Status of theoretical study Quark-Meson Coupling (QMC) model (quark-based relativistic mean field model)

JSPS and Collab. meeting at JLab, 05/06/2009

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P.A.M. Guichon, R. Shyam, A.W. Thomas

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

PLB, to appear, arXiv:0812.1547 [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)
- Photoproduction of Λ-hypernuclei
- Discussion, outlook for hypernuclei

Introduction

- (Large) nuclei in terms of quarks and gluons (or QCD) ???!!!
- NN,NNN,NNNN... interactions $\Longrightarrow$ Nucleus ? $\Longleftarrow$ shell model, MF model,...
- Lattice QCD: still extracting NN and NY interactions, [Y=hyperons: Λ,Σ,Ξ]
- Hypernuclei ? (Nucleus+Y) bound states
- Quark model based description of nucleus

How to describe a 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!

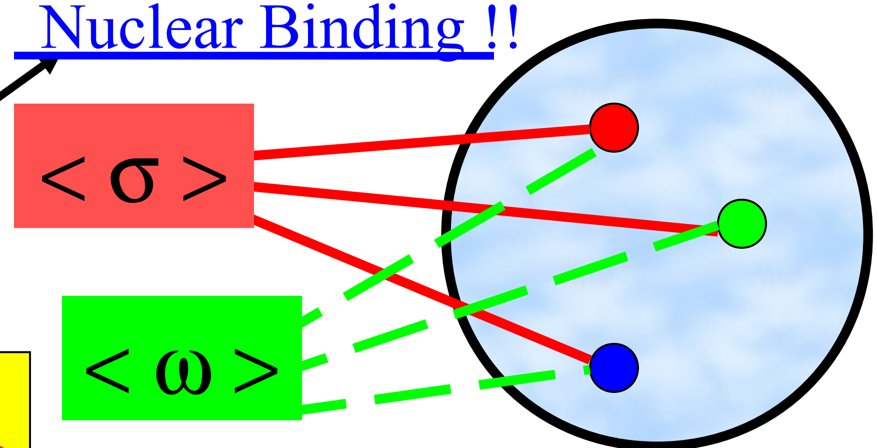
$\Longrightarrow$ Planned Expts.: (JLab?), J-PARC,
GSI-FAIR

The QMC model P.A.M. 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 !!



$m^*_q = m_q - g^q_\sigma \sigma = m_q - V^q_\sigma$

⇓ nonlinear in σ

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

$M^*_N = M_N - V^N_\sigma$

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

1. Start

$V^N_\omega = 3V^q_\omega$

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

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 !

⟹ <u>Novel Saturation mechanism !</u>

Nuclear (Neutron) matter, E/A

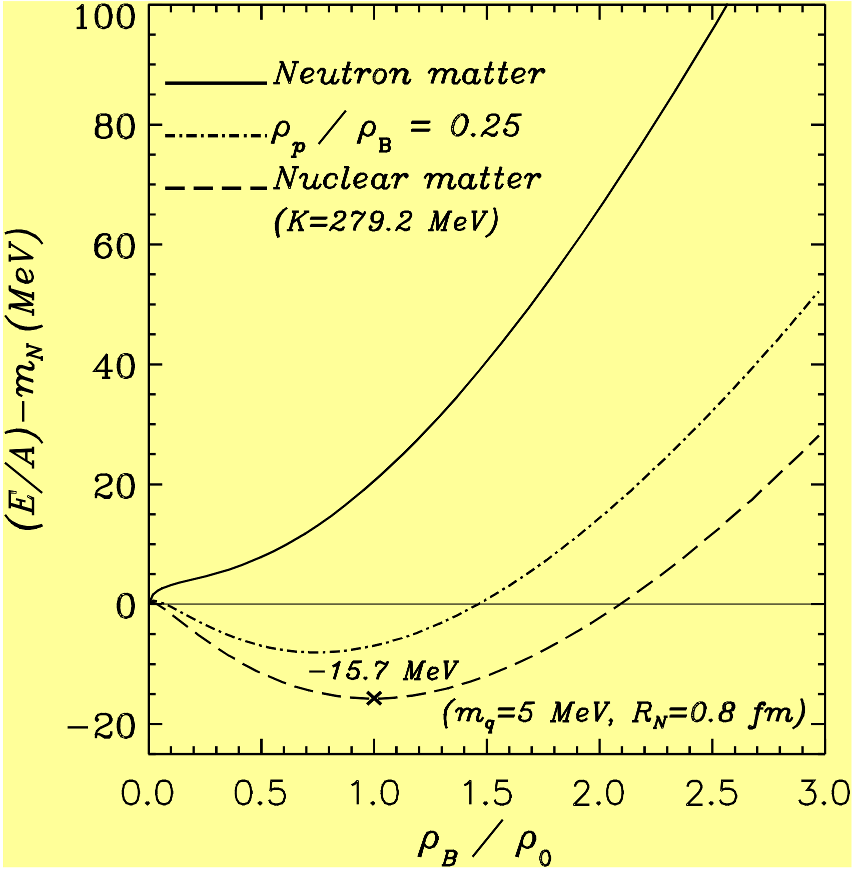
New saturation mechanism !

Incompressibility

K ≈ 280 MeV

(200 ~ 300 MeV)

PLB 429, 239 (1998)



Finite nuclei (^{208}Pb energy levels)

NPA 609, 339 (1996)

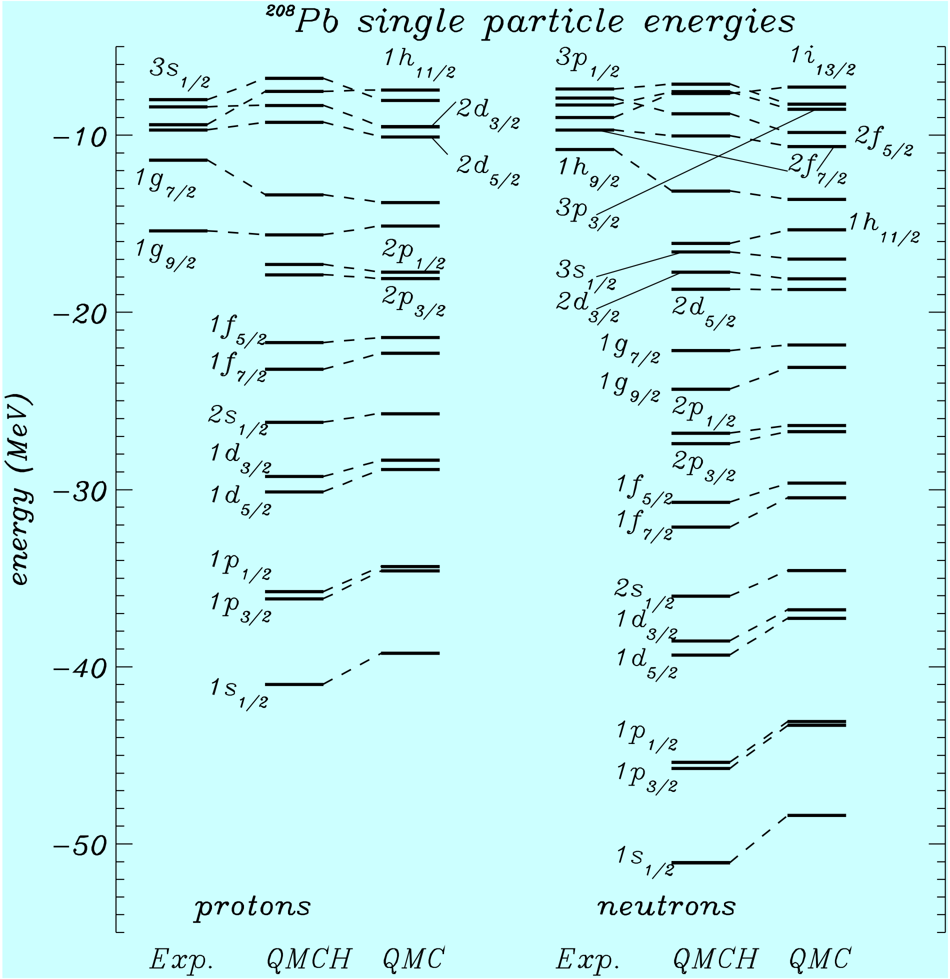
Large mass nuclei

Based on **quarks** !

↓

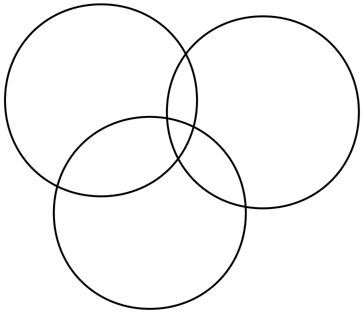
Hypernuclei

(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:**



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

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:

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

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

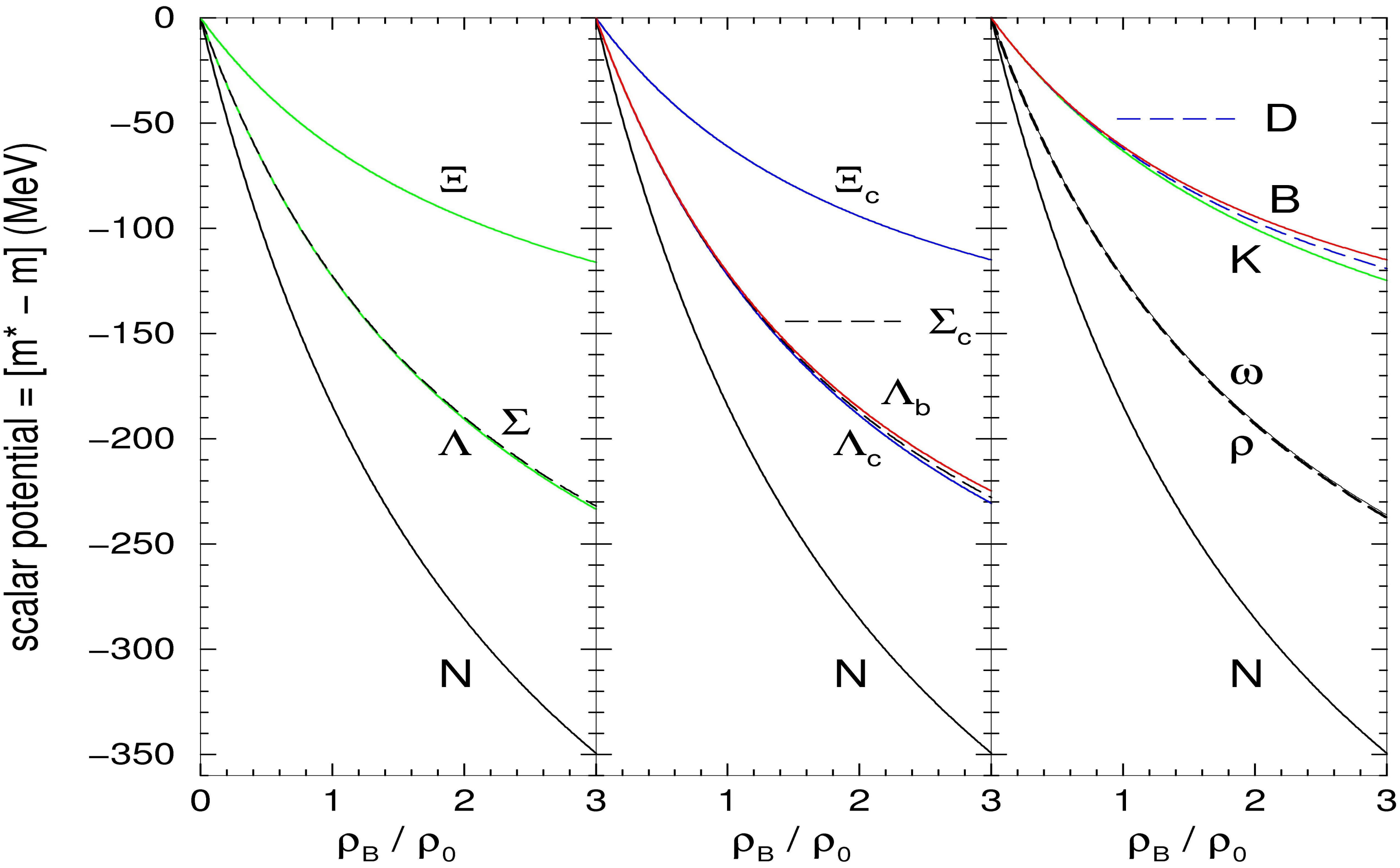
highlights
scalar polarizability

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)

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

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

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

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

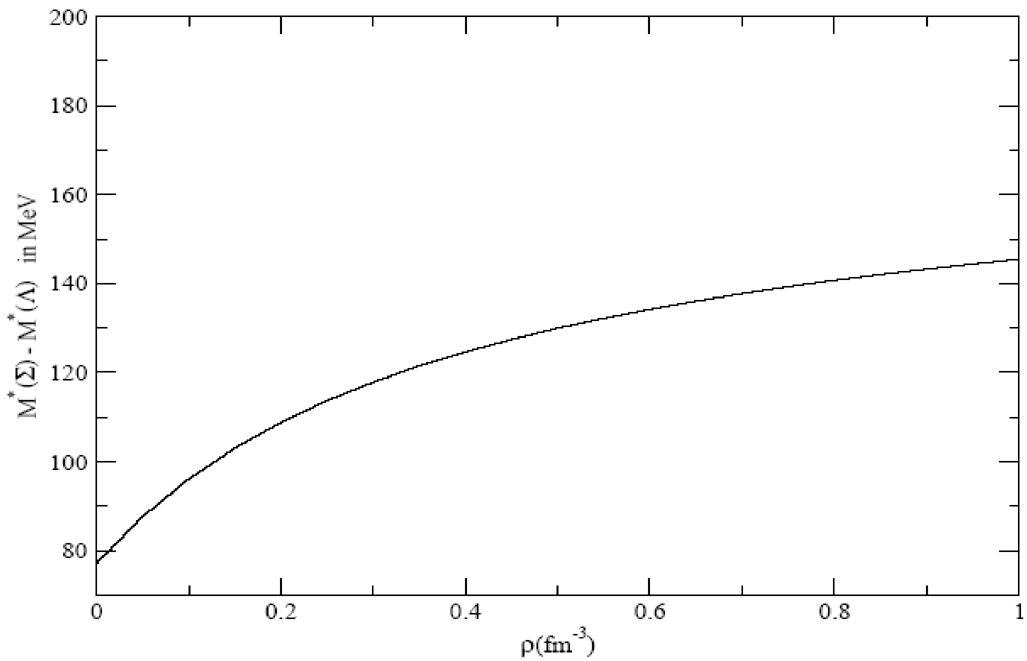
$$\Delta E_M(\Sigma) = \alpha_c M(m_q,m_q,R)$$

$$-4\alpha_c M(m_q,m_s,R)$$

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…

Difference of Sigma and Lambda effective mass



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)**

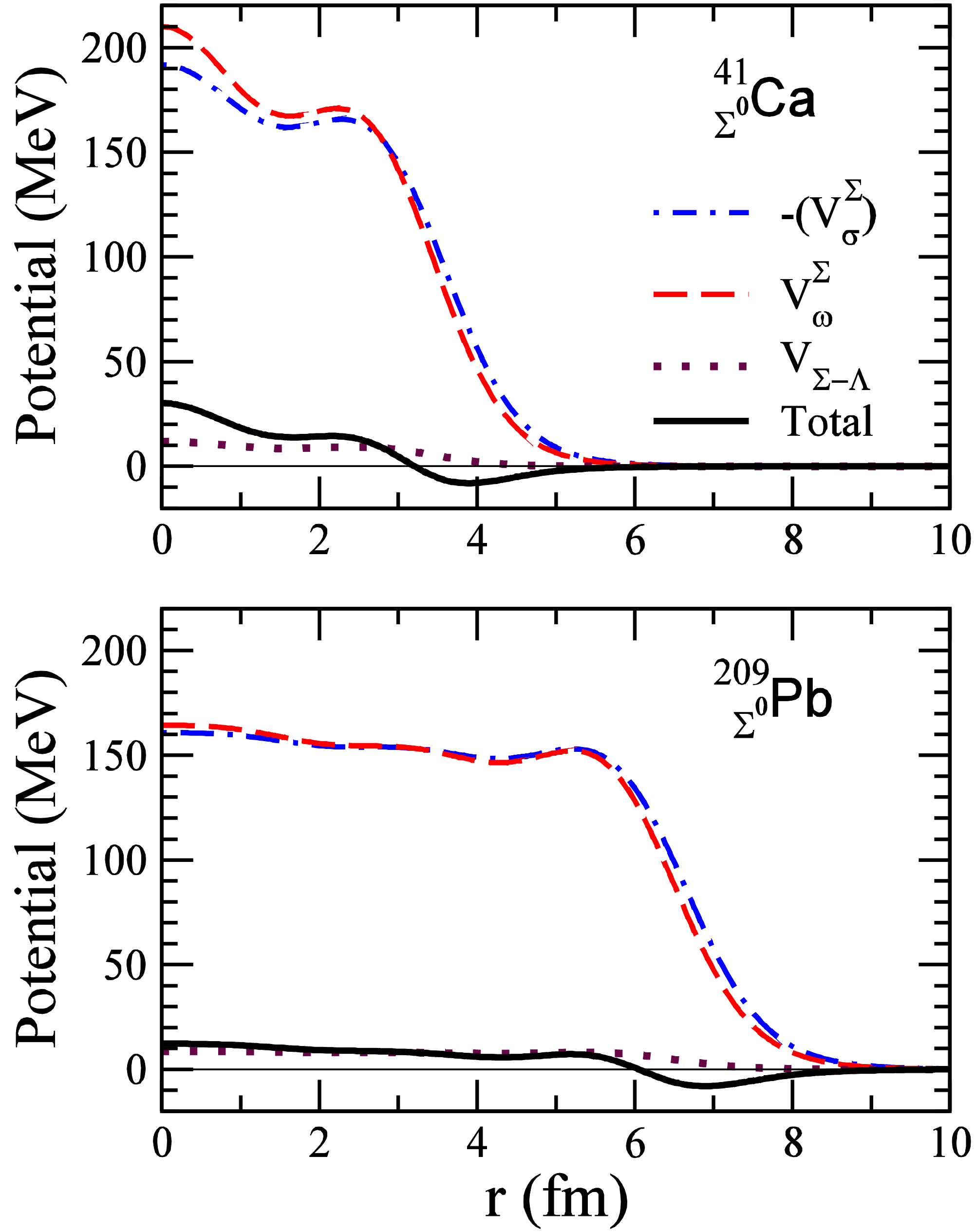
Σ^0 potentials ($1s_{1/2}$)

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) (arXiv:0712.1925 [nucl-th])

	$^{16}_{\Lambda}O$ 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) (arXiv:0712.1925 [nucl-th])

	$^{89}_{\Lambda}$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

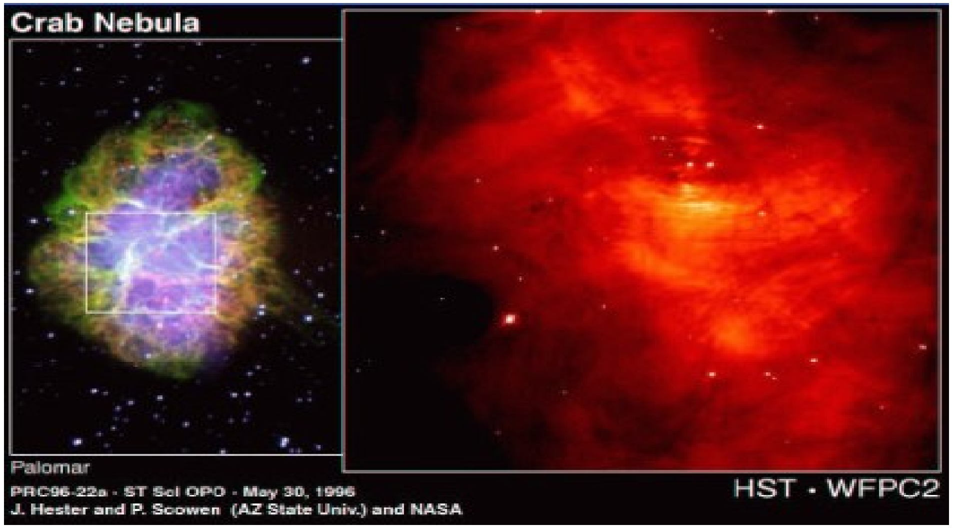
A mass formula (SY) [C. Samanta, JPG 32, 363 (2006)] vs. QMC(|E($1s_{1/2}$)| averaged)

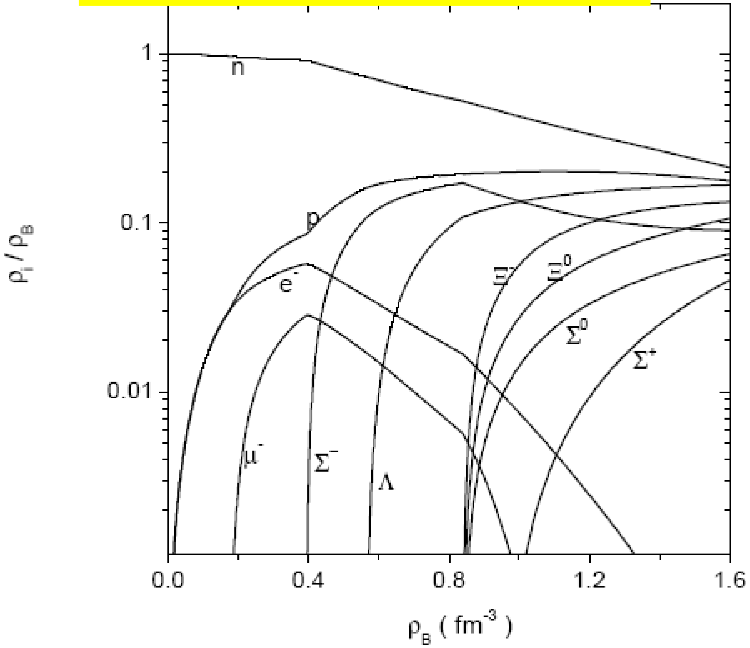
$^{A}_{Y}Z$	SY(Ex)	BWMH	QMC	$^{A}_{Y}Z$	SY(Ex)	BWMH	QMC
$^{12}_{\Lambda}B$	11.37	12.0	15.5	$^{89}_{\Lambda}Sr$		22.5	24.2
$^{28}_{\Lambda}Al$		17.6	20.1	$^{15}_{\Lambda}N$	13.59	13.7	-----
$^{40}_{\Lambda}K$		19.3	20.7	$^{33}_{\Lambda}S$	17.96	18.4	-----
$^{51}_{\Lambda}V$	19.90	20.4	-----	$^{52}_{\Lambda}V$		20.5	22.5
$^{12}_{\Xi-}Be$		12.1	5.7	$^{17}_{\Xi-}N$		18.0	8.8
$^{28}_{\Xi-}Mg$		24.8	11.4	$^{40}_{\Xi-}Ar$		29.5	16.1
$^{41}_{\Xi-}K$		30.0	14.6	$^{49}_{\Xi-}K$		31.1	11.8
$^{52}_{\Xi-}Ti$		32.4	14.3	$^{89}_{\Xi-}Rb$		38.7	18.0
$^{91}_{\Xi-}Y$		39.3	19.2	$^{209}_{\Xi-}Ti$		50.2	25.4

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

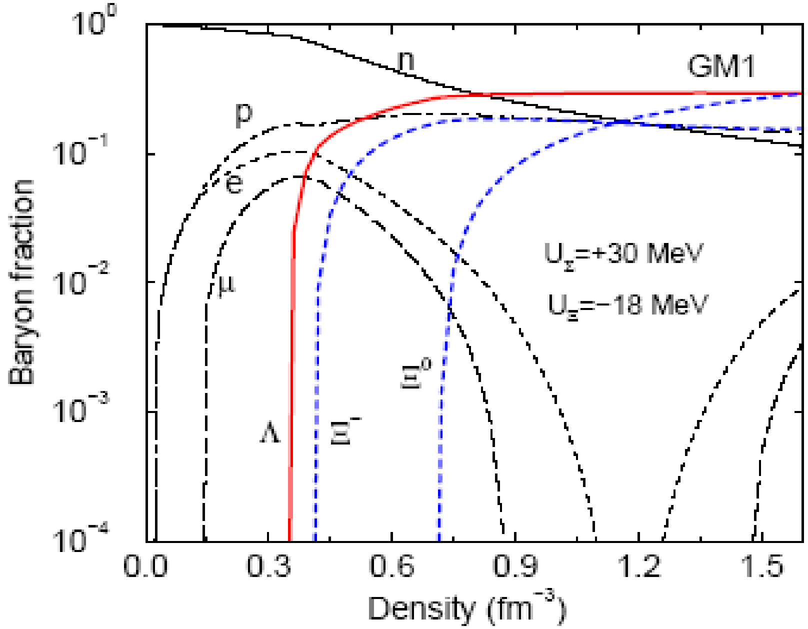
- Hyperons enter at just 2-3 ρ_0
- Hence need effective **Σ-N** and **Λ-N** forces in this density region!
- Hypernuclear data is important input (J-PARC, FAIR, JLab)





Σ

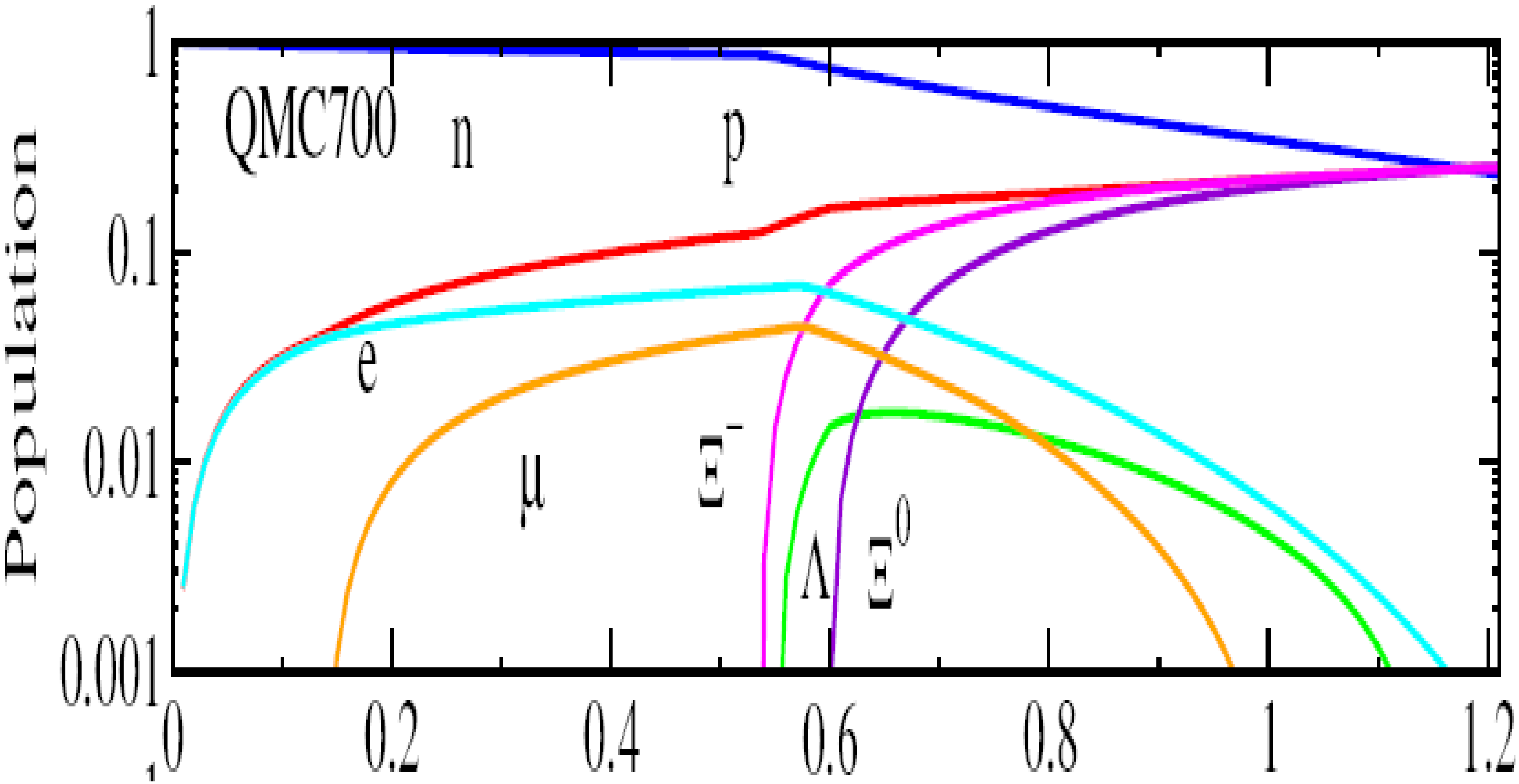
?



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, arXiv:0812.1547 [nucl-th], to appear in PLB

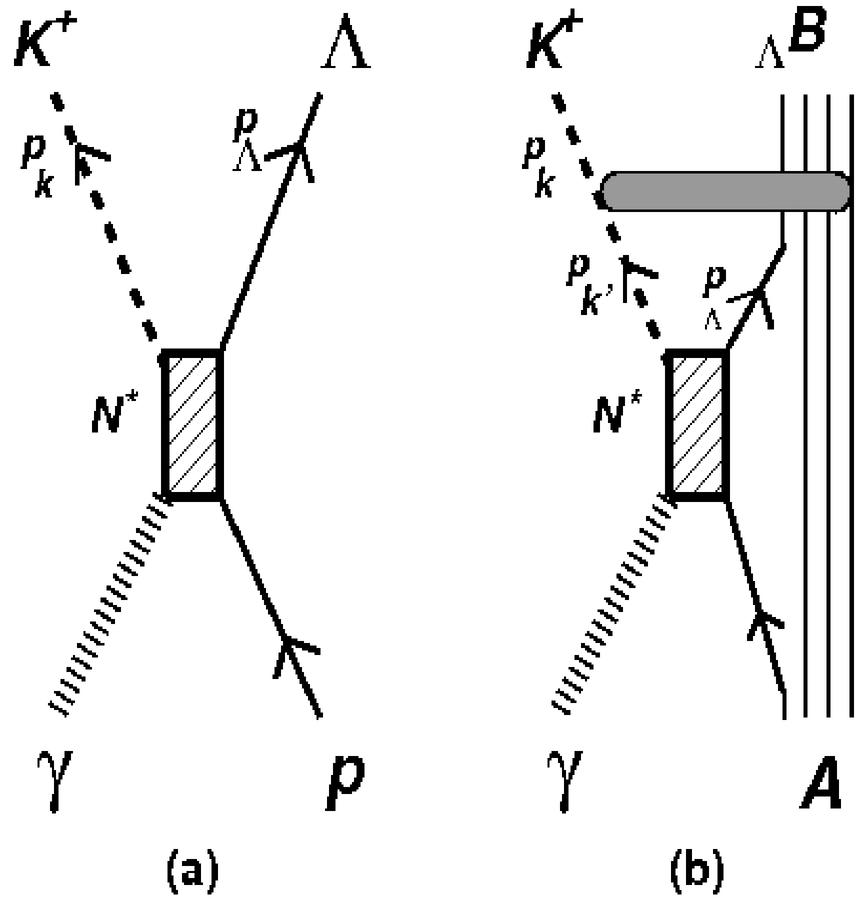
Λ and K^+ are produced via s-channel N* excitation (dominant)

S_{11}(1650), P_{11}(1710) P_{13}(1720)

⇕

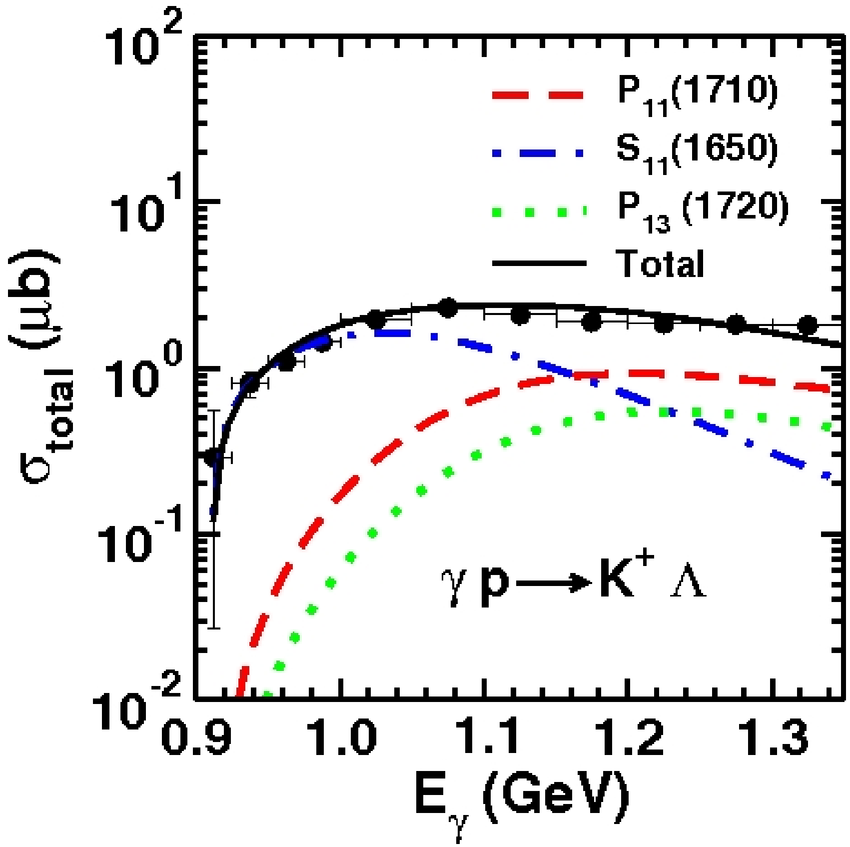
Energy region of interests, hypernuclei production

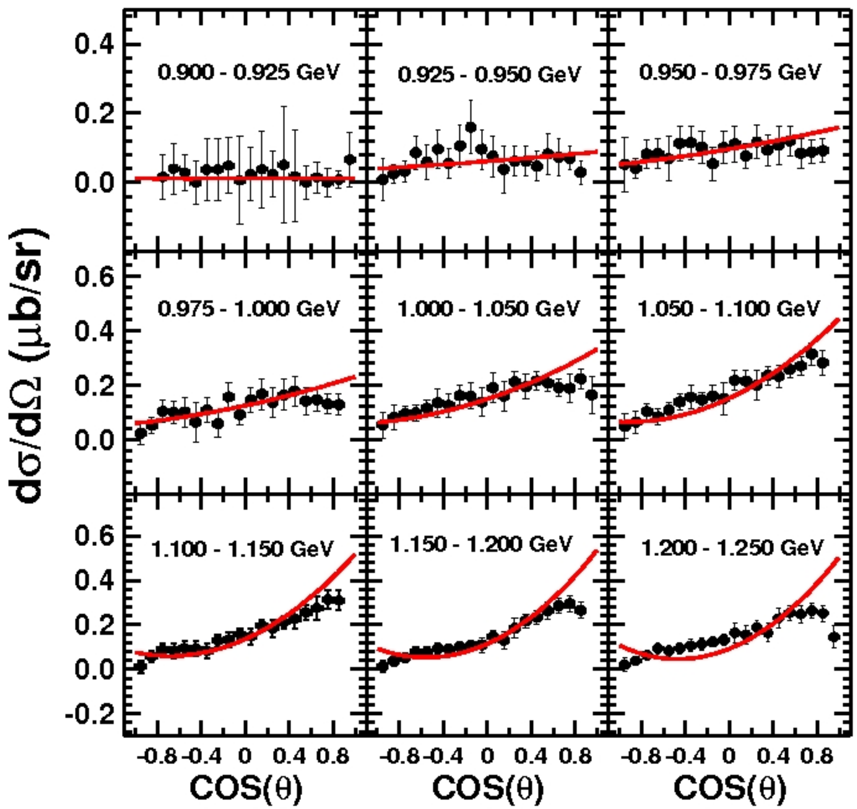
(~ 10 % ambiguity due to the other background ⇒)



Elementary γ p ⟶ K^+ Λ reaction

R. Shyam, KT, A.W. Thomas, arXiv:0812.1547 [nucl-th], to appear in PLB

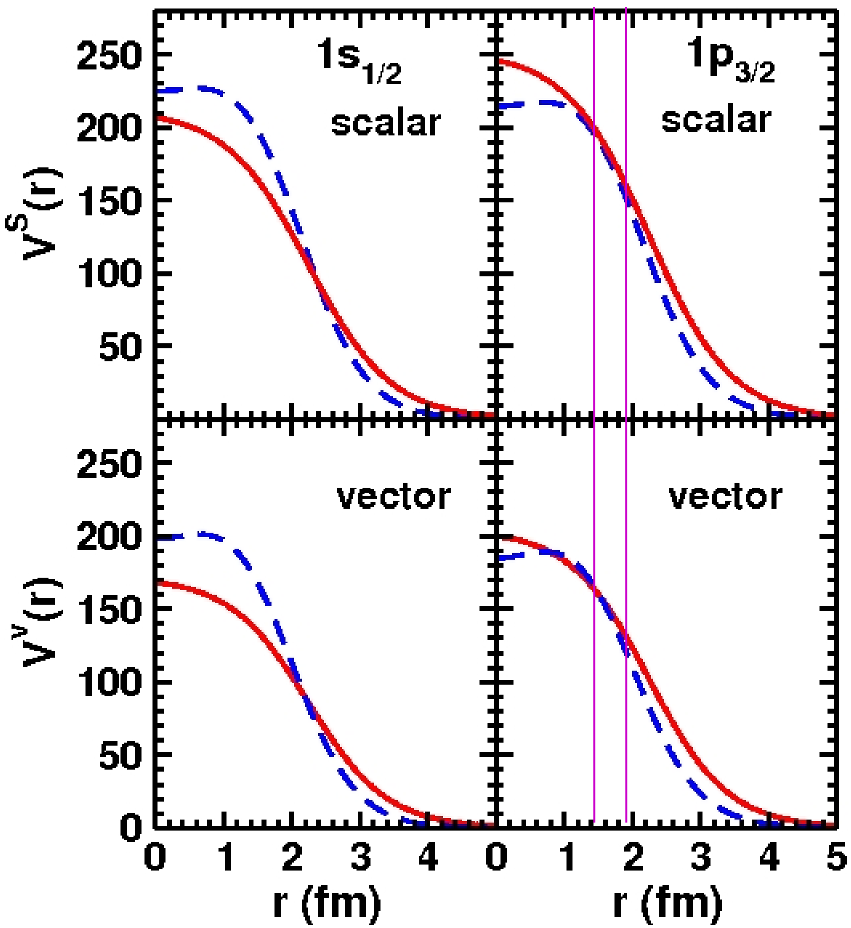


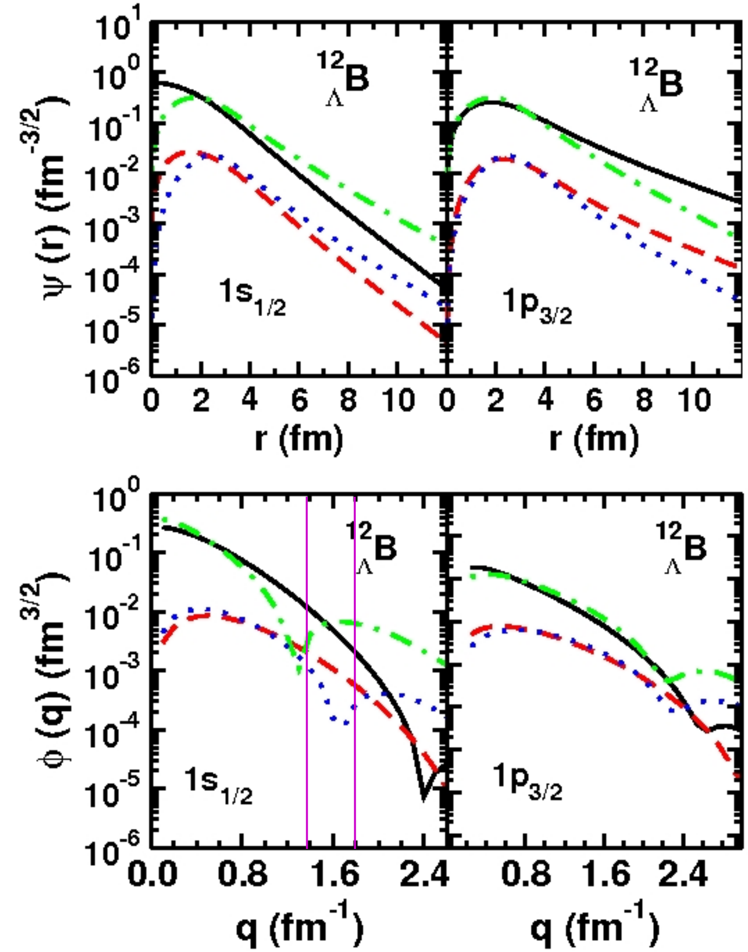


${}^{12}_{\Lambda}$B hypernucleus (MeV)

State	**Exp.**	**QMC**	V_V (W.S)	V_S (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: $^{12}C(\gamma,K^+)^{12}_{\Lambda}B$

arXiv:0812.1547, to appear in PLB

$E_{th} \sim$ 695 MeV

$d\sigma/d\Omega$ at

Kaon angle $\theta = 10°$

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

(wave functions!) ⇒

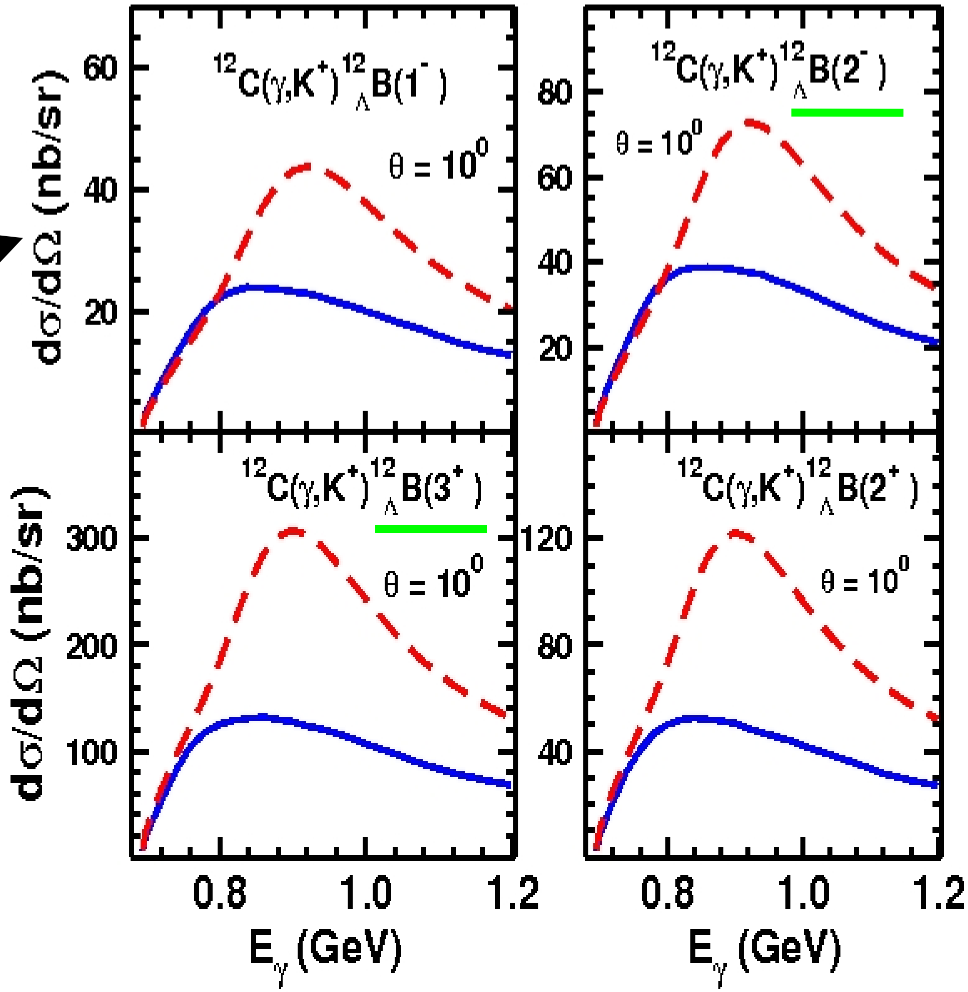
$2^+, 3^+ \Leftrightarrow (1p^{-p}_{3/2}, 1p^{\Lambda}_{3/2})$

(potentials!) ⇒

Diracp (phenomenological)

QMC

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



Summary: Hypernuclei photoproduction

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

Discussion, outlook

1. Study of Ξ-hypernuclei

   $\Uparrow$ $\Rightarrow$ $A(K^-,K^+)_\Xi B$ reaction

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

3. Heavier Λ-hypernuclei photoproduction

   (1, 2, 3 $\Longrightarrow$ on-going !)

4. Electroproduction of Λ-hypernuclei