Photoproduction of Λ Hypernuclei in the Quark-Meson Coupling (QMC) model

Hyp-X, "RICOTTI", Tokai, Japan, Sep. 14 – 18, 2009

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R. Shyam, A.W. Thomas

PLB, 676, 51 (2009)

NPA 814, 66 (2008), arXiv:0903.5478 [nucl-th]

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

Outline

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

Introduction, motivation

- **(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**

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**

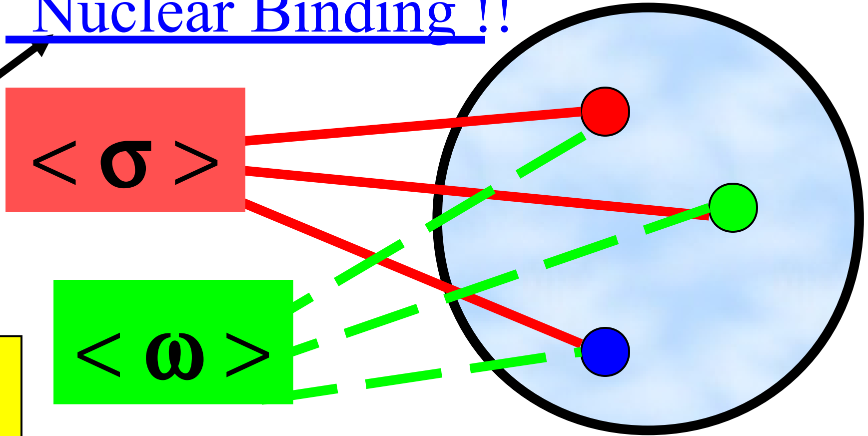
$\Longrightarrow$ **Planned** Expts.: **(**JLab**?)**, **J-PARC**,
GSI-FAIR

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 !!



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

⇓ nonlinear in σ

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

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

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

1. Start

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

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

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.

Nuclear (Neutron) matter, E/A

New saturation mechanism !

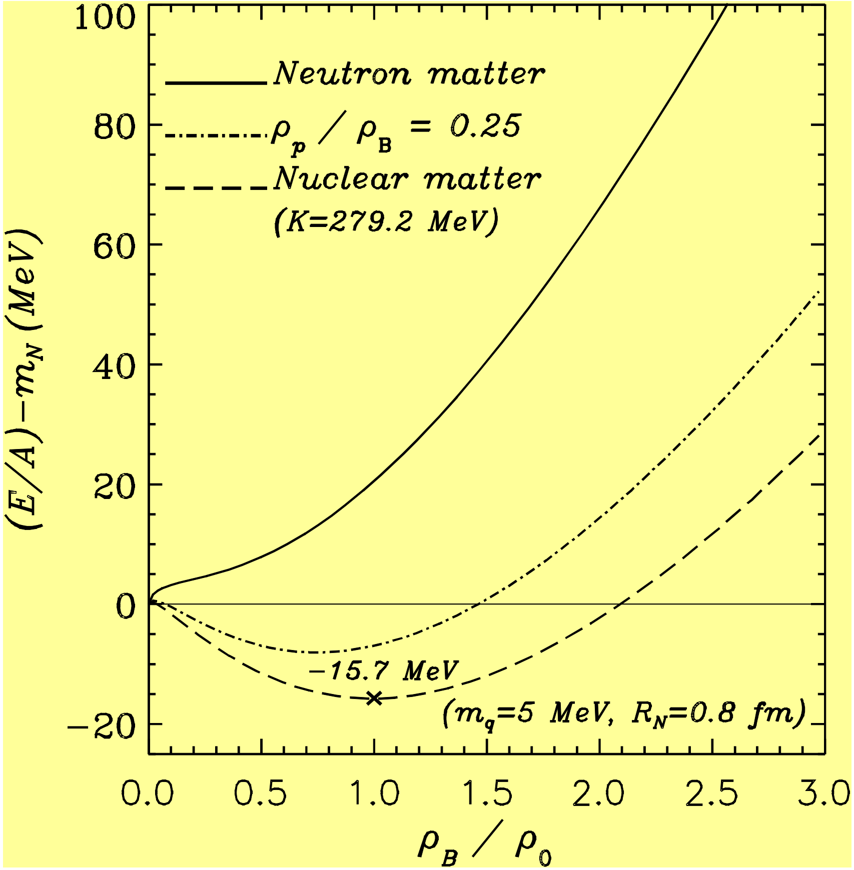
Incompressibility

(~ spring constant)

K ≈ 280 MeV

(200 ~ 300 MeV)

PLB 429, 239 (1998)



Finite nuclei: ^{208}Pb energy levels

NPA 609, 339 (1996)

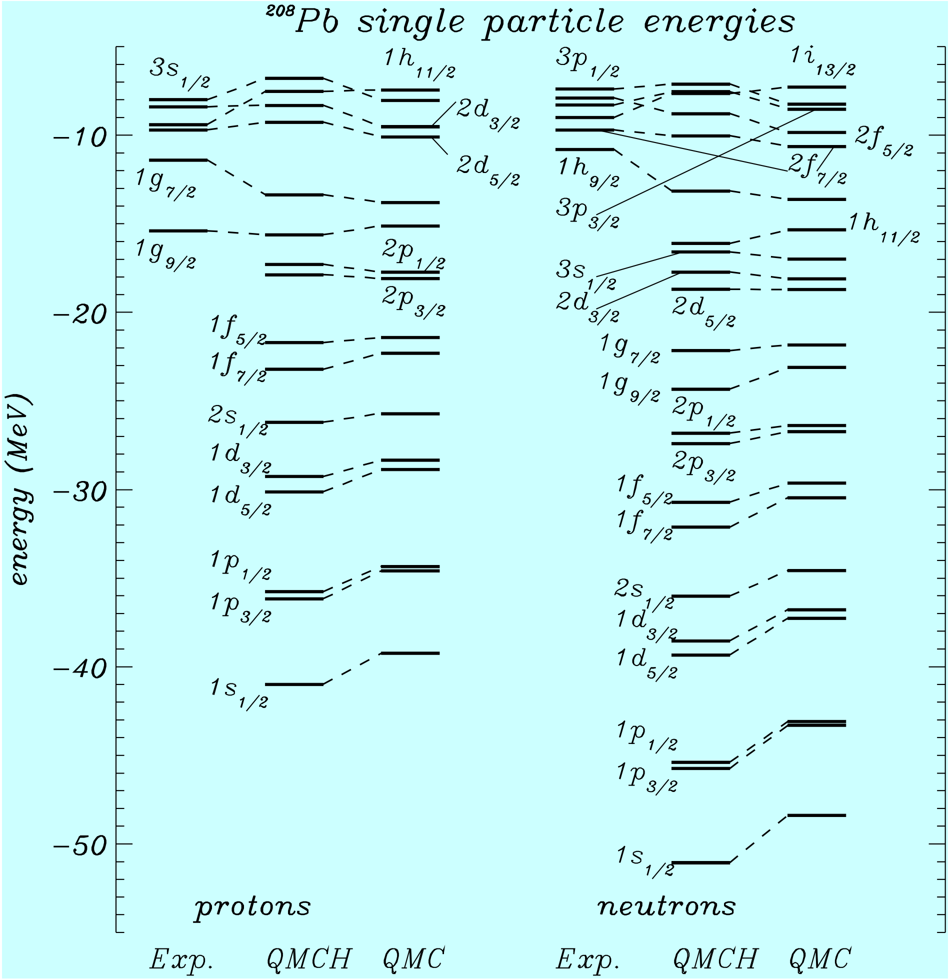
Heavy mass nuclei

Based on quarks !

↓

Hypernuclei

(the latest version of QMC)



QMC $\Longleftrightarrow$ QHD

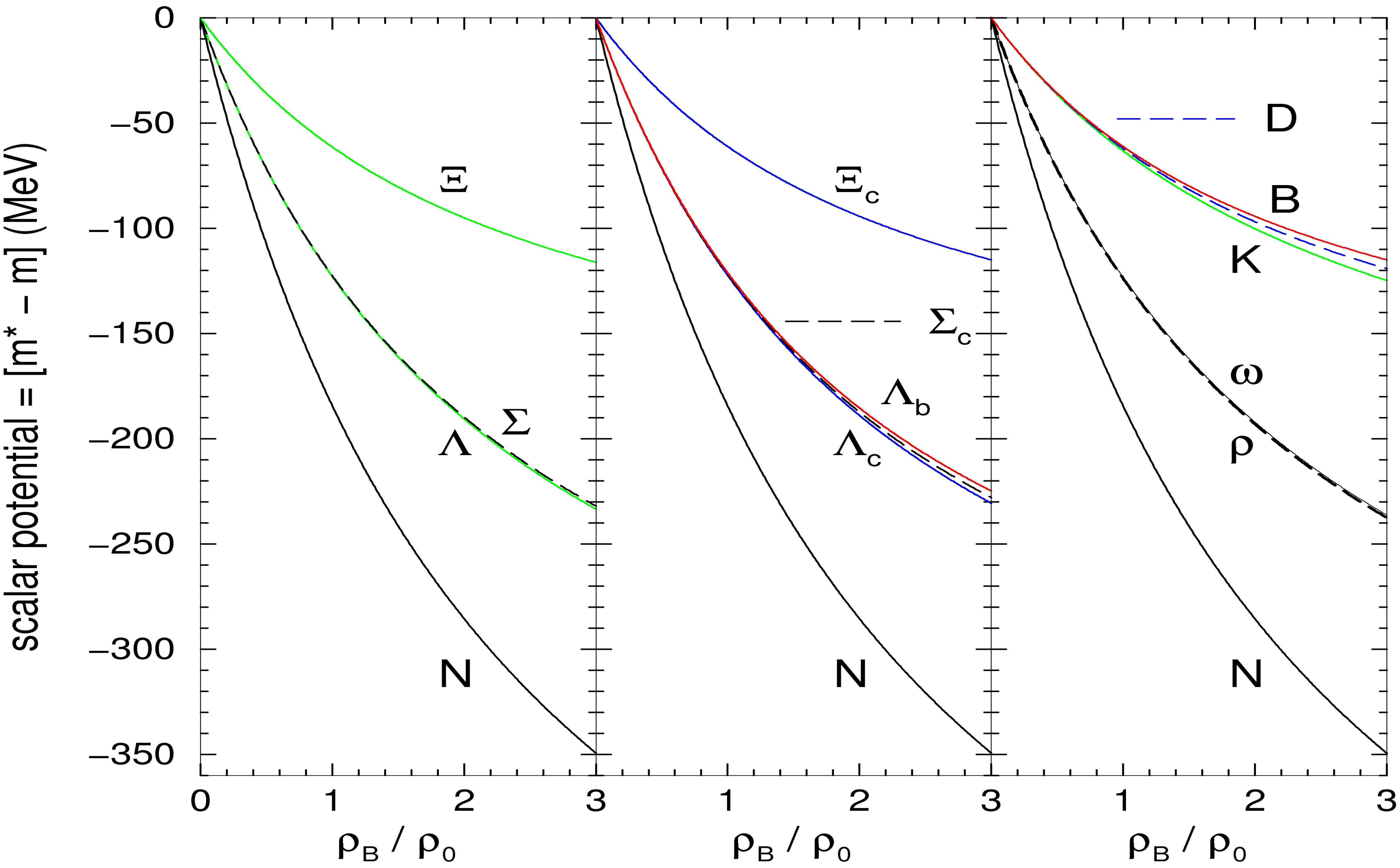
- QHD shows importance of **relativity** :
  mean **σ, ω** and **ρ** fields
- **QMC** goes **far beyond QHD** by incorporating effect of hadron ***internal structure***

- 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 next !

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)

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

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

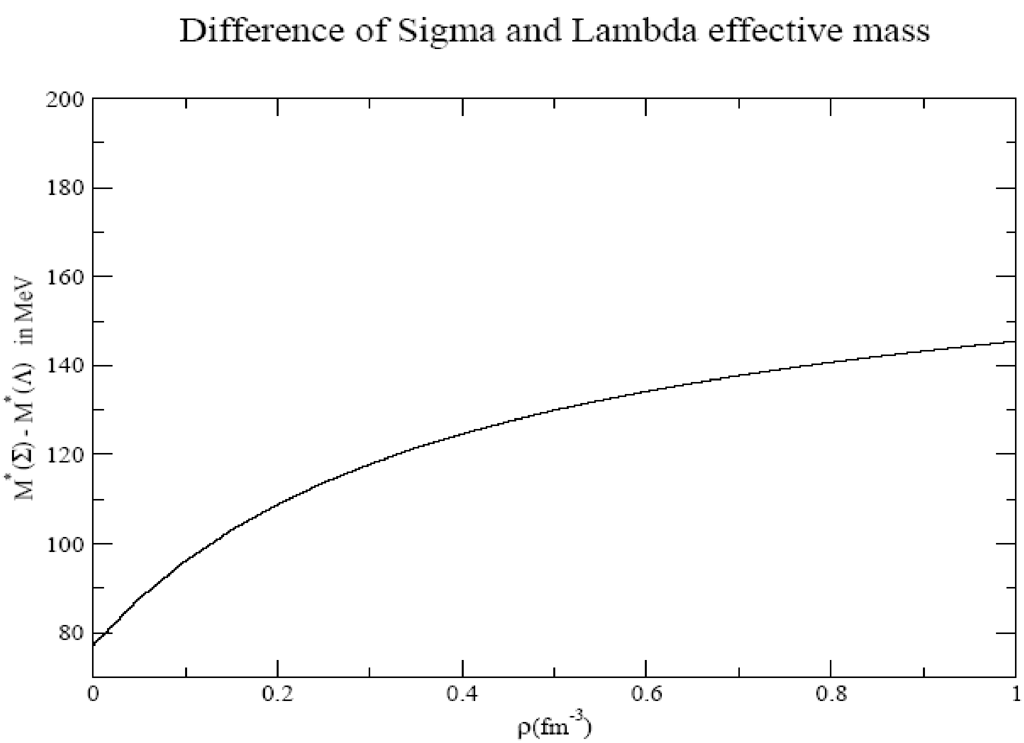
$$\Delta E_M = -3\alpha_c \sum_{a,\, i<j} \lambda_i \lambda_j \vec{\sigma}_i \cdot \vec{\sigma}_j \; M(m_i,m_j,R)$$

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

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

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

Σ^0 potentials
($1s_{1/2}$)

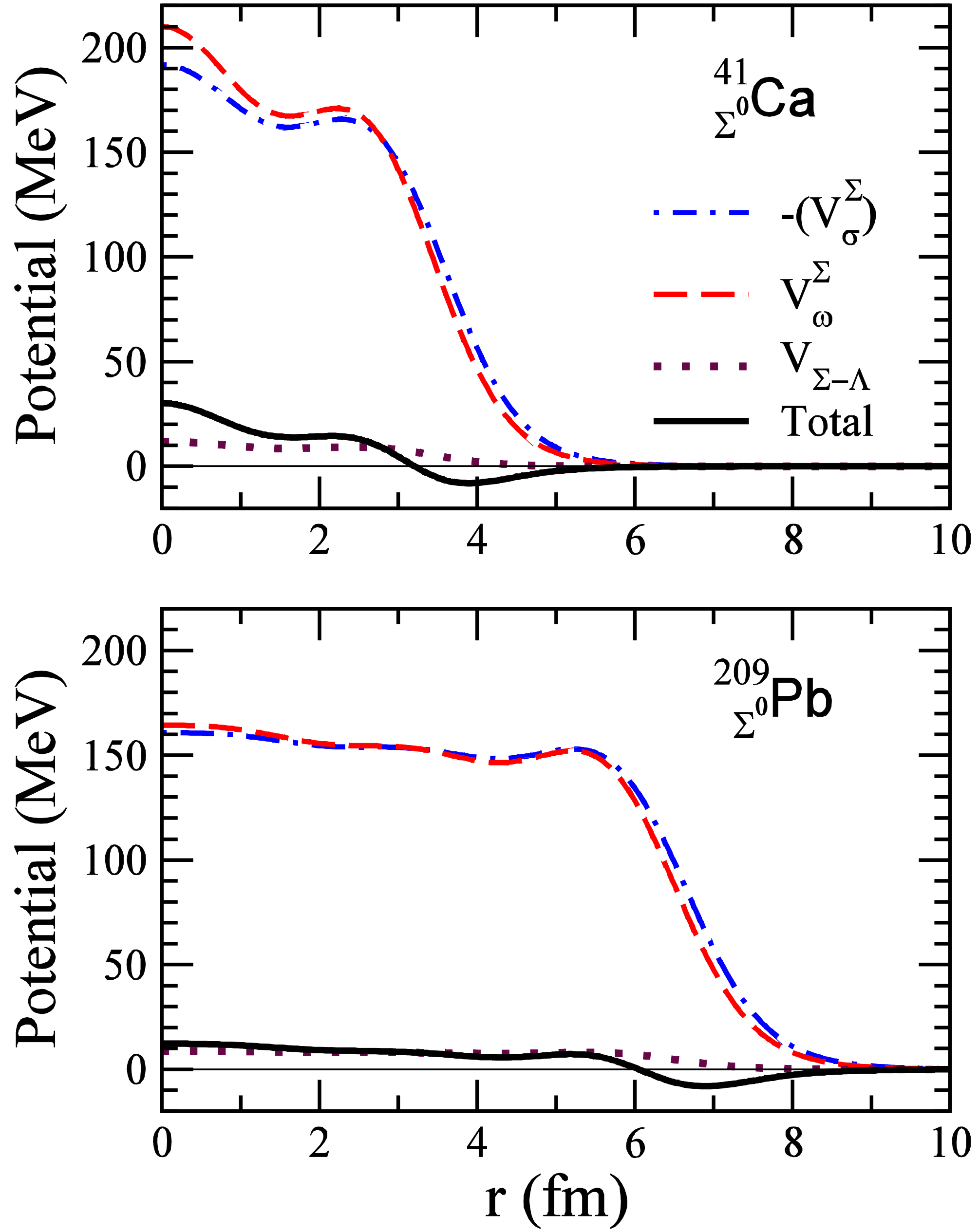
Repulsion in center

Attraction in surface

No Σ nuclear bound state!

HF couplings for hyperons ⇔ successful for high density neutron star

(NPA 792, 341 (2007))



Hypernuclei spectra 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

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)

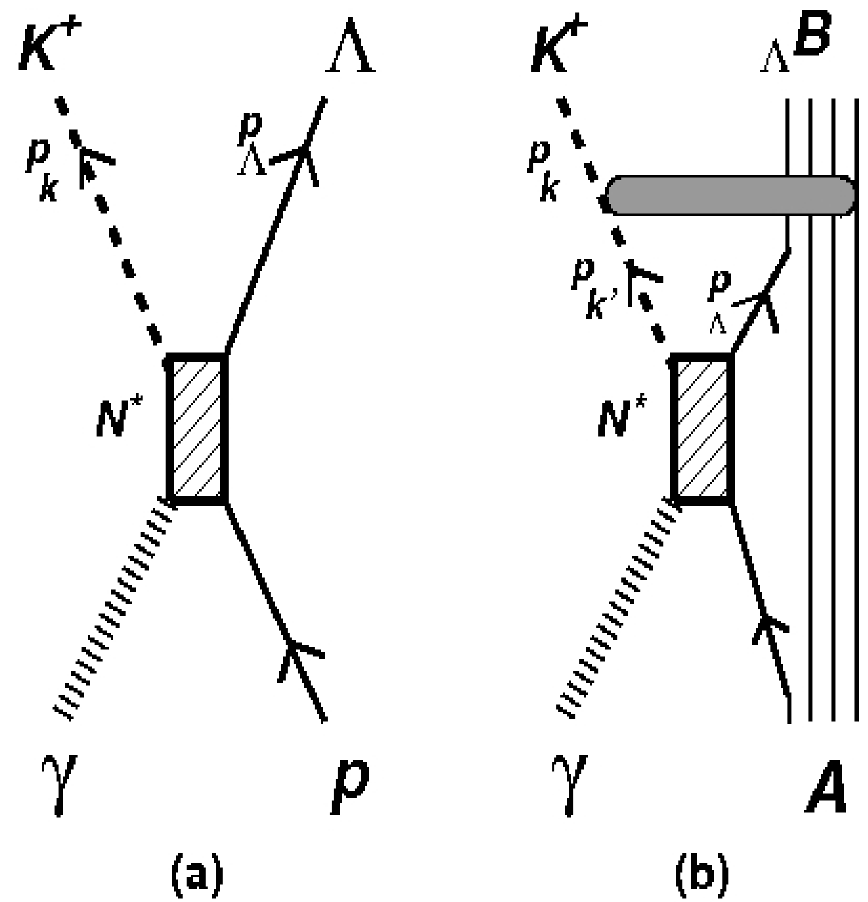
S_{11}(1650), P_{11}(1710)

P_{13}(1720)

⇕

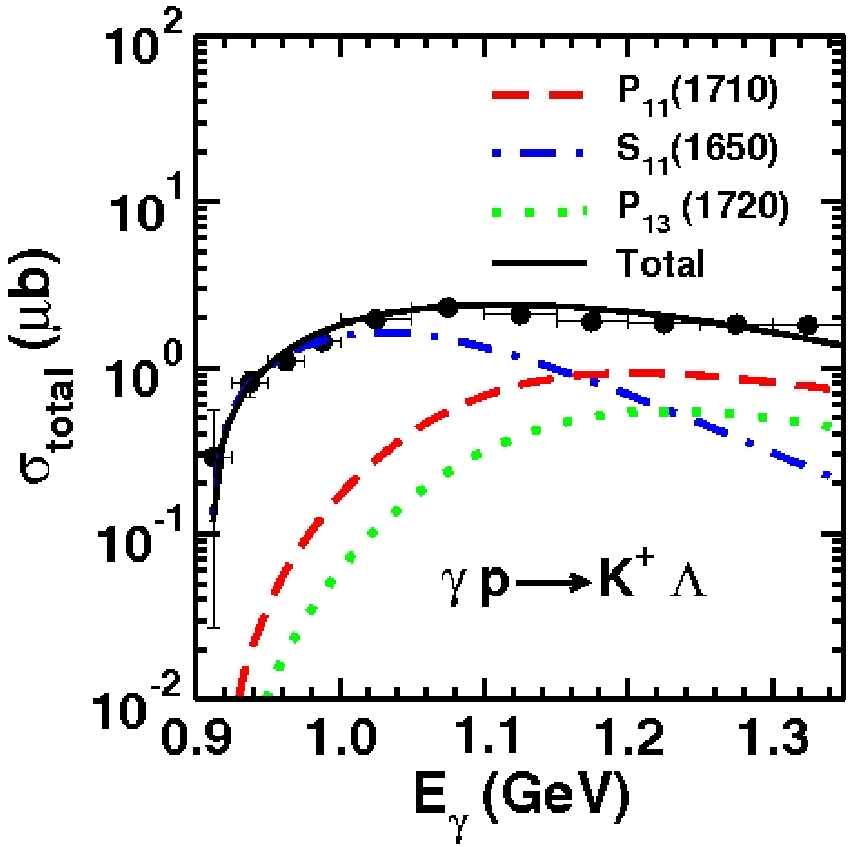
Energy region of interests, hypernuclei production

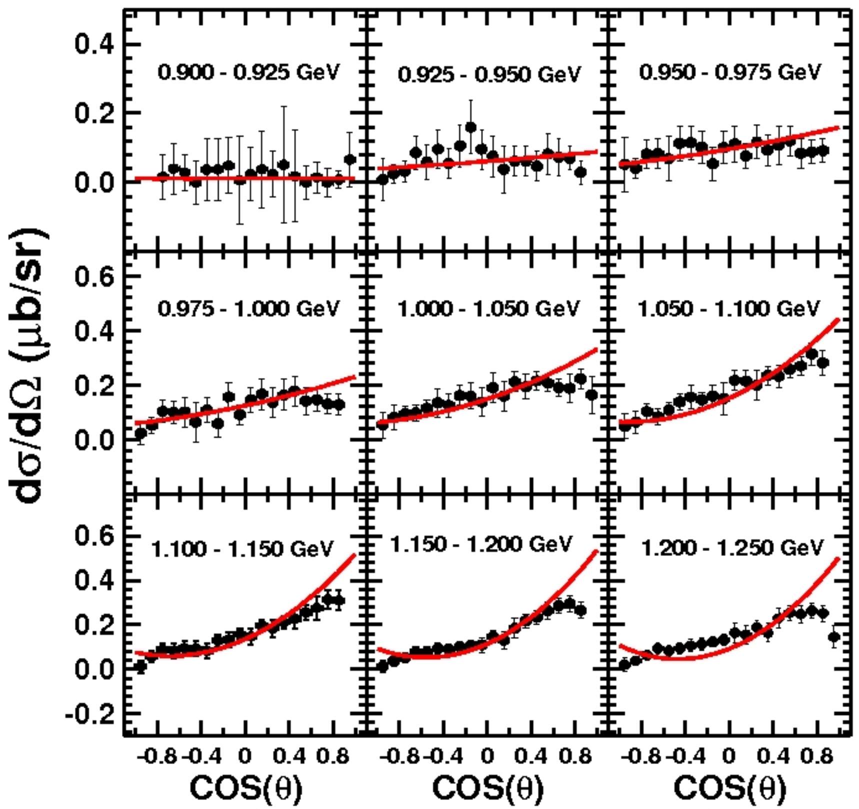
(~ **10 % ambiguity** due to the other background ⇒)



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

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





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 $\theta = 10°$

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

(wave functions!) ⇒

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

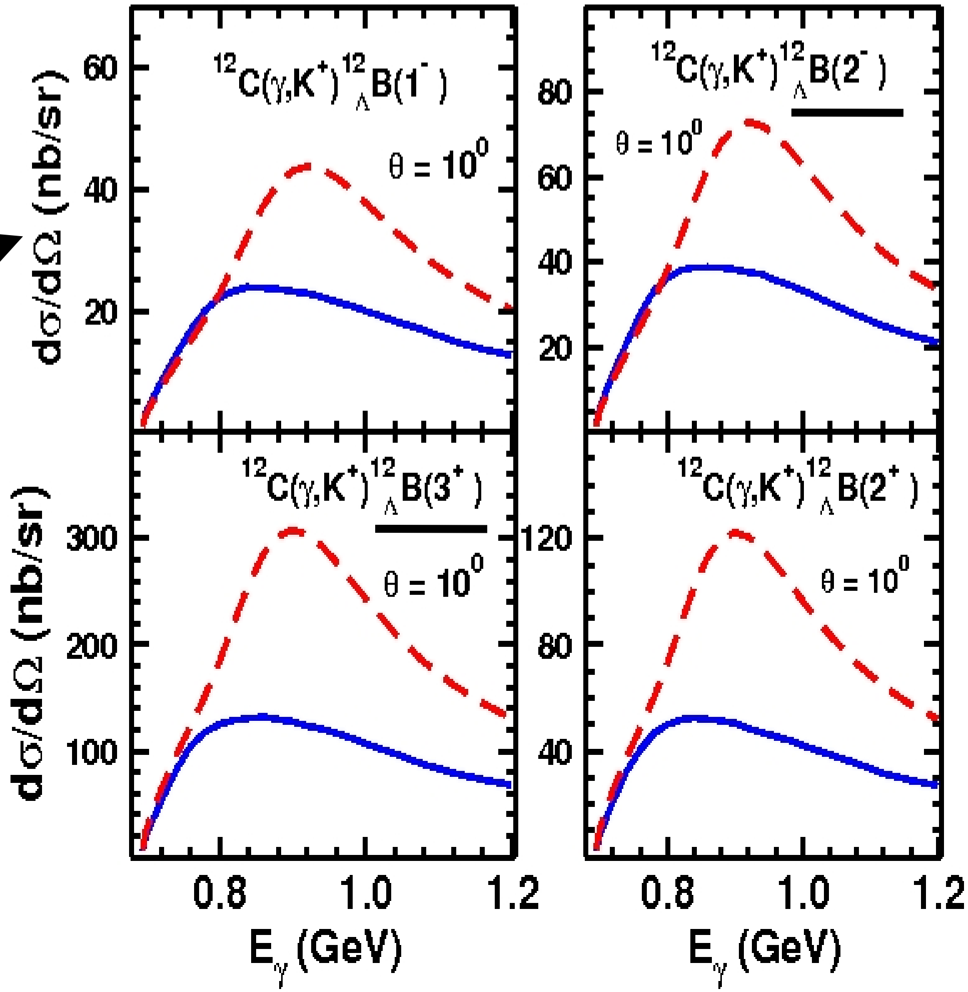
(potentials!) ⇒

Diracp

(phenomenological)

QMC

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



Summary: Λ 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 $\theta = 10°$ shows **distinguishable difference!**
3. **Back ground** inclusion (higher energies)
4. **Heavier Λ** hypernuclei

Discussions

1. Study of Ξ hypernuclei
   ⇑ $\Rightarrow$ $A(K^-, K^+)_\Xi B$ reaction
2. Elementary $K^- p \longrightarrow \Xi K^+$ reaction
3. Heavier Λ hypernuclei **photoproduction**
4. Electroproduction of Λ hypernuclei
5. Λ_c hypernuclei **???!!!**

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

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

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

Lower component is **enhanced** !

$\Longrightarrow$ $g_A^* < g_A$: $\sim |U|^{**}2 - (1/3)\ |L|^{**}2$,

$\Longrightarrow$ **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 !

Hypernuclei spectra 1

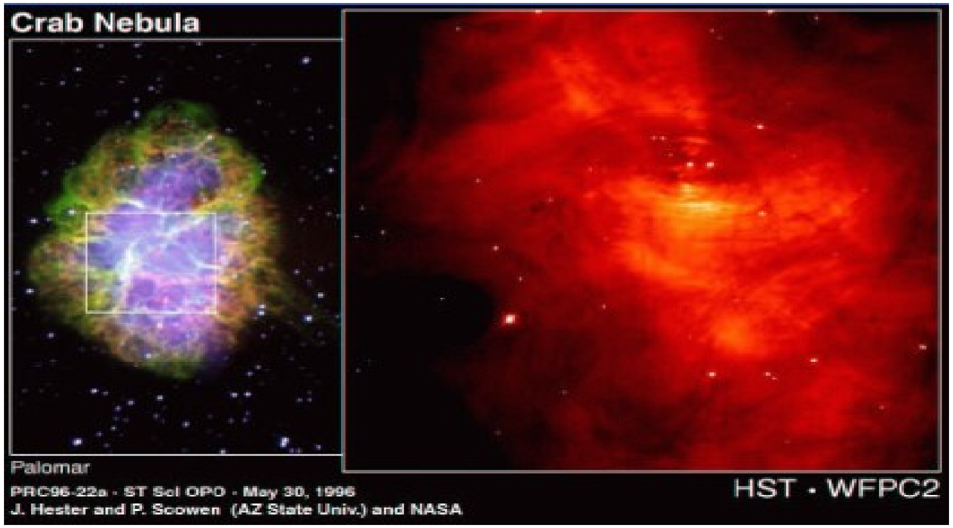
NPA 814, 66 (2008)

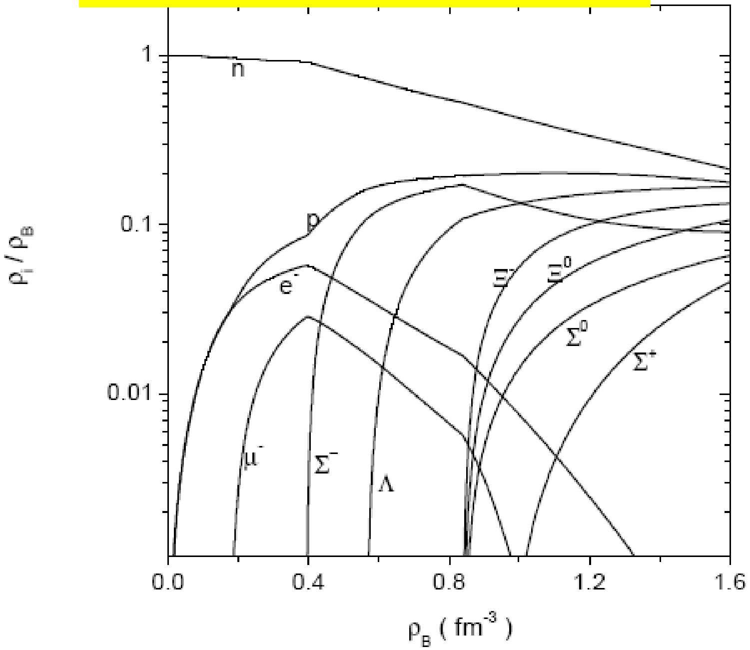
	$^{16}_{\Lambda}O$ Exp.	$^{17}_{\Lambda}O$	$^{17}_{\Xi^0}O$	$^{40}_{\Lambda}Ca$ Exp.	$^{41}_{\Lambda}Ca$	$^{41}_{\Xi^0}Ca$	$^{49}_{\Lambda}Ca$	$^{49}_{\Xi^0}Ca$
$1s_{1/2}$	-12.4	-16.2	-5.3	-18.7	-20.6	-5.5	-21.9	-9.4
$1p_{3/2}$		-6.4			-13.9	-1.6	-15.4	-5.3
$1p_{1/2}$	-1.85	-6.4			-13.9	-1.9	-15.4	-5.6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

${}^{12}_{\Lambda}$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

- **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)

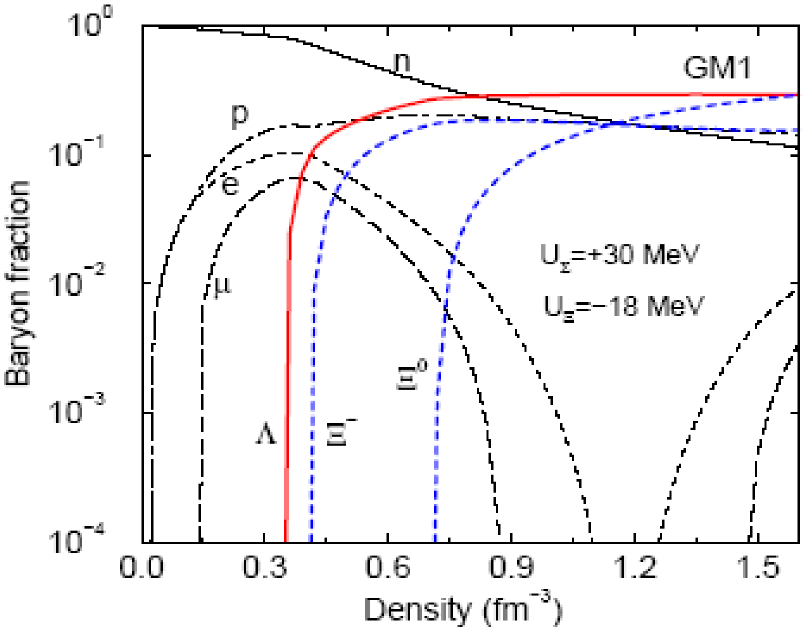




Σ

⟷

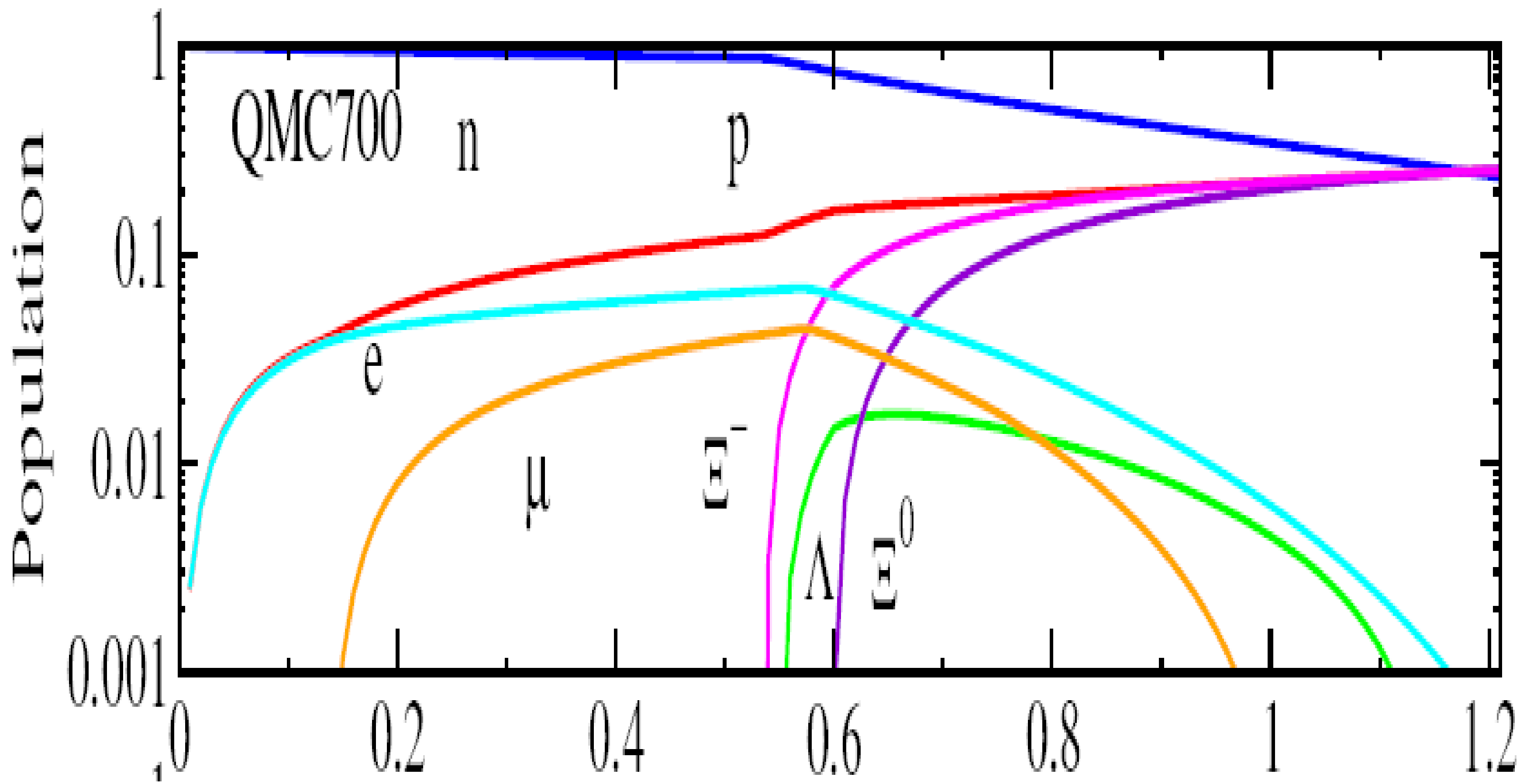
?



From Schaffner-Bielich (2005)

Consequences for Neutron Star

New QMC model, fully relativistic, Hartree-Fock treatment



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