Hypernuclear Physics with Quark-Meson Coupling (QMC) model (quark-based relativistic mean field theory)

Hall C Physics Invs. before the 12 GeV upgrade, 08/07/2009

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NPA 814, 66 (2008), PLB, 676, 51 (2009), arXiv:0903.5478 [nucl-th]

(K. Saito, KT, A.W. Thomas, PPNP, 58, 1 (2007))

Outline

- Introduction
- **QMC** model, **finite nuclei**
- Hypernuclei in the latest QMC model (Σ,Λ,Ξ): **no** heavy Σ hypernuclei as in experiments
- **Photoproduction** of Λ-hypernuclei
- Discussions

Introduction

- **(Heavy) nuclei** in terms of **quarks** and **gluons** (or **QCD**) **???!!!**
- **NN**,**NNN**,NNNN,NNNNN..... interactions $\Longrightarrow$ **Nucleus ?** $\Longleftarrow$ shell model, **MF** model,**density** functional theory...**BUT ?**
- **Lattice QCD**: **still** extracting **NN** and **NY**

2-body interactions, [**Y**=hyperons: Λ,Σ,Ξ]

- **Hypernucleus ?** (Nucleus+**Y**) bound states
- **Quark** model based description of **nucleus**

Description of **Nucleus** ?

- **Nucleus**: System of **many nucleons** bound by the strong interaction ⇔ **QCD**
- **Many-body problem**: **difficult!** even using N (hadronic) degrees of freedom

⟹ **“super-difficult”** via **quarks** & **gluons**

Hope: **lattice QCD** (future !???)

Nuclear shell model, QMD (molecular dynamics [**quarks**]), **Mean field model**

Hypernuclei: **SU(3)** so bad ?

Λ hypernuclei: **well established** Expts.

up to **Pb** core nucleus, many states

Σ^+ hypernuclei: **only** ${}^4_\Sigma$**He** **confirmed**

$\Longrightarrow$ Probably **no** other **heavy** Σ hypernuclei

Ξ hypernuclei: **hints – not confirmed**

$\Longrightarrow$ **Planned** Expts.: **(**JLab**?)**, **J-PARC**,

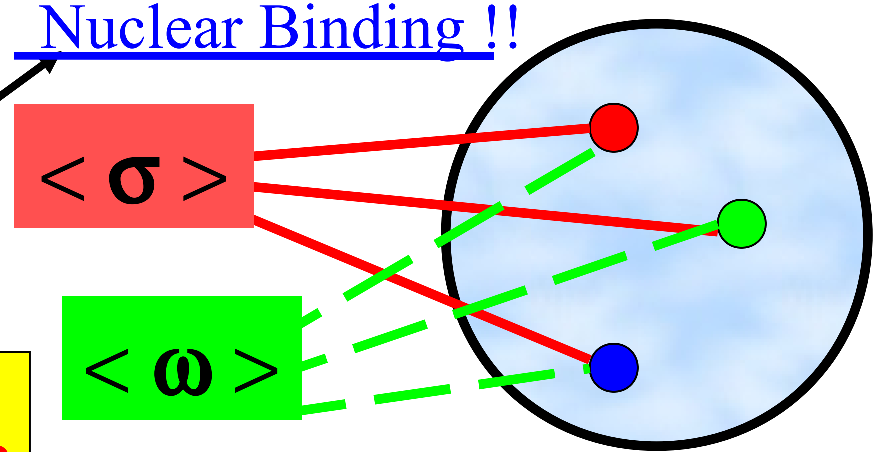
GSI-FAIR

The QMC model P. Guichon, PLB 200, 235 (1988)

(For a review, PPNP 58, 1 (2007))

Light (u,d) quarks interact **self-consistently** with mean **σ** and **ω** fields

Nuclear Binding !!



$m^*_q = m_q - g_\sigma^q \sigma = m_q - V_\sigma^q$

⇓ nonlinear in σ

$M^*_N \cong M_N - g_\sigma^N \sigma + (d/2)(g_\sigma^N \sigma)^2$

$M^*_N = M_N - V_\sigma^N$

$$[i\, \partial\cdot\gamma - (m_q - V_\sigma^q) + \gamma_0 V_\omega^q]\, q = 0$$

1. Start

$V_\omega^N = 3 V_\omega^q$

$$[i\, \partial\cdot\gamma - M^*_N + \gamma_0 V_\omega^N]\, \mathbf{N} = 0$$

Self-consistent !

At Nucleon Level Response to the Applied Scalar Field is the Scalar Polarizability

Nucleon response to **a chiral invariant scalar field** is then a nucleon property of great interest…

$$M^*(\vec{R}) = M - g_\sigma \sigma(\vec{R}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{R})\right)^2$$

Non-linear dependence: **scalar polarizability**
(d)**¼ = 0.22 R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level (**e.g. QMC**), this is the **ONLY** place the response of the **internal structure** of the nucleon enters.

Bound quark Dirac spinor ($1s_{1/2}$)

Quark Dirac spinor in a **bound hadron:**

$$q_{1s}(r) = \begin{pmatrix} U(r) \\ i\sigma\cdot\hat{r}\, L(r) \end{pmatrix} \chi$$

Lower component is **enhanced** !

$\Longrightarrow$ $g_A^* < g_A$: ~ |U|**2 – (1/3) |L|**2,

$\Longrightarrow$ **Decrease** of scalar density $\Longrightarrow$

Decrease in **Scalar Density**

Scalar density (quark): ~ **|U|**2 - |L|**2**,

⇓

M_N*, **N** wave function, **Nuclear** scalar density etc., are **self-consistently** **modified** due to the N **internal structure** change !

⟹ **Novel Saturation** mechanism !

Nuclear (Neutron) matter, E/A

New saturation mechanism !

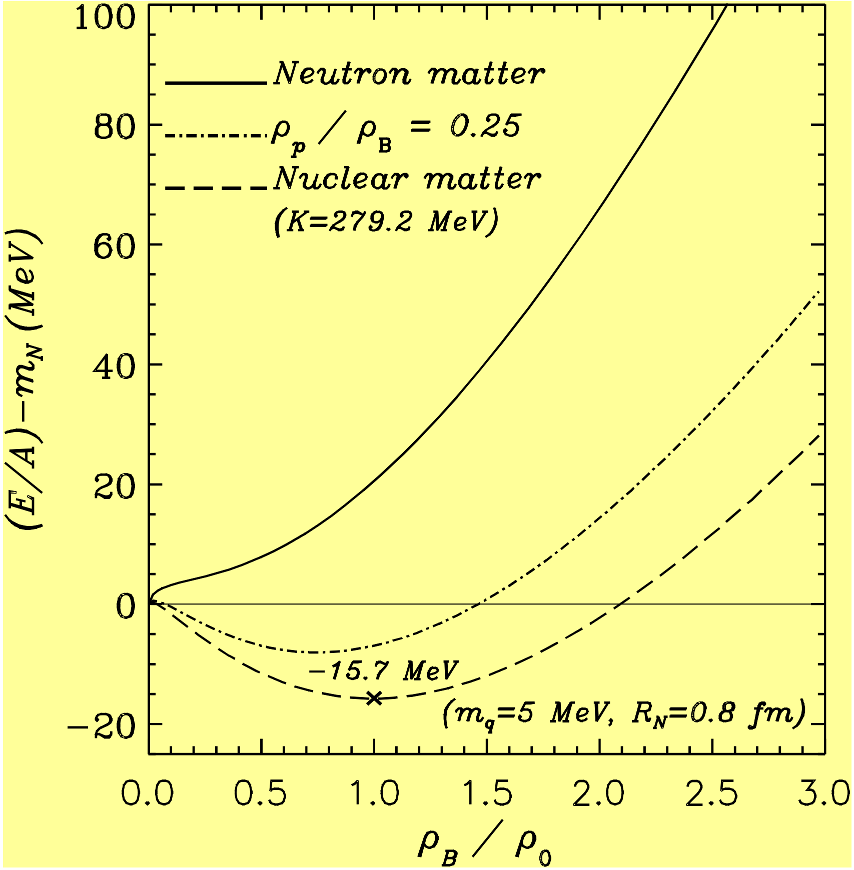
Incompressibility

(~ spring constant)

K ≈ 280 MeV

(200 ~ 300 MeV)

PLB 429, 239 (1998)



Finite nuclei: ^{208}Pb energy levels

NPA 609, 339 (1996)

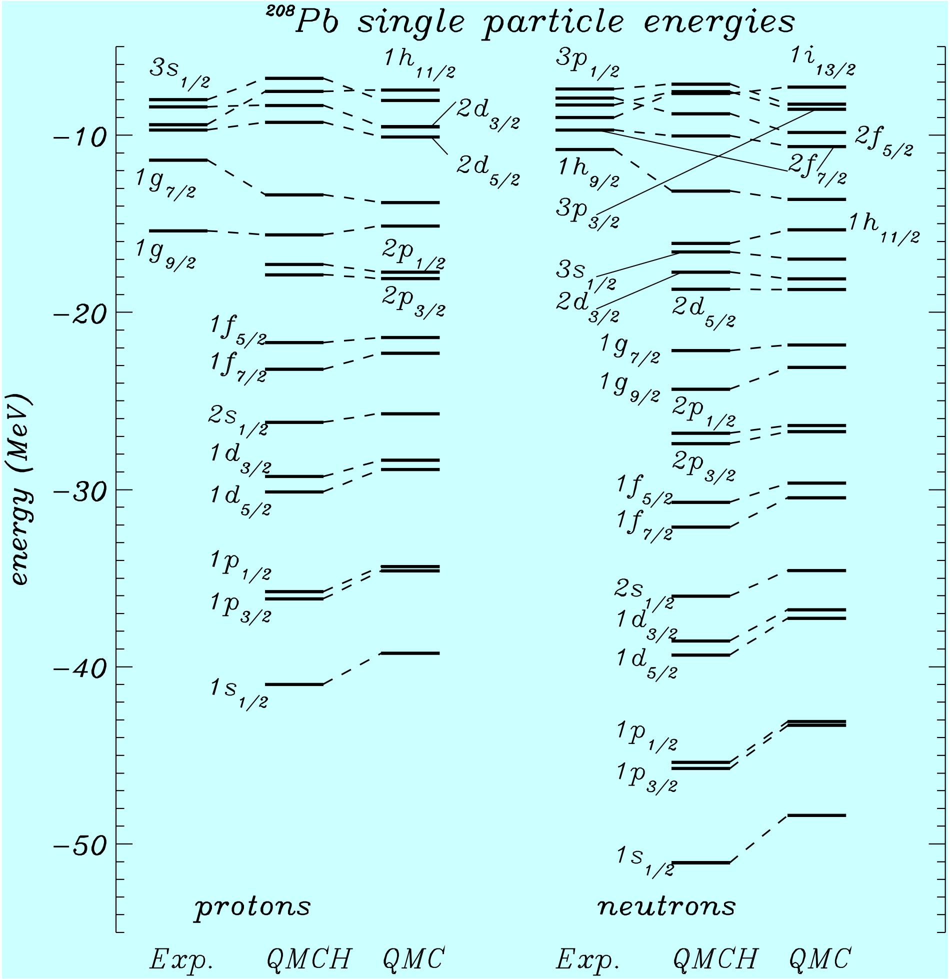
Heavy mass nuclei

Based on **quarks** !

↓

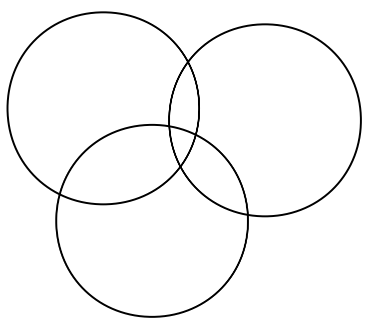
Hypernuclei

(the latest version of QMC)



Summary : Scalar Polarizability

- Can always rewrite **non-linear coupling** as linear coupling plus non-linear scalar self-coupling – **likely physical origin of non-linear versions of QHD**
- In nuclear matter this is the **only** place the **internal structure** of the nucleon enters in MFA
- Consequence of **polarizability** in atomic physics is **many-body forces:**



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

Non-linearity

QMC $\Longleftrightarrow$ QHD

- QHD shows importance of **relativity** :
  mean **σ, ω** and **ρ** fields
- **QMC** goes **far beyond QHD** by incorporating effect of hadron ***internal structure***

- Minimal model couples these mesons to ***quarks*** in relativistic quark model – e.g. MIT bag, or confining NJL

- g_σ^q , g_ω^q, g_ρ^q fitted to ρ_0 , **E/A** and **symmetry energy**

- ***No additional parameters :*** predict change of structure and binding in nuclear matter of **all hadrons**:
  e.g. **ω, ρ, η, J/ψ, N, Λ, Σ, Ξ** $\Longrightarrow$ see later !

Linking QMC to Familiar Nuclear Theory

Since early 70's tremendous amount of work in nuclear theory is based upon **effective forces**

- Used for everything from nuclear astrophysics to collective excitations of nuclei

- **Skyrme Force**: **Vautherin and Brink**

In Paper : **Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)**

explicitly obtained **effective force, 2- plus 3- body, of Skyrme type**

- equivalent to QMC model (required expansion around $\boldsymbol{\sigma} = 0$)

Physical Origin of Density Dependent Force of the Skyrme Type within the QMC model

That is, apply new effective force directly to calculate nuclear properties using Hartree-Fock (as for usual well known force)

	E_B (MeV, exp)	E_B (MeV, QMC)	r_c (fm, exp)	r_c (fm, QMC)
^{16}O	7.976	7.618	2.73	2.702
^{40}Ca	8.551	8.213	3.485	3.415
^{48}Ca	8.666	8.343	3.484	3.468
^{208}Pb	7.867	7.515	5.5	5.42

» 4%

» 1%

- Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:

$$\mathcal{H}_0 + \mathcal{H}_3 = \rho^2 \left[\frac{-3\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\,G_\sigma)^3} - \frac{G_\sigma}{2\,(1 + d\rho\,G_\sigma)} + \frac{3\,G_\omega}{8} \right] +$$

$$(\rho_n - \rho_p)^2 \left[\frac{5\,G_\rho}{32} + \frac{G_\sigma}{8\,(1 + d\rho\,G_\sigma)^3} - \frac{G_\omega}{8} \right],$$

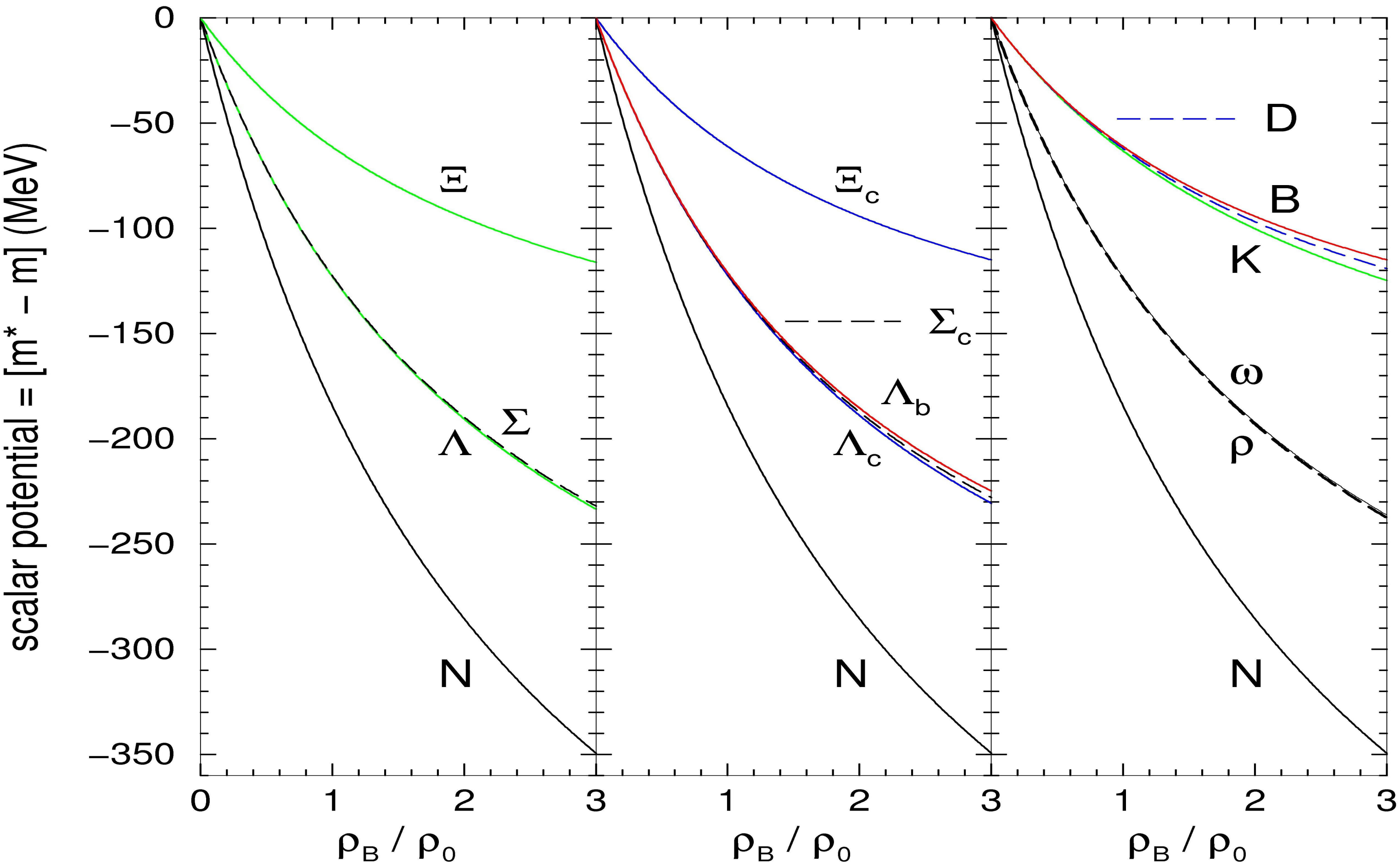
○ highlights scalar polarizability

Spin-Orbit Splitting

	Neutrons (Expt)	Neutrons (QMC)	Protons (Expt)	Protons (QMC)
^{16}O $1p_{1/2}$-$1p_{3/2}$	**6.10**	**6.01**	**6.3**	**5.9**
^{40}Ca $1d_{3/2}$-$1d_{5/2}$	**6.15**	**6.41**	**6.0**	**6.2**
^{48}Ca $1d_{3/2}$-$1d_{5/2}$	**6.05 (Sly4)**	**5.64**	**6.06 (Sly4)**	**5.59**
^{208}Pb $2d_{3/2}$-$2d_{5/2}$	**2.15 (Sly4)**	**2.04**	**1.87 (Sly4)**	**1.74**

Agreement generally very satisfactory – **NO parameter** adjusted to fit

Scalar potentials in QMC respects SU(3) (light quark # !)



Λ and Σ ⇔ Self-consistent **OGE** color hyperfine interaction

- Λ and Σ hypernuclei are more or less similar (channel couplings) ⇔ improve !
- Ξ potential: **weaker (~1/2)** of Λ and Σ (Light quark #, or SU(3))
- Very **small spin-orbit splittings** for Λ hypernuclei ⟺ **SU(6) quark model**

Bag mass and **color mag.** HF int. contribution (**OGE**)

T. DeGrand *et al.*, PRD 12, 2060 (1975)

$$M = [N_q \Omega_q + N_s \Omega_s]/R - Z_0/R + 4\pi B R^3/3$$

$$+ \underline{(F_s)}^n \Delta E_M(f) \qquad (f = N, \Delta, \Sigma, \Lambda, \Xi \ldots)$$

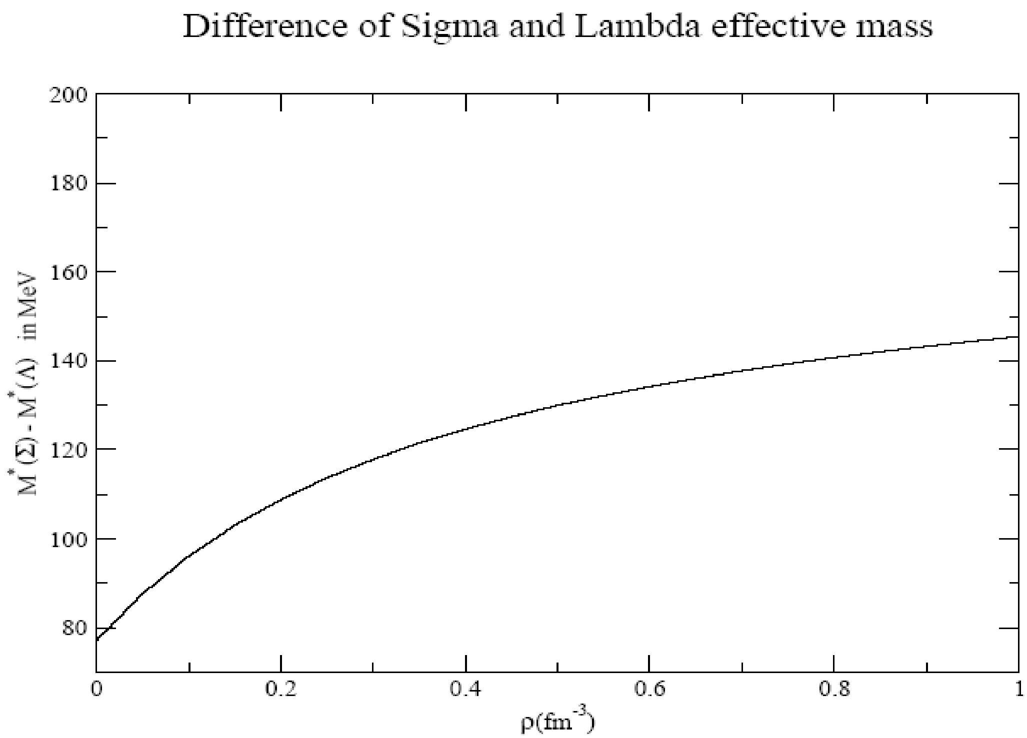
$$\Delta E_M = -3\alpha_c \sum_{a,\, i<j} \lambda_i \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j \; M(m_i, m_j, R)$$

$$\Delta E_M(\Lambda) = -3\alpha_c \; M(m_q, m_q, R), \quad (q = u, d)$$

$$\Delta E_M(\Sigma) = \alpha_c M(m_q, m_q, R)$$
$$-4\alpha_c M(m_q, m_s, R)$$

Latest QMC: Includes Medium Modification of Color Hyperfine Interaction

N - Δ and **Σ - Λ** splitting arise from **one-gluon-exchange** in MIT Bag Model : as **" σ "** so does this splitting…



Σ - Λ splitting

Σ-hypernuclei unbound!!

Guichon, Thomas, Tsushima, Nucl. Phys. A841 (2008) 66

Octet and Decuplet masses (GeV)

NPA 814, 66 (2008) (arXiv:0712.1925 [nucl-th])

Fs	ms	Λ	Σ	Ξ	Σ*	Ξ*	Ω
1	0.341	1.135	1.176	1.355	1.416	1.599	1.784
0.726	**0.297**	**1.107**	**1.189**	**1.325**	**1.368**	**1.507**	**1.654**
Expt.		1.116	1.193	1.318	1.385	1.533	1.672

R_N=0.8 fm, N, Δ masses → B=0.5541 fm^{-1}, Z_0=2.6422,

α_c=0.4477, (0.55), Less enhanced the "Coulomb-spike" for **s** quark

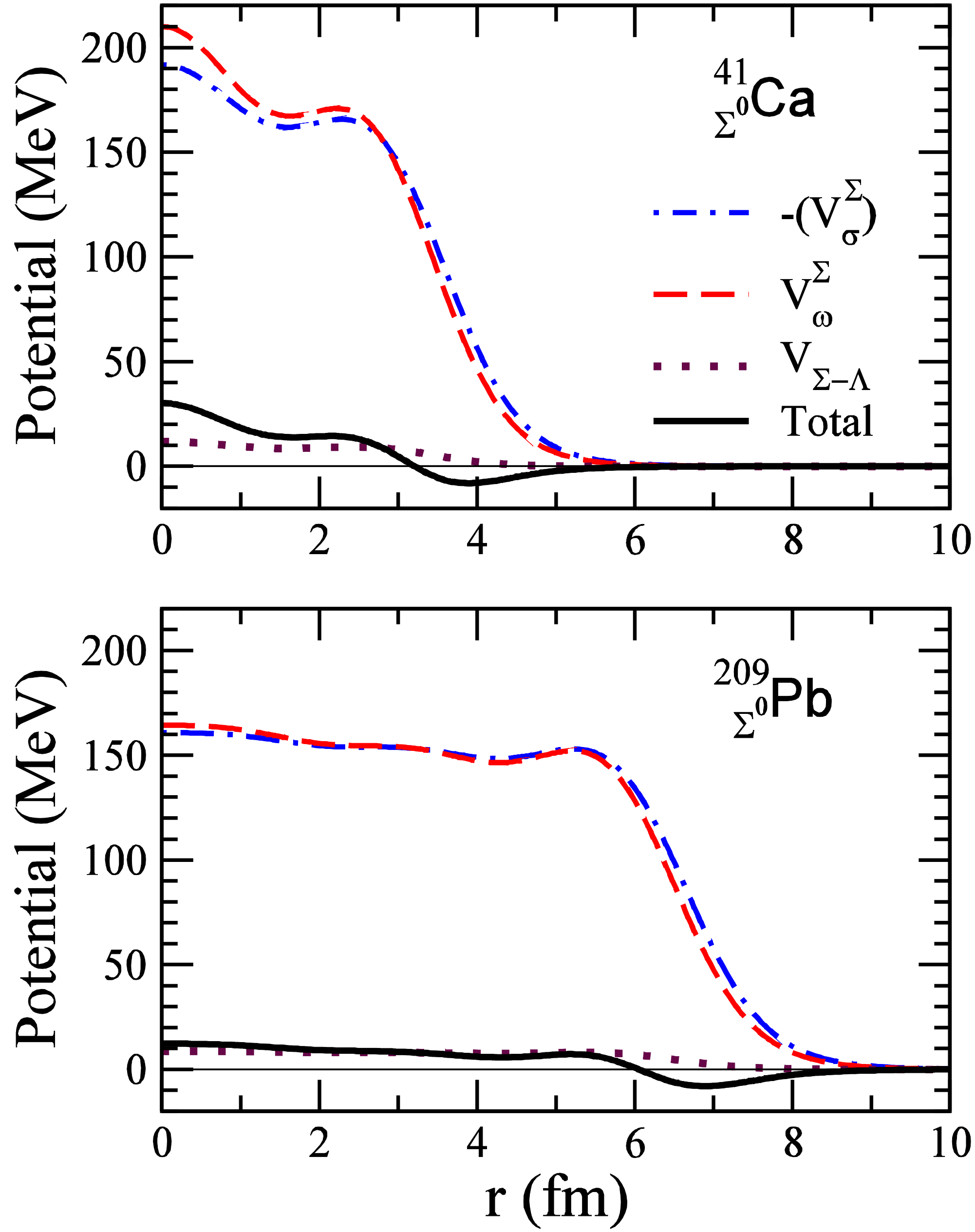
⟹independent, Fs,ms: fit to Λ,Σ, Ξ masses **(predictions)**

Σ^0 potentials (1s$_{1/2}$)

Repulsion
in center
Attraction
in surface

No Σ nuclear bound state!

HF couplings for hyperons ⇔ successful for high density neutron star
(NPA 792, 341 (2007))



Hypernuclei spectra 1

NPA 814, 66 (2008)

	$^{16}_{\Lambda}O$ Exp.	$^{17}_{\Lambda}O$	$^{17}_{\Xi^0}O$	$^{40}_{\Lambda}Ca$ Exp.	$^{41}_{\Lambda}Ca$	$^{41}_{\Xi^0}Ca$	$^{49}_{\Lambda}Ca$	$^{49}_{\Xi^0}Ca$
$1s_{1/2}$	-12.4	-16.2	-5.3	-18.7	-20.6	-5.5	-21.9	-9.4
$1p_{3/2}$		-6.4			-13.9	-1.6	-15.4	-5.3
$1p_{1/2}$	-1.85	-6.4			-13.9	-1.9	-15.4	-5.6
$1d_{5/2}$					-5.5		-7.4	
$2s_{1/2}$					-1.0		-3.1	
$1d_{3/2}$					-5.5		-7.3	

Hypernuclei spectra 2

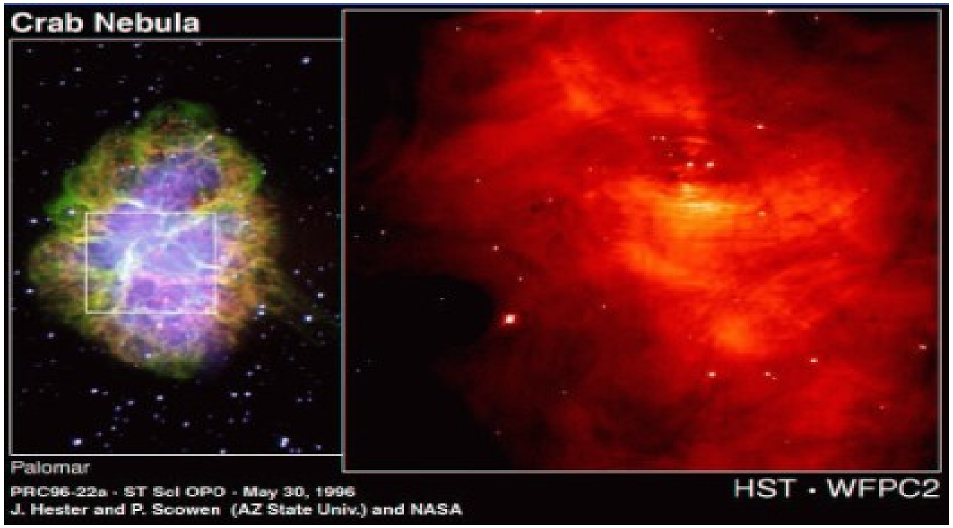
NPA 814, 66 (2008)

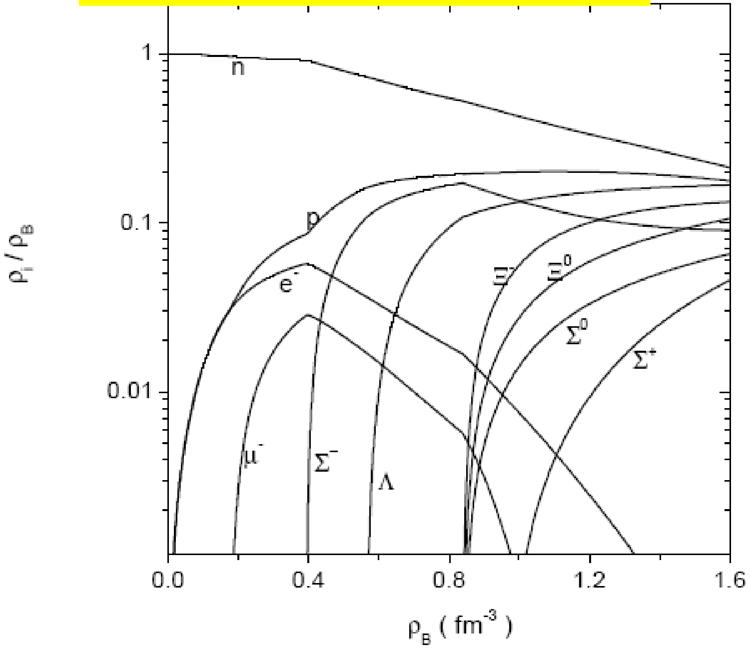
	$^{89}_{\Lambda}$Yb Exp.	$^{91}_{\Lambda}$Zr	$^{91}_{\Xi^0}$Zr	$^{208}_{\Lambda}$Pb Exp.	$^{209}_{\Lambda}$Pb	$^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-23.1	-24.0	-9.9	-26.3	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.5	-19.4	-7.2	-21.9	-24.0	-12.7
$1d_{5/2}$	-9.1	-13.4	-3.1	-16.8	-20.1	-9.6
$2s_{1/2}$		-9.1	–		-17.1	-8.2
$1d_{3/2}$	(-9.1)	-13.4	-3.4	(-16.8)	-20.1	-9.8

Summary: hypernuclei

- The latest version of QMC (OGE color hyperfine interaction included self-consistently in matter) $\Longrightarrow$
- Λ single-particle energy **$1s_{1/2}$ in Pb** is **-26.9** MeV (Exp. **-26.3** MeV) $\Longleftarrow$ no extra parameter!
- **Small** spin-orbit splittings for the Λ
- **No** Σ nuclear bound state !!
- Ξ is expected to form nuclear bound state

- **Hyperons** enter at just 2-3 ρ_0
- Hence need effective **Σ-N** and **Λ-N** forces in this density region!
- **Hypernuclear data is important input** (J-PARC, FAIR, JLab)

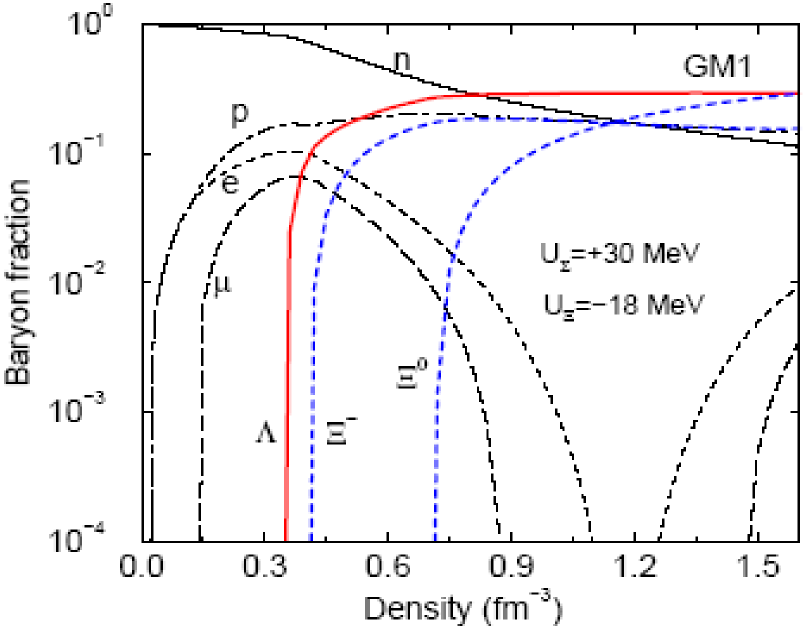




Σ

⟷

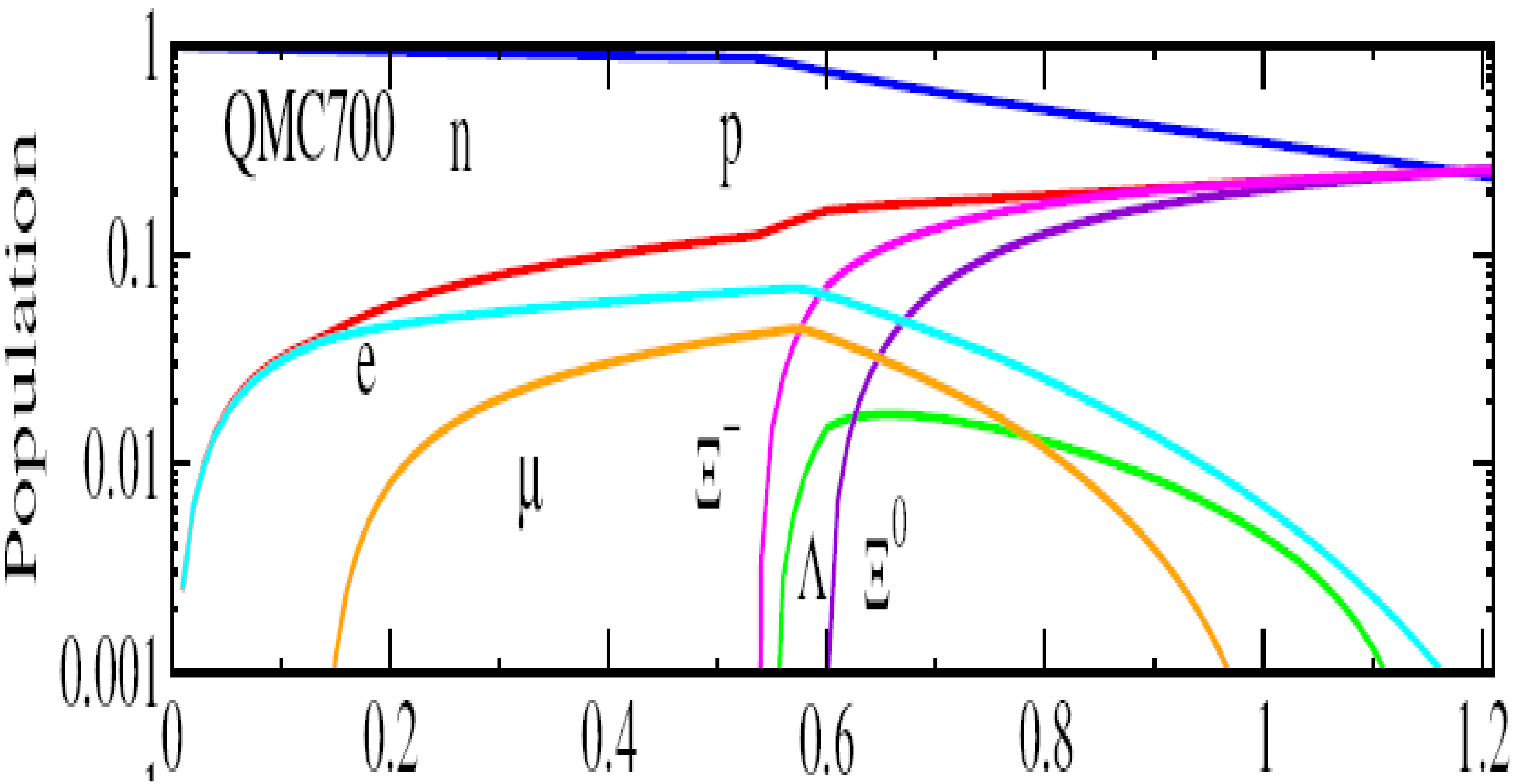
?



From Schaffner-Bielich (2005)

Consequences for Neutron Star

New QMC model, fully relativistic, Hartree-Fock treatment



Stone et al., Nucl. Phys. A792 (2007) 341

Photoproduction of Λ Hypernuclei

R. Shyam, KT, A.W. Thomas, PLB 676, 51 (2009)

Λ and K^+ are produced via **s-channel**

N* excitation (dominant)

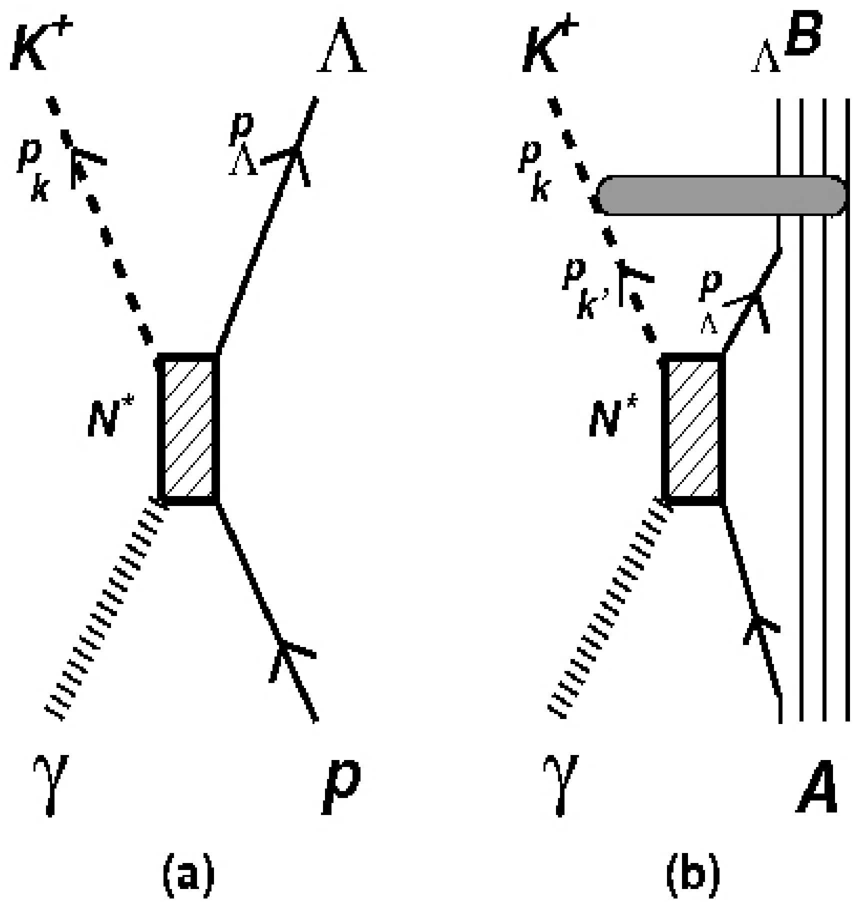
S11(1650), P11(1710)

P13(1720)

⇕

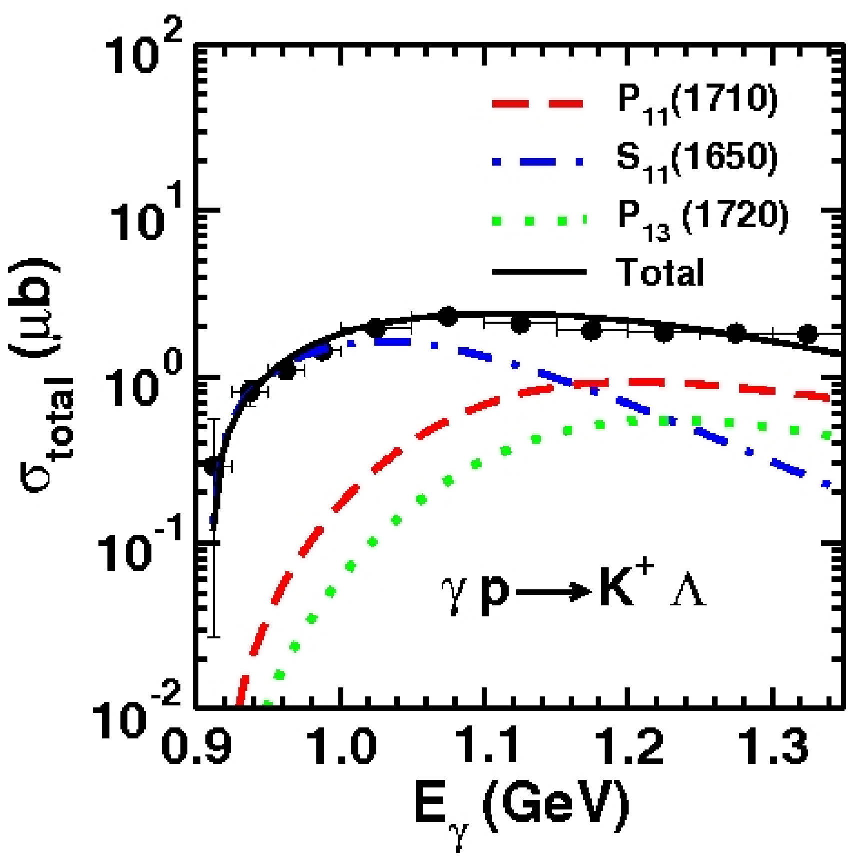
Energy region of interests, hypernuclei production

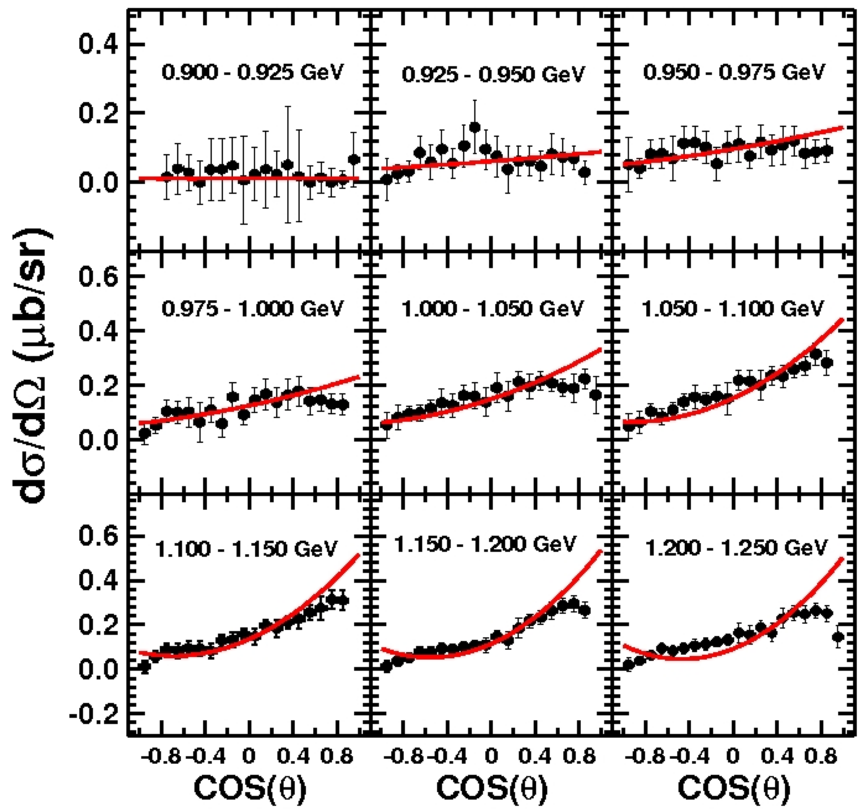
(~ **10 % ambiguity** due to the other background ⇒)



Elementary $\gamma\, p \longrightarrow K^+ \Lambda$ reaction

R. Shyam, KT, A.W. Thomas, PLB 676, 51 (2009)

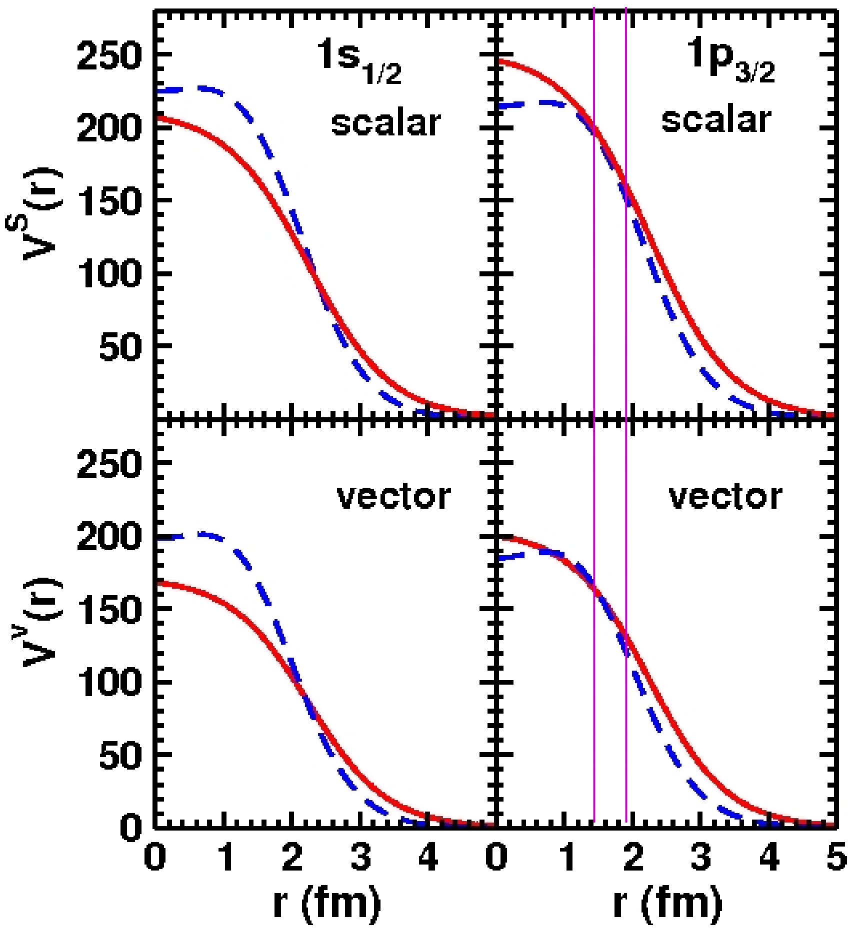


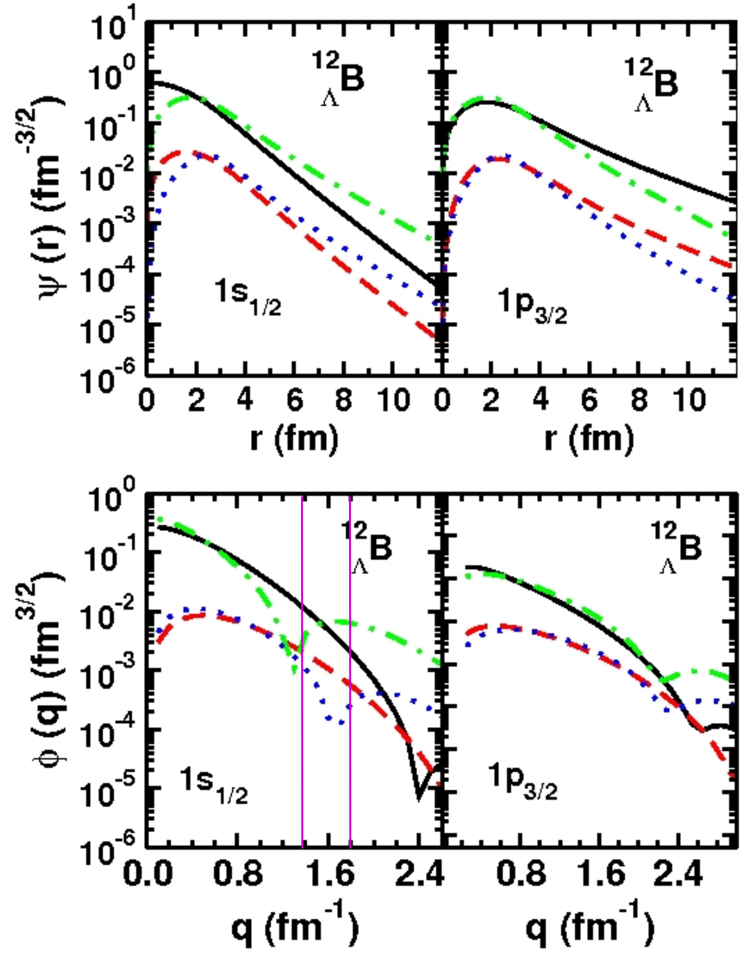


${}^{12}_{\Lambda}$B hypernucleus (MeV)

State	Exp.	QMC	Vv (W.S)	Vs (W.S)
${}^{12}_{\Lambda}B\,1s_{1/2}$	**11.37**	**14.93**	171.78	-212.69
${}^{12}_{\Lambda}B\,1p_{3/2}$	**1.73**	**3.62**	204.16	-252.28
${}^{12}_{\Lambda}B\,1p_{1/2}$	**1.13**	**3.62**	227.83	-280.86
$(p1p_{3/2})^{-1}$ ${}^{12}C$	15.96 Sep. energy	(≅OK)	382.60	-472.34

Potentials and wave functions





QMC, W.S. type

|QMCU|, |QMCL|, |DiracpU|, |DiracpL|

Differential cross sections: $^{12}C(\gamma,K^+)^{12}_{\Lambda}B$

PLB 676, 51 (2009)

$E_{th} \sim 695$ MeV

$d\sigma/d\Omega$ at

Kaon angle θ **= 10°**

$1^-, 2^- \Leftrightarrow (1p^{-p}_{3/2}, 1s^{\Lambda}_{1/2})$

(wave functions!) ⇒

$2^+, 3^+ \Leftrightarrow (1p^{-p}_{3/2}, 1p^{\Lambda}_{3/2})$

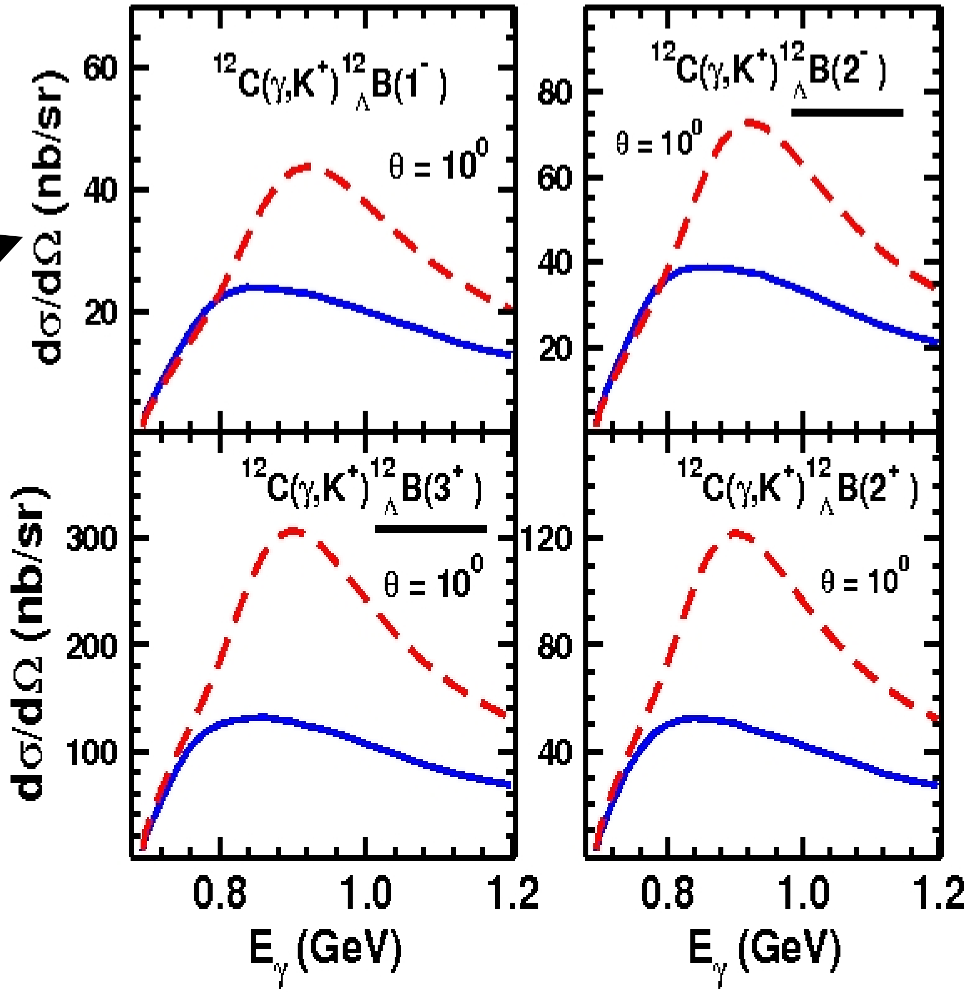
(potentials!) ⇒

Diracp

(phenomenological)

QMC

$|q| \cong [1.4, 1.7]$ fm $^{-1}$



Summary: Hypernuclei **photoproduction**

1. **First attempt** to study photoproduction of Λ-hypernuclei ($^{12}C(\gamma,K^+)^{12}_{\Lambda}B$ reaction) via **quark-based** model (**QMC**)
2. $d\sigma/d\Omega$ at Kaon angle θ **= 10°** shows **distinguishable difference!**
3. Back ground inclusion for higher energies
4. **Heavier** hypernuclei

Discussions

1. Study of Ξ hypernuclei

   ⇑ ⇒ $A(K^-, K^+)_{\Xi}B$ reaction

2. Elementary $K^- p \longrightarrow \Xi K^+$ reaction

3. Heavier Λ hypernuclei **photoproduction**

   (1, 2 ⟹ waiting! 3. Nearly ready!)

4. Electroproduction of Λ hypernuclei

5. Λ_c hypernuclei **???!!!**