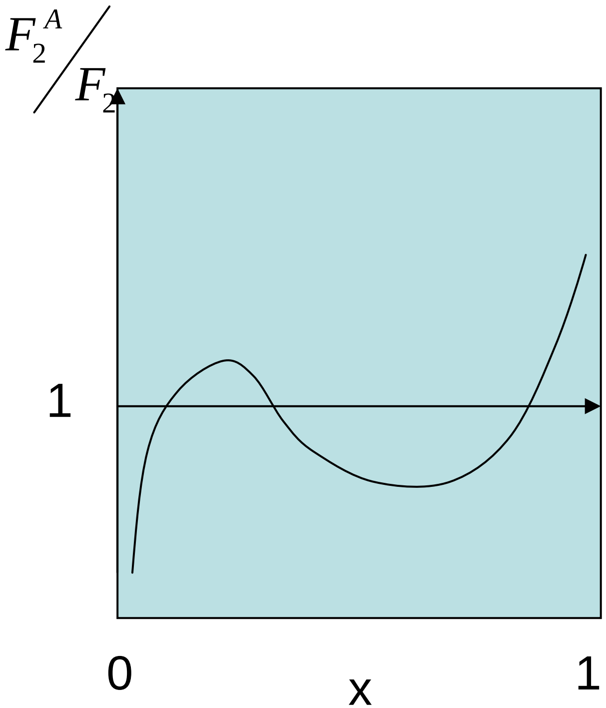
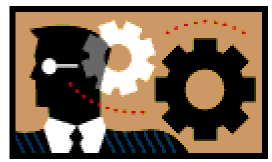
Quark structure and nuclear effective force

in collaboration with A.W. Thomas

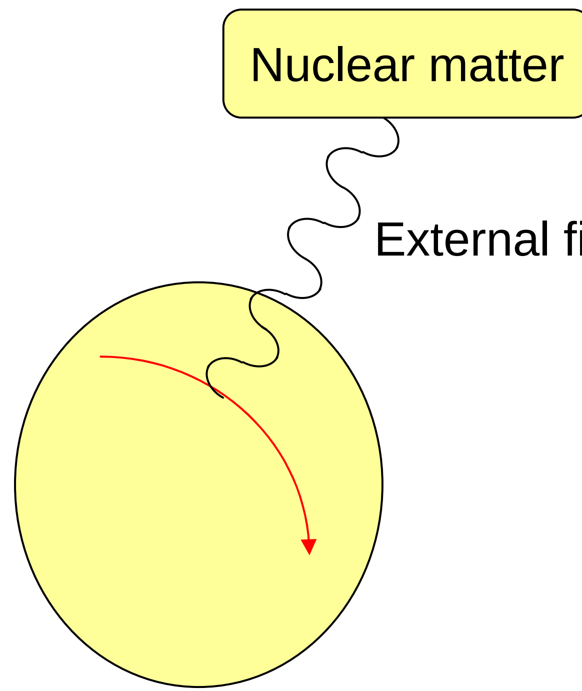
Phys. Rev. Lett.93, 132502 (2004)

EMC effect





A bag in matter

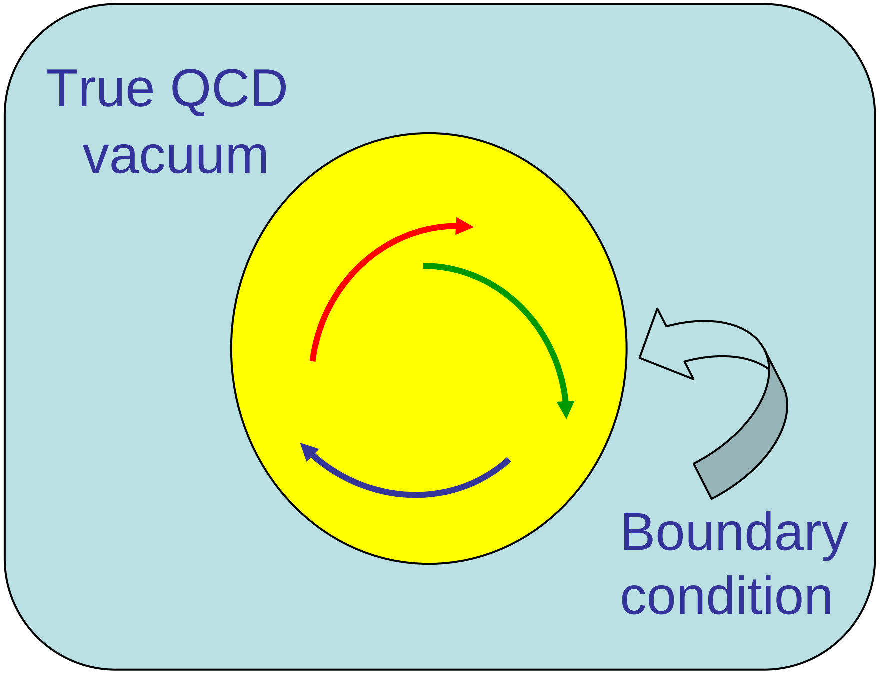


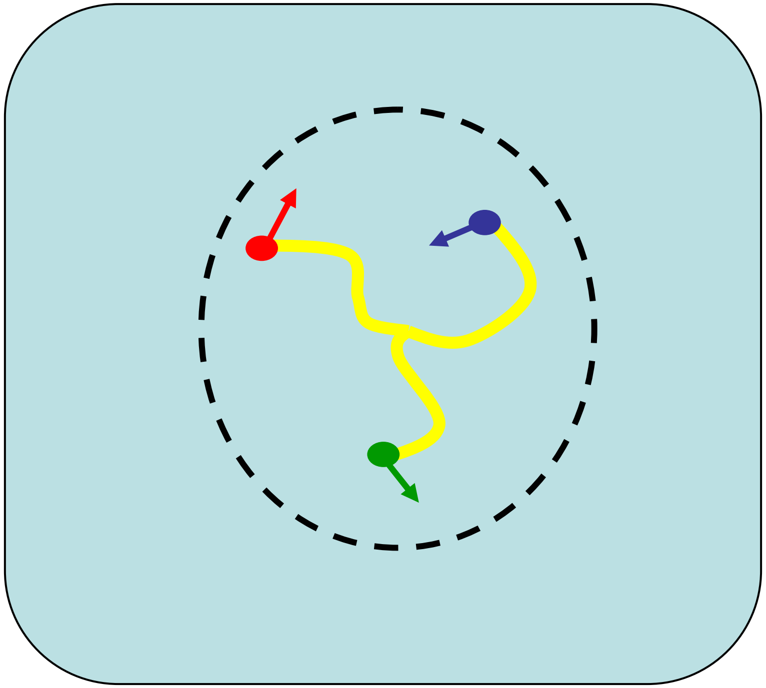
Effect of the coupling to the (constant) external fields

$$\sigma: \quad m_q \to m_q - g_\sigma^q \sigma \quad (attraction)$$

$$\omega: \quad E_q \to E_q + g_\omega^q \omega \quad (repulsion)$$

(NB: here ◆ is a chiral invariant)

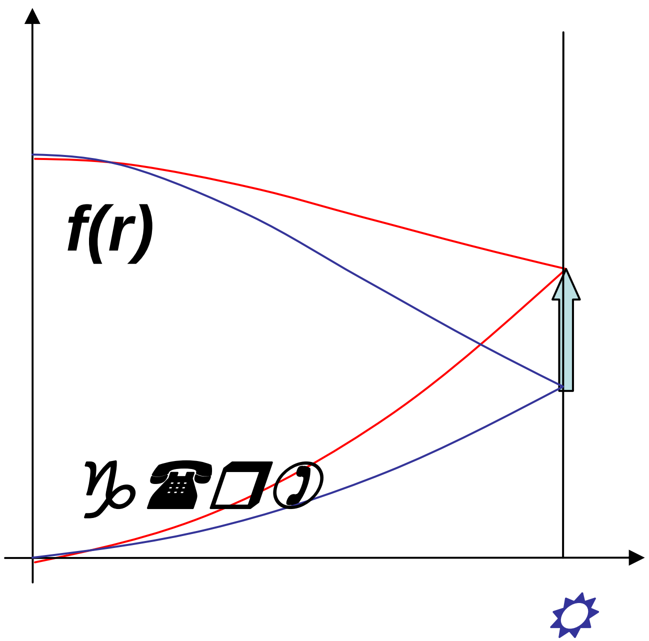




This is just a schematic representation of this

In the true picture, the confined quarks are floating in the non perturbative vacuum. They are coupled to every of its fluctuactions.

Quark field $$\psi_q(x) = e^{iE_q t} \begin{pmatrix} f(r) \\ i\vec{\sigma}.\hat{r}\, g(r) \end{pmatrix} \chi_{1/2}$$

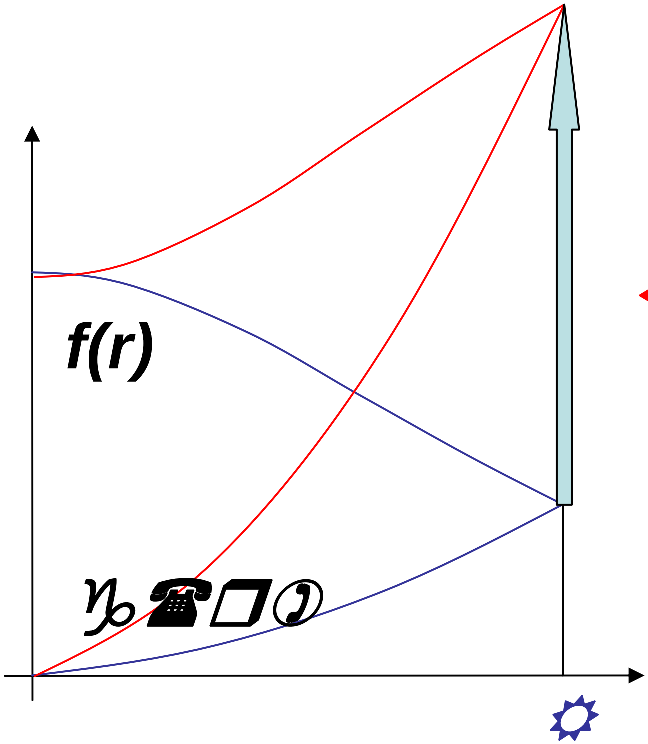


scalar field effect

Choose the constant so that $$E_q(\sigma) + g_\omega^q \omega \approx E_q(0)$$

Quark structure has changed but not the nucleon energy (binding~0)

Try the couplings constant from Walecka model (QHD)



$$g_\sigma = 3 g_\sigma^q \int d\vec{r}\, \overline{\psi}\psi \,, \quad g_\omega = 3 g_\omega^q$$

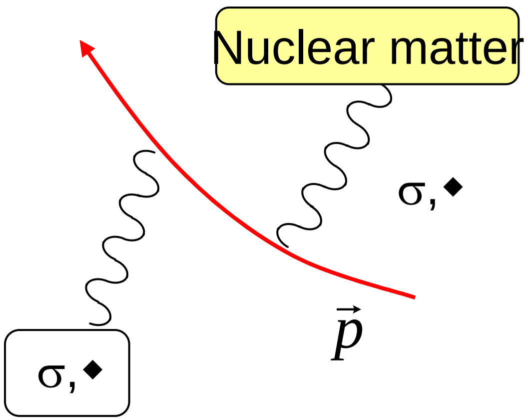
scalar field effect
at nuclear matter density

Absurd because (for instance) $\mu \approx f(R) g(R)$

Something wrong somewhere….

QHD simplified

Point like nucleon



$$M \to M - g_\sigma \sigma, \;\; E \to E + g_\omega \omega$$

$$\sigma(\rho) = g_\sigma \rho \int_0^{k_F} d\vec{p}\, \sqrt{1-v^2} \Big/ \int_0^{k_F} d\vec{p}$$

$$\omega(\rho) = g_\omega \rho$$

$$v \approx \frac{p}{M} \to v \approx \frac{p}{M - g_\sigma \sigma}$$

(non relativistic to simplify presentation)

As ♦⑨ , ■⑨ $\sqrt{1-v^2}$ ⑩ So ♦(❐) ⑨ less than ❐ while ♦(❐)

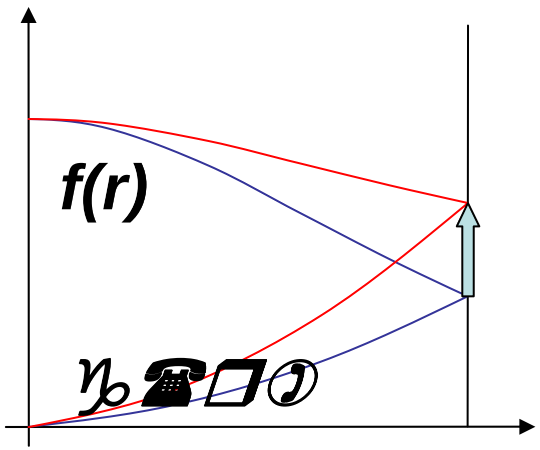
At some point repulsion overcomes attraction ⇨ saturation

In QHD, nuclear saturation is due to the Lorentz contraction factor $\sqrt{1-v^2}$ ⇨ Efficient only if $g_\sigma \sigma$ is large

Consider a uniform distribution of *non overlapping static* bags :

$$\sigma(\rho) = \rho(3g_\sigma^q)\int_{Bag} d\vec{r}\,\overline{\psi}\psi\Big|_\sigma$$

$$\omega(\rho) = \rho(3g_\omega^q)\int_{Bag} d\vec{r}\,\psi^+\psi\Big|_\sigma = \rho g_\omega$$



$$\int_B d\vec{r}\,\overline{\psi}\psi\Big|_\sigma = \int_B d\vec{r}\,(f^2 - g^2)$$ ⑩ when ♦⑨

♦☎❒➂⑨ less than ❒, while ♦(❒)”❒

Saturation mechanism due to the change of the quark structure

More efficient than the QHD mechanism because

At quark level: $m_q^* = (m_q \sim 0) - g_\sigma \sigma$

At nucleon level: $M^* = M - g_\sigma \sigma$

The quark meson coupling model

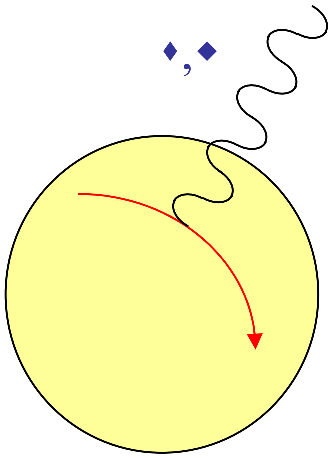
(Phys. Lett B200,235,1988)

Hypothesis : (red boxes are relaxed later)

- ❑Uniform nuclear matter (N=Z)
- ❑In a time average sens, nuclear matter (at moderate density) is a collection of non overlapping quark bags (quasi-nucleons)
- ❑The quarks in different bags interact by the exchange of mesons.
- ❑Fermi motion and Pauli blocking are neglected
- ❑The meson fields are replaced by their mean value

$$\sigma(r) \rightarrow \frac{1}{A}\sum_i \sigma_i(r) = \sigma$$

Only the ♦ and ◆ (time component) need to be considered.



For one particular bag : $E = M(\sigma) + g_\omega \omega$

$$M(\sigma) = \frac{3\Omega(\sigma)}{R_B} + BV - \frac{Z}{R_B}$$

Φ(♦) and R_B are given by the bag equations :

$$\begin{cases} -i\gamma^0 \vec{\gamma}.\vec{\nabla}\psi + (m_q - g_\sigma^q \sigma)\psi = \dfrac{\Omega(\sigma)}{R_B} \qquad (r < R_B) \\ (1 + i\vec{\gamma}.\hat{r})\psi(R_B) = 0, \quad \dfrac{\partial M(\sigma)}{\partial R_B} = 0 \end{cases}$$

Numerical study ⇨

$$M(\sigma) \approx M(0) - g_\sigma \sigma + \frac{d}{2}(g_\sigma \sigma)^2, \qquad d = 0.22 R_B$$

$$g_\sigma = 3 g_\sigma^q \int_B d\vec{r}\, \overline{\psi}\psi \Big|_{\sigma=0}$$

provided $g_\sigma \sigma \leq 400 MeV$ (enough for density ~ normal)

Meson fields :

$$E_{tot} = A\left[M(\sigma) + g_\omega \omega\right] + E_{mesons}$$

$$E_{mesons} = \frac{1}{2}\int d\vec{r}\left[(\nabla\sigma)^2 + m_\sigma^2\sigma^2 - (\nabla\omega)^2 - m_\omega^2\omega^2\right]$$

$$= \frac{1}{2}V_\infty\left(m_\sigma^2\sigma^2 - m_\omega^2\omega^2\right), \qquad (V_\infty = A/\rho)$$

Equation for ♦,♦

$$\frac{\delta E_{tot}}{\delta\sigma} = \frac{\delta E_{tot}}{\delta\omega} = 0$$

A little algebra ⇒

$$g_\sigma\sigma = \frac{G_\sigma\rho}{1 + d\rho G_\sigma}, \qquad g_\omega\omega = G_\omega\rho$$

$$G_\sigma = g_\sigma^2 / m_\sigma^2 \qquad G_\omega = g_\omega^2 / m_\omega^2$$

Inject ♦,♦ in the total energy: ⟹ $$\frac{E_{tot}}{A} = M - \frac{1}{2}\frac{G_\sigma \rho}{1 + d\rho G_\sigma} + \frac{1}{2} G_\omega \rho$$

N-body forces

Fix G_σ, G_ω

$$\frac{\partial}{\partial \rho}\frac{E_{tot}}{A}\bigg|_{\rho_0} = 0, \quad \rho_0 = 0.16\, fm^{-3}, \quad \frac{E_{tot}}{A}\bigg|_{\rho_0} = M - 16 MeV$$

$$\Longrightarrow \quad G_\sigma = 7.2\ fm^2, \quad G_\omega = 5\ fm^2$$

Nucleon structure is little changed :

$$\frac{g_A(\rho_0)}{g_A(0)} = 0.92, \quad \frac{R_B(\rho_0)}{R_B(0)} = 0.99, \quad \frac{\mu(\rho_0)}{\mu(0)} = 1.07$$

Good surprise: compressibility K=220MeV

Including Fermi motion and blocking

$$E_{tot} = A\left[M(\sigma) + g_\omega \omega\right] + E_{mesons}$$

$$E_{tot} = A\left[\frac{\int_0^{k_F} d\vec{p}\sqrt{p^2 + M^2(\sigma)}}{\int_0^{k_F} d\vec{p}} + g_\omega \omega\right] + E_{mesons}$$

and redo the stuff.

Then QHD becomes a special case (corresponding to d=0)

With $d=0.22R_B$ the quark mechanism dominates over the relativistic mechanism.

This was still for uniform matter. Wait for 6 years…

Finite nuclei

(PAMG, K.Saito, E. Rodionov, AW Thomas, NPA601,349)

Look there for details

Framework : Born Oppenheimer Approximation

Nucleon velocity<<Quark velocity

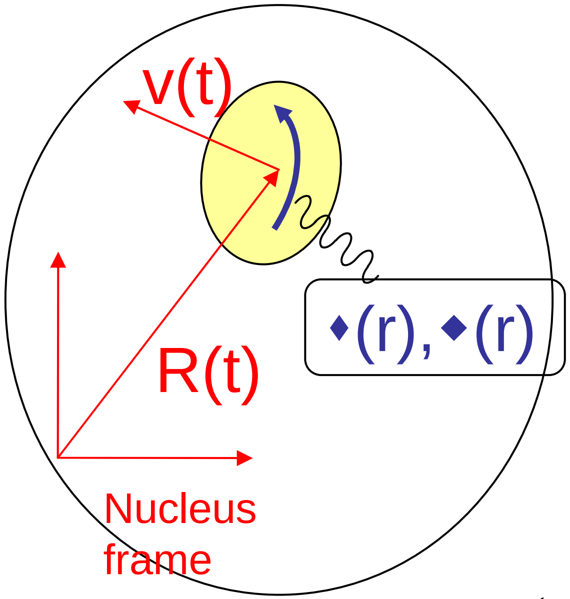
The characteristic time (♦) it takes to the quark to adjust its motion is small enough that, during this time, the nucleon motion is locally inertial (rather than frozen in the strict BOA)

$$\vec{R}(t) \approx R(0) + \dot{\vec{R}}(0)t \quad for \;\; t < \tau$$

Estimate: $\dot{R} \sim 0.3, \quad \tau \sim 1/400 MeV \approx 0.5\, fm \rightarrow \dot{R}\tau \sim 0.15\, fm$

which is small before the typical distance over which the density varies appreciably.

(NB: the motion of the nucleon is classical. Quantization is done at the end.)



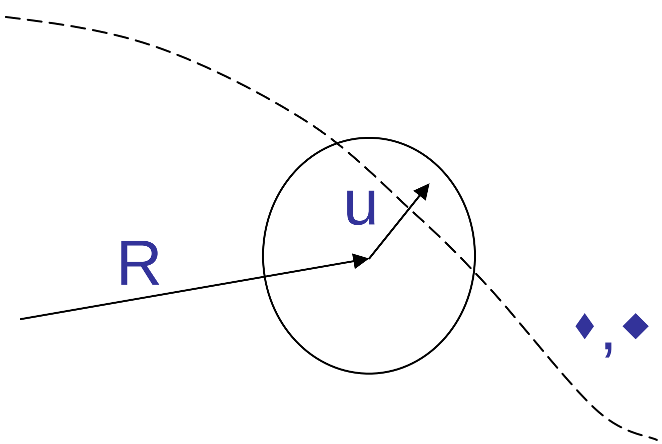
At each time t one one goes to the instantantaneous rest frame (IRF):

IRF(t)= L(v) Nucleus frame

and one evaluates the energy momentum of the bag in the fields as seen in the IRF

$$(th\,\xi = v = \dot{R})$$

Nucleus	IRF
σ	σ
$\omega^0 \equiv \omega$	$\omega\, ch\, \xi$
$\vec{\omega} = 0$	$-\,\omega\, \hat{v}\, sh\, \xi$



$$\sigma(\vec{R}+\vec{u}) \approx \sigma(\vec{R}) + \vec{u}.\vec{\nabla}\sigma\Big|_R$$

Constant in the bag volume: Treated exactly

Perturbation

Constant part of the fields

$$\begin{cases} E' = M(\sigma) + g_{\omega}\omega(\vec{R})\, ch\,\xi \\ \vec{P}' = -g_{\omega}\omega(\vec{R})\, ch\,\xi\,\hat{v} \end{cases}$$

$$\begin{cases} E = \sqrt{P^2 + M^2(\sigma)} + g_{\omega}\omega(\vec{R}) \\ \vec{P} = M(\sigma)\, ch\,\xi\,\hat{v} \end{cases}$$

IRF

Nucleus

Non relativistic approximation (moderate density!)

$$E(\vec{R},\vec{P}) = \frac{P^2}{2M(\sigma)} + M(\sigma) + g_{\omega}\omega(\vec{R})$$

LO relativistic saturation

Quark saturation

$$M(\sigma) \approx M(0) - g_{\sigma}\sigma + \frac{d}{2}(g_{\sigma}\sigma)^2$$

Perturbative effect of the variable part of the fields

$$\Delta E' = \frac{\mu_S}{M(\sigma)} \vec{S}.\vec{\nabla}(g_\omega \omega) \times \vec{v} + O(v^3) \qquad (\mu_S \approx 0.9)$$

describes the spin precession in the “magnetic” field

$$\vec{B} = \vec{\nabla} \times \vec{\omega}_{IRF} = \vec{\nabla} \times (-\omega \vec{v})$$

seen in the IRF.
The corresponding equation of motion (in the IRF)

$$\frac{d\vec{S}}{dt} = -\frac{\mu_S g_\omega}{M(\sigma)} \vec{S} \times \vec{B}$$

must be written in the nucleus frame. Use BMT equation…

Bargman Michel Telgdi covariant spin equation

$$\frac{d\Sigma^{\mu}}{d\tau} = -F^{\mu\nu}\Sigma_{\nu} + u^{\mu}u_{\rho}F^{\rho\sigma}\Sigma_{\nu} - u^{\mu}\Sigma_{\nu}\frac{du^{\nu}}{d\tau}$$

with Σ, τ covariant spin and proper time.

Apply to the nucleus frame:

$$\frac{d\vec{S}}{dt} = \frac{g_{\omega}\mu_{S}}{M(\sigma)}\left(\vec{\nabla}\omega \times \vec{v}\right) \times \vec{S} - \frac{1}{2}\left(\frac{d\vec{v}}{dt} \times \vec{v}\right) \times \vec{S} + O(v^{3})$$

$$Eq.of\ motion \rightarrow \frac{d}{dt}\left(M(\sigma)\vec{v}\right) = -\vec{\nabla}\left(g_{\omega}\omega + M(\sigma)\right)$$

$$\frac{d\vec{S}}{dt} = \frac{1}{2M(\sigma)}\vec{\nabla}\left[(2\mu_{S} - 1)g_{\omega}\omega - M(\sigma)\right] \times \vec{v}.\vec{S}$$

In terms of potential energy

$$V_{SO} = \frac{1}{2M(\sigma)} \vec{\nabla}\left[(2\mu_S - 1) g_\omega \omega - M(\sigma)\right] \times \vec{v}.\vec{S}$$

Remark: assume $M(\sigma) = M - g_\sigma \sigma \quad (d = 0)$

$$V_{SO} = \frac{1}{2M(\sigma)} \vec{\nabla}\left[(2\mu_S - 1) g_\omega \omega + g_\sigma \sigma\right] \times \vec{v}.\vec{S}$$

For a Dirac particle $V_{SO} = \frac{1}{2M(\sigma)} \vec{\nabla}\left[g_\omega \omega + g_\sigma \sigma\right] \times \vec{v}.\vec{S}$

This is approximatively correct because $2\mu_S - 1 \approx 1 \quad (\mu_S \approx 0.9)$

Completely wrong for an isovector interaction since $\mu_V = 4.7$

Summary: the (classical) energy of the (quasi) nucleon is

$$E(\vec{R},\vec{P}) = \frac{P^2}{2M(\sigma)} + M(\sigma) + g_\omega \omega(\vec{R}) + V_{SO}$$

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

$$\vec{v} = \frac{\vec{P}}{M(\sigma)} + O(v^3)$$

$$V_{SO} = \frac{1}{2M^2(\sigma)} \vec{\nabla}\left[(2\mu_S - 1) g_\omega \omega(\vec{R}) - M(\sigma)\right] \times \vec{P}.\vec{S}$$

Add the effect of the rho meson $(\,field\;\; b^\alpha, \alpha = 1,2,3)$

$$g_\omega \omega \rightarrow g_\omega \omega + g_\rho \frac{\vec{\tau}}{2}.\vec{b}$$

$$(2\mu_S - 1) g_\omega \omega \rightarrow (2\mu_S - 1) g_\omega \omega + (2\mu_V - 1) g_\rho \frac{\vec{\tau}}{2}.\vec{b}$$

Remarks:

- The fields $\sigma(\vec{R}), \omega(\vec{R})$ acting on the nucleon at $\vec{R}$ are those created by the OTHER nucleons.

- The spin-orbit interaction has been obtained as a first order perturbation. By consistency $M(\sigma) \to M$

- Quantization $\vec{P} \to -i\vec{\nabla}_R$ allows 2 orderings in the kinetic energy

$$T_1 = \vec{P}.\frac{1}{2M(\sigma)}\vec{P} \;,\; T_2 = P^2\frac{1}{4M(\sigma)} + \frac{1}{4M(\sigma)}P^2$$

however $T_1 - T_2 \sim \nabla^2\sigma$ which can be abosrbed in a change of m_σ . In practice

$$T_1 \leftrightarrow T_2$$ amounts to $\Delta m_\sigma \sim 50 MeV$

For definiteness we chose the ordering 1

Total energy

$$E_{tot} = \sum_i E(i) + \frac{1}{2}\int d\vec{r}\left[(\nabla\sigma)^2 + m_\sigma^2\sigma^2 - (\nabla\omega)^2 - m_\omega^2\omega^2\right]$$

with

$$E(i) = \vec{P}_i . \frac{1}{2M[\sigma(\vec{R}_i)]}\vec{P}_i + M[\sigma(\vec{R}_i)] + \ldots$$

$$\frac{\delta E_{tot}}{\delta\sigma(\vec{R})} = \frac{\delta E_{tot}}{\delta\omega(\vec{R})} = 0 \quad \text{determine} \quad \sigma(\vec{R}), \omega(\vec{R})$$

$$-\nabla^2\omega(\vec{r}) + m_\omega^2\omega(\vec{r}) = g_\omega \sum_i \delta(\vec{r} - \vec{R}_i)$$

$$-\nabla^2\sigma(\vec{r}) + m_\sigma^2\sigma(\vec{r}) =$$

$$g_\sigma(1 - d g_\sigma \sigma(\vec{r}))\sum_i \left[\delta(\vec{r} - \vec{R}_i) - \vec{P}_i . \frac{\delta(\vec{r} - \vec{R}_i)}{M^2(\sigma)}\vec{P}_i\right]$$

First attempt (1995): mean field approximation

- Replace: $\sigma(\vec{r}) \rightarrow < \sigma(\vec{r}) > ...$

- Solve the equations self consistently

Using the coupling fixed on nuclear matter:

Sensible results for charge density (A=16,40)

Spin orbit splitting much too small (1/2)

However it is known that for the spin-orbit interaction the exchange (Fock) term adds to the direct term, can make a factor ~2!

But we had no Fock term...☹

8 years later…

Step 1: $E_{tot} = \sum_i E(i) + E_{mesons}$

Step 2: $\frac{\delta E_{tot}}{\delta \sigma} = \frac{\delta E_{tot}}{\delta \sigma} = 0 \rightarrow \sigma(\vec{r}) = \sigma_{sol}(\vec{r}, \vec{R}_1 \ldots \vec{R}_A)$

$\omega(\vec{r}) = \omega_{sol}(\vec{r}, \vec{R}_1 \ldots \vec{R}_A)$

(*analytical*!)

Step 3: $E_{tot}(\sigma \rightarrow \sigma_{sol}, \omega \rightarrow \omega_{sol}) = H_{eff}(\vec{R}_1, \ldots \vec{R}_A)$

Allows antisymmetrization

Makes ontact with conventional nuclear physics

$H_{eff}(1,2,\ldots A)$ is pretty complicated: N-body finite range forces
Can't be used as such (according to many-body practitionners)

$$-\nabla^2\sigma(\vec{r}) + m_\sigma^2\sigma(\vec{r}) = \overbrace{g_\sigma(1 - dg_\sigma\sigma(\vec{r}))\sum_i\left[\delta(\vec{r}-\vec{R}_i) - \vec{P}_i.\frac{\delta(\vec{r}-\vec{R}_i)}{M^2(\sigma)}\vec{P}_i\right]}^{\rho_S(\vec{r})}$$

Approximation scheme: STEP 1

$$S(\vec{r}) = g_\sigma(1 - dg_\sigma\sigma)\rho_S$$

Write this as $\sigma(\vec{r}) = \frac{S(\vec{r})}{m_\sigma^2} + \frac{\nabla^2\sigma}{m_\sigma^2}$

Grosso modo $\sigma(\vec{r})$ follows the nuclear density $\Rightarrow \frac{\nabla^2\sigma}{m_\sigma^2} \sim \frac{\sigma}{a^2 m_\sigma^2}$

with $a \sim 1\,fm$ the nuclear skin. Take $m_\sigma \sim 600\,Mev$

$\frac{1}{a^2 m_\sigma^2} \sim \frac{1}{10} << 1 \Rightarrow$ In the term $\nabla^2\sigma / m_\sigma^2$ one can replace $\sigma(\vec{r})$ by its approximate value $\sigma(\vec{r}) \approx S(\vec{r})/m_\sigma^2$

New field equation (idem for $\omega(\vec{r})$)

$$\sigma(\vec{r}) = \frac{S(\vec{r})}{m_\sigma^2} + \frac{\nabla^2 S(\vec{r})}{m_\sigma^4}$$

$$\sigma(\vec{r}) = \frac{S(\vec{r})}{m_\sigma^2} + \frac{\nabla^2 S(\vec{r})}{m_\sigma^4}$$

Approximation scheme: STEP 2

$$S(\vec{r}) = g_\sigma (1 - d g_\sigma \sigma) \rho_S \qquad \rho_S(\vec{r}) = \sum \delta(\vec{r} - \vec{R}_i) - \text{relat. corr.}$$

Nuclear matter estimate

$$g_\sigma \sigma \sim 300 MeV \text{ at } \rho = 0.16\, fm^{-3}$$

$$d = 0.22\, R_B,\, R_B = 0.8\, fm \rightarrow \; d g_\sigma \sigma \sim 0.27$$

⇒ $d g_\sigma \sigma$ is a reasonnable expansion parameter (*at normal density*)

Iterative solution of the field equation:

$$\sigma = \frac{g_\sigma \rho_S}{m_\sigma^2} - \frac{g_\sigma \rho_S (d g_\sigma \sigma)}{m_\sigma^2} + \frac{\nabla^2 S(\sigma)}{m_\sigma^4}$$

Zeroth order solution σ_0

Approximation scheme: STEP 3

Insert the field solutions in $$E_{tot} = \sum_i E(i) + E_{mesons}$$

Remember that $\sigma(\vec{R}_i)$ is the field due to $j \neq i$

$$\sum_i \sum_j \ldots \rightarrow \sum_{i \neq j} \ldots$$ etc...

Simplify…

$$H_{QMC} = \sum_i \frac{\overleftarrow{\nabla}_i . \overrightarrow{\nabla}_i}{2M} + \frac{G_\sigma}{2M^2} \sum_{i \neq j} \overleftarrow{\nabla}_i . \delta(\vec{R}_{ij}) \overrightarrow{\nabla}_i$$

Kinetic and non local terms

$$+ \frac{1}{2} \sum_{i \neq j} \left(\frac{G_\omega}{m_\omega^2} - \frac{G_\sigma}{m_\sigma^2} + \frac{G_\rho}{m_\rho^2} \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right) \nabla_i^2 \left[\delta(\vec{R}_{ij}) \right]$$

Finite range

$$+ \frac{1}{2} \sum_{i \neq j} \left(G_\omega - G_\sigma + G_\rho \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right) \delta(\vec{R}_{ij})$$

2 body

3,4 body

$$+ \frac{dG_\sigma^2}{2} \sum_{i \neq j \neq k} \delta(\vec{R}_{ij}) \delta(\vec{R}_{jk}) + \frac{d^2 G_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta(\vec{R}_{ij}) \delta(\vec{R}_{jk}) \delta(\vec{R}_{kl})$$

$+ 5 \ldots N$ body forces

$$+ \frac{i}{4M^2} \sum_{i \neq j} \overleftarrow{\nabla}_i \delta(\vec{R}_{ij}) \times \overrightarrow{\nabla}_i . \vec{\sigma}_i \left[G_\sigma + (2\mu_S - 1) G_\omega + (2\mu_V - 1) G_\rho \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right]$$

Spin orbit

Done…

Antisymmetry ⟹ forces with N>4 do not contribute.

Set:
$$R_B = 0.8\, fm,$$
$$m_\omega = 780 MeV, m_\rho = 770 MeV, m_\sigma = 500 \div 600 MeV$$

Fix:
$$G_\sigma \equiv \frac{g_\sigma^2}{m_\sigma^2},\ G_\omega \equiv \frac{g_\omega^2}{m_\omega^2},\ G_\rho \equiv \frac{g_\rho^2}{m_\rho^2}$$
on nuclear matter:

$$\frac{E_B}{A}(\rho = 0.16\, fm^{-3}) = -15.85 MeV + \left(\frac{N-Z}{A}\right)^2 30 MeV$$

Get:
$$G_\sigma = 12.6\, fm^2,\ G_\omega = 9.6\, fm^2,\ G_\rho = 9.7\, fm^2 \quad (m_\sigma = 600 MeV)$$

H_{QMC} is completely determined.

H_{QMC} has about the same form as the succesfull Skyrme force.

⇨ **Consider the Skyrme force as the experience**

$$V_{skyrme} = \sum_{i<j} v_{ij} + \sum_{i<j<k} v_{ijk} \qquad v_{123} = t_3 \delta(\vec{R}_{12}) \delta(\vec{R}_{23})$$

$$v_{12} = t_0(1 + x_0 P_\sigma)\delta(\vec{R}_{12})$$

$$+ \frac{t_2}{4} \overleftarrow{\nabla}_{12} \delta(\vec{R}_{12}).\vec{\nabla}_{12} - \frac{t_1}{8}\left[\delta(\vec{R}_{12})\vec{\nabla}^2_{12} + \overleftarrow{\nabla}^2_{12}\delta(\vec{R}_{12})\right]$$

$$+ \frac{i}{4} W_0(\vec{\sigma}_1 + \vec{\sigma}_2).\overleftarrow{\nabla}_{12} \times \delta(\vec{R}_{12})\vec{\nabla}_{12} \qquad (\nabla_{12} = \nabla_1 - \nabla_2)$$

Compare the Hartree-Fock hamiltonians to get $x_0, t_{0,1,2,3}$, and W_0

	QMC	QMC	SkIII	QMC(N=3)
$m_\sigma (MeV)$	500	600		600
$t_0 (MeV\ fm^3)$	-1071	-1082	-1129	-1047
x_0	0.89	0.59	0.45	0.61
$t_3 (MeV\ fm^6)$	16620	14926	14000	12996
M_{eff}/M	.915	.814	.763	.821
$5t_2 - 9t_1 (MeV\ fm^5)$	-7622	-4330	-4030	-4036
$W_0 (MeV\ fm^5)$	118	97	120	91
$K(MeV)$	327	327	355	364

$$\frac{M_{eff}}{M} = \left(1 + \frac{(3t_1 + 5t_2) M \rho_0}{8} \right)^{-1}$$

CONCLUSION

We get a pretty good *caricature* of low energy nuclear physics.
(20% deviation with repect to SkIII)

Essential ingredients:

- Response of the quark structure to the nuclear medium (N-body forces)
- Minimal relativistic effects (spin orbit)
- Formulation as a many body problem (antisymmetrization)

To improve

- Limitation to about normal density (field solution)
- Include pion effects (improves K and effective mass)


'BOU
VRR