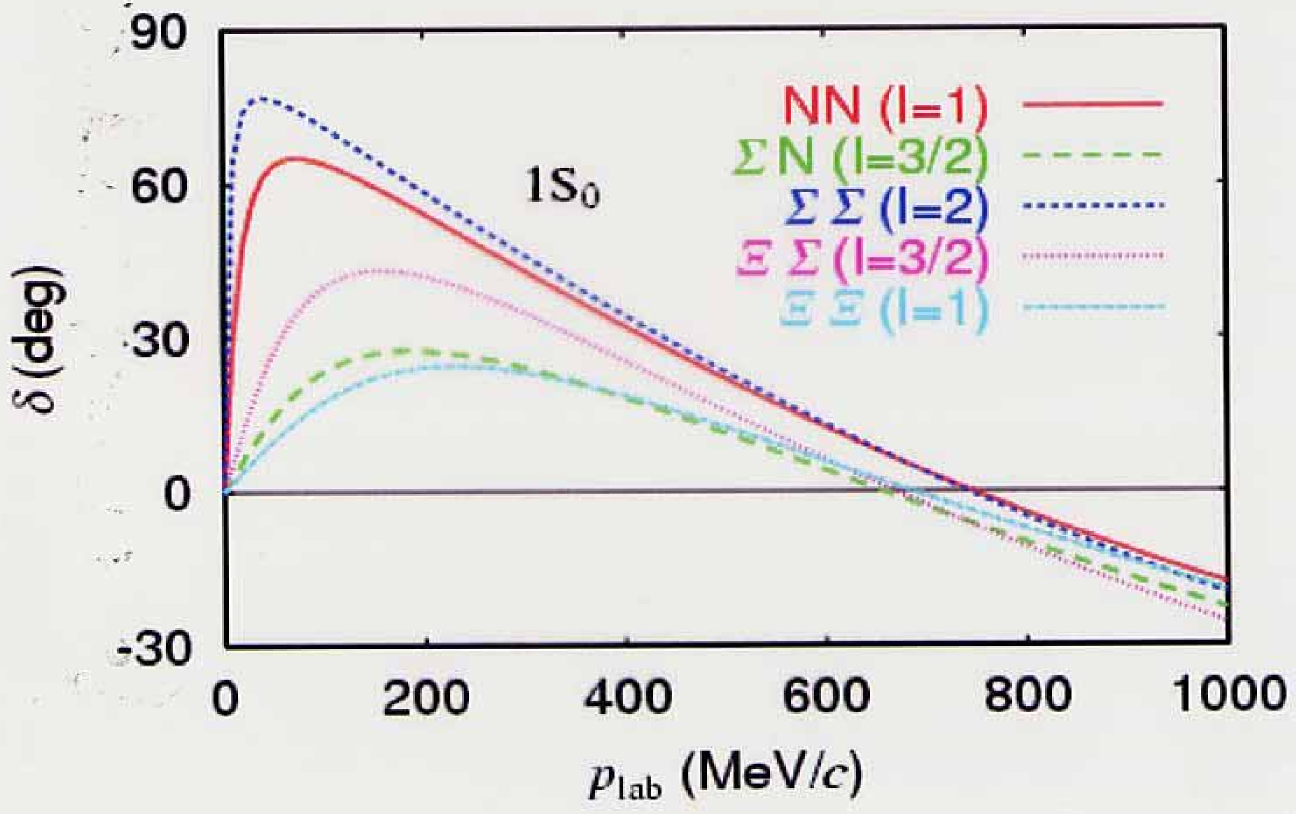
ג'קת נ'ם

Schaffner et al.
PR C 46, 322 (92)



Fujiwara et al.
PRC 64 (2001) 054001.

$^1S_0$ phase shifts for B_8B_8 interactions with the pure (22) state (fss2)



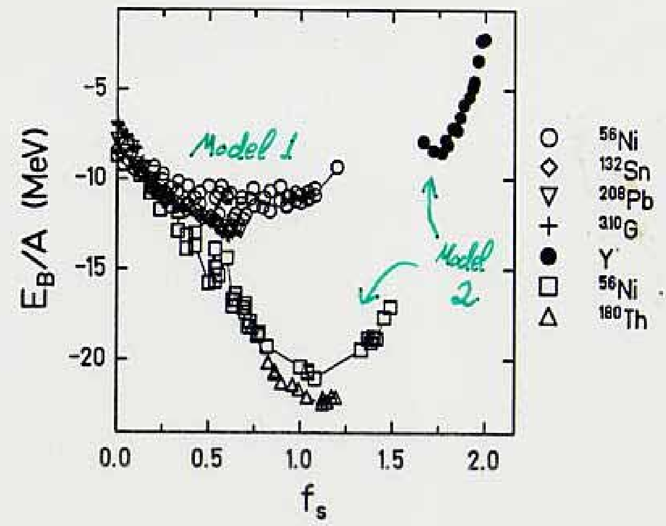


Figure 1: The binding energy of several SHM species vs. the strangeness fraction $f_s = |S|/A$

Schaffner Dover, Gal, C. Greiner, Stöcker

PRL 71 (1993) 1328 ; Ann. Phys. 235 (1994) 35 .

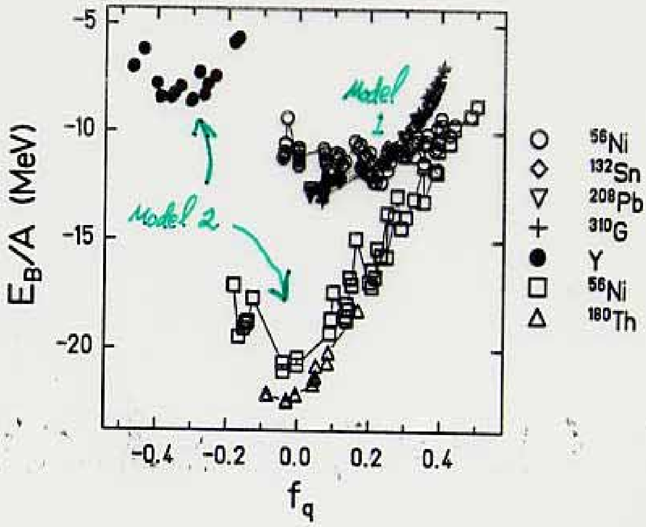
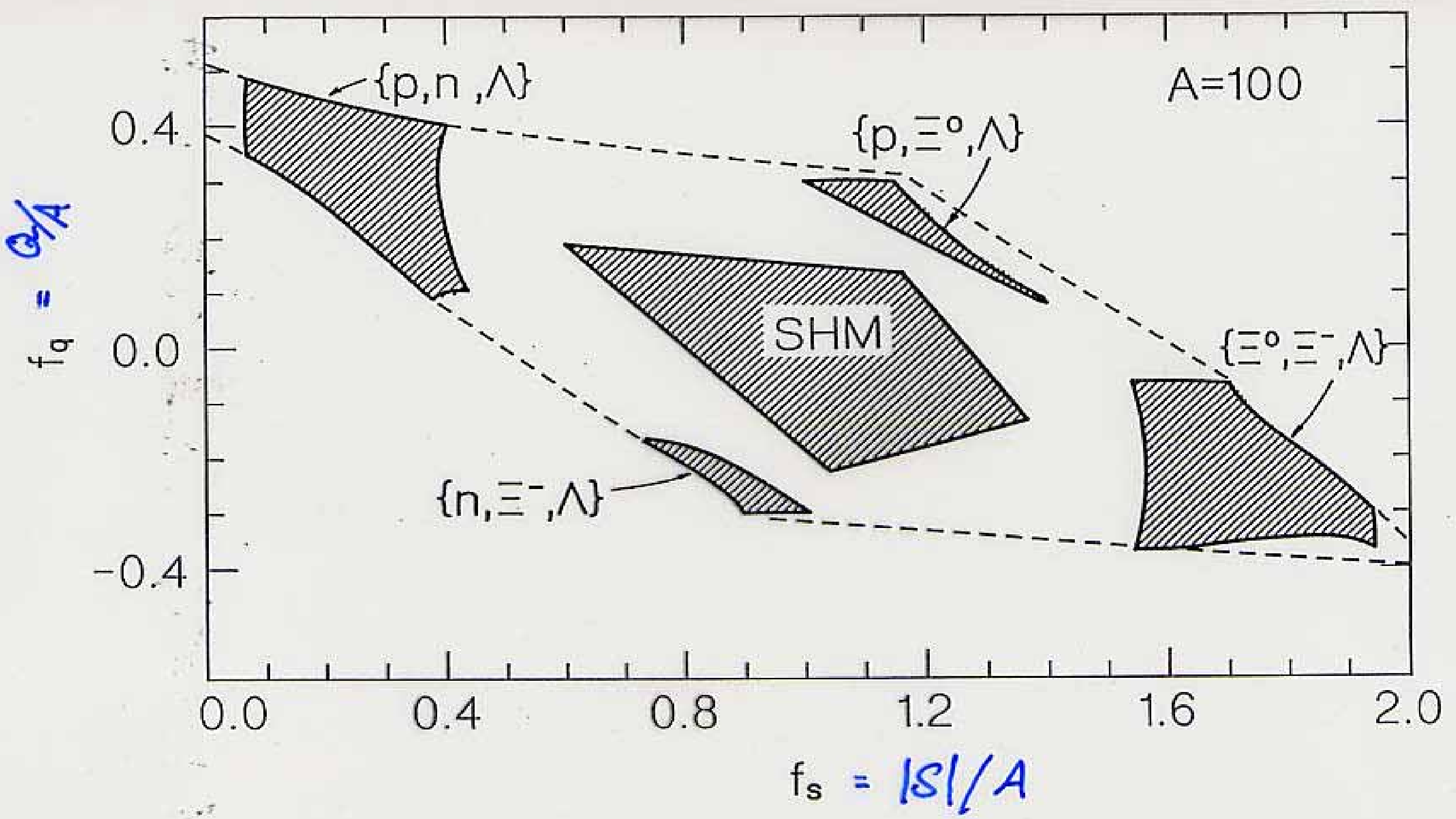


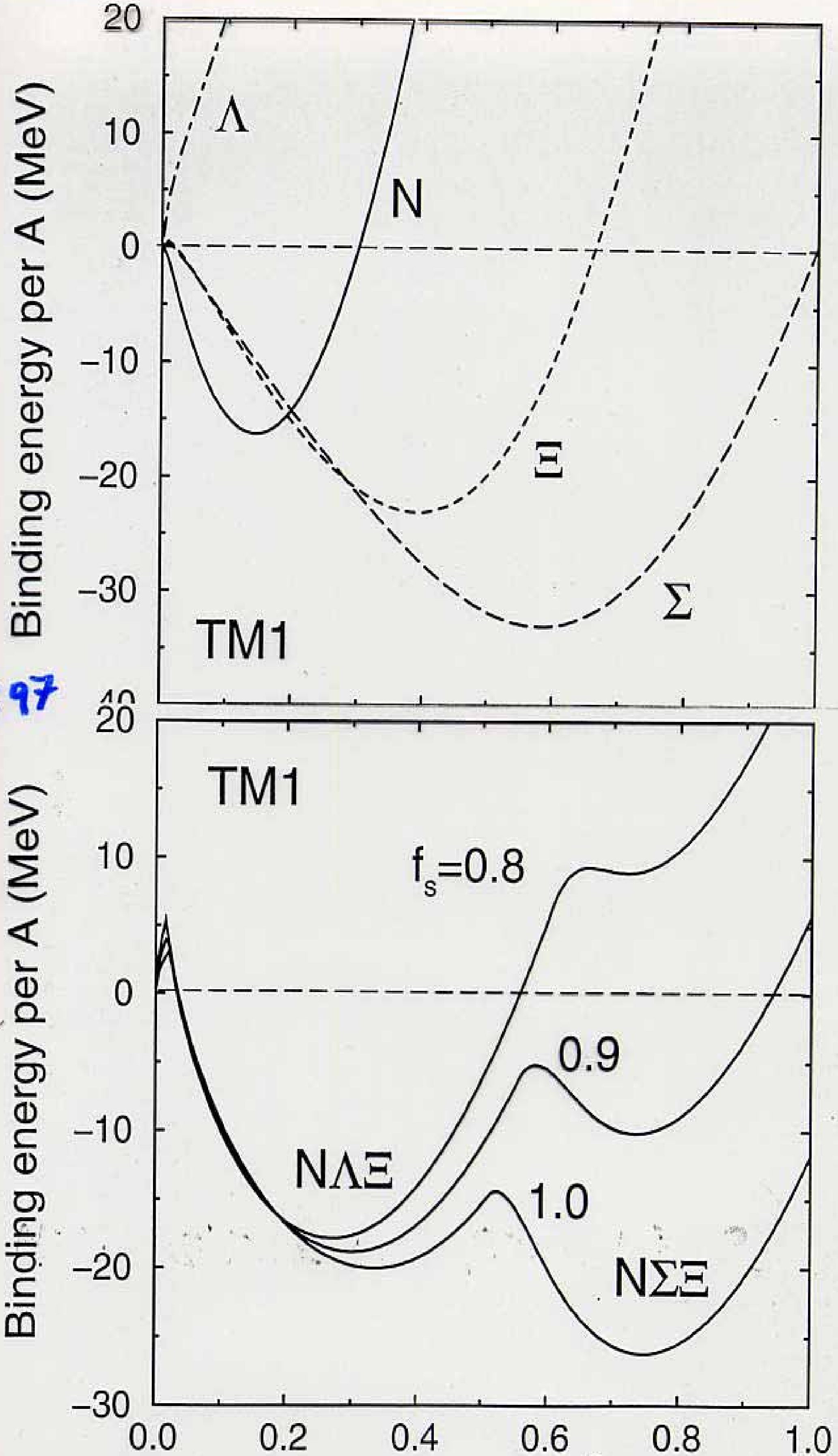
Figure 2: The binding energy of several SHM species vs. the charge fraction $f_q = Z/A$.

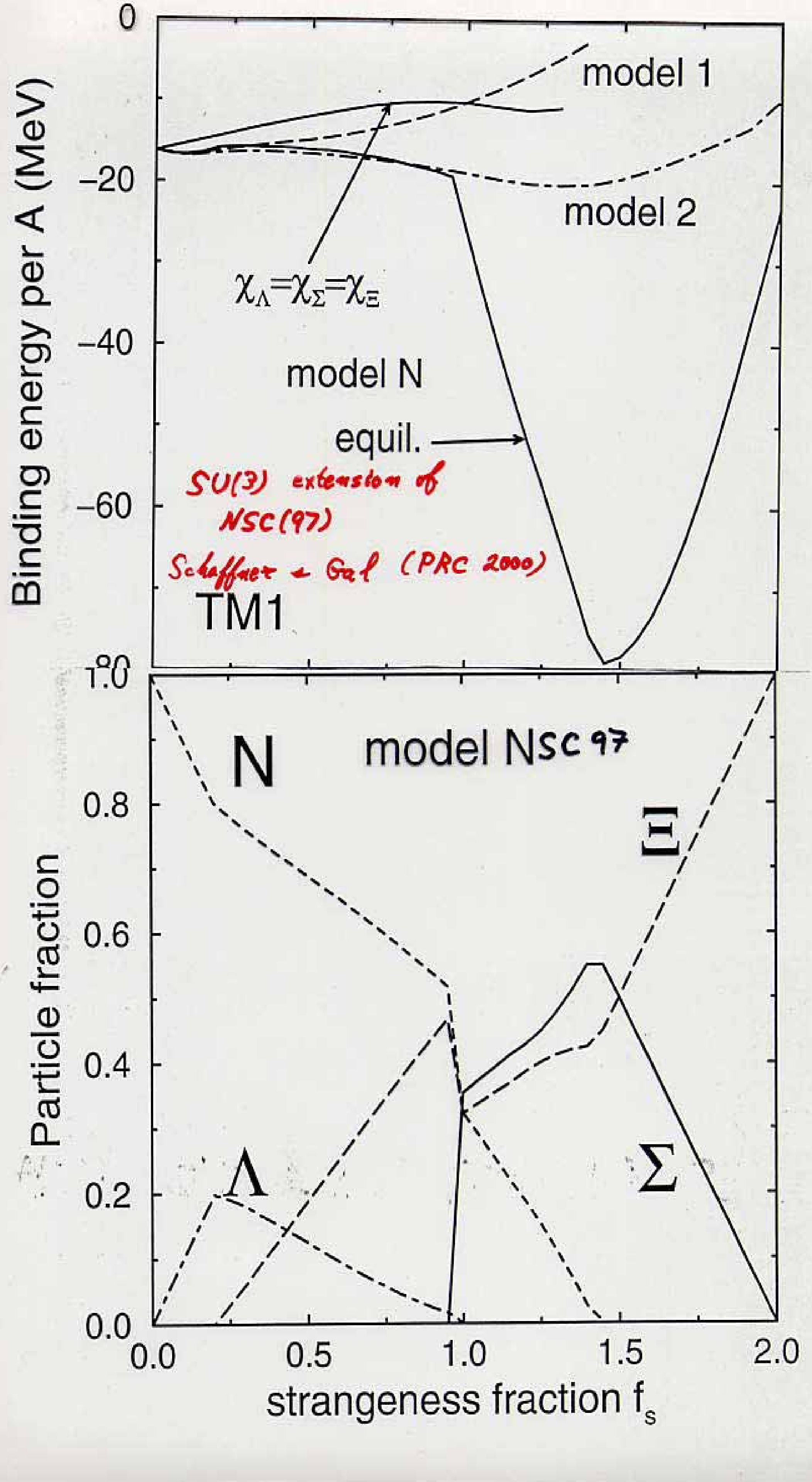


Balberg, Gal, Schaffner
Fig. 5

application of the generalized Bethe Weizsäcker mass formula
(Dover, Gal NPA 1993)

NSC 97


Binding energy per A (MeV)
20
10
0
−10
−20
−30
−40
Λ
N
Ξ
Σ
TM1
Binding energy per A (MeV)
20
10
0
−10
−20
−30
TM1
f_s=0.8
0.9
1.0
NΛΞ
NΣΞ
0.0
0.2
0.4
0.6
0.8
1.0
Density ρ (fm^-3)



SU(3) extension of NSC(97)
Schaffner + Gal (PRC 2000)

CONCLUSION

strange hadronic matter is stable against strong interactions. $\{p, n, \Lambda, \Xi^0, \Xi^-\}$

$\tau \lesssim 10^{-10} - 10^{-12}$ sec

$\rho \sim 2\rho_0$

$f_s \sim 1$

$f_q \sim 0$

$E_B/A \sim -15 - -25$ MeV, but perhaps even more

model dependence is NOT strong

* lightest bound $^{7}_{\Xi^0\Lambda\Lambda}\mathrm{He}$

detection sensitivity of 10^{-n} at AGS => $n \geq |S| + A - 3$

consolidate $S = -2$ hadron/nuclear physics

(* perhaps $^{6}_{\Xi^0\Lambda}\mathrm{He}$ is bound)

NSC97: phase transition $N\Lambda\Xi \rightarrow N\Sigma\Xi$

$(f_s \approx 1)$