Description relativiste chirale de la matière nucléaire incluant des effets du confinement.

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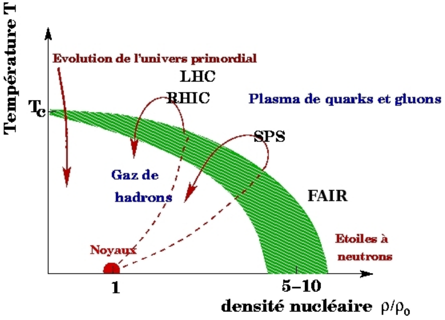
3 avril 2009 CEA Saclay

Matière Nucléaire



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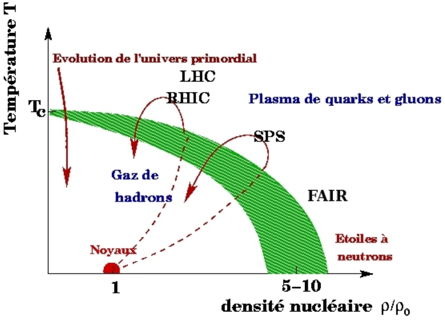

- Matière nucléaire froide : $E/A = -15,96$ MeV, $\rho_0 = 0,16\ \mathrm{fm}^{-3}$, $K = 9\rho^2 \frac{\partial^2 E}{\partial \rho^2} \simeq 250$ MeV.

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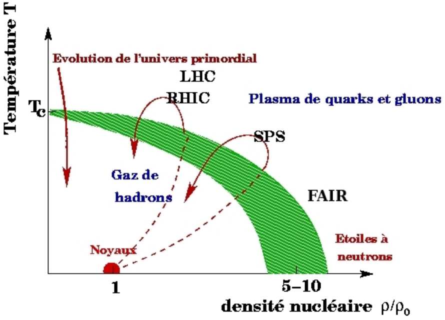

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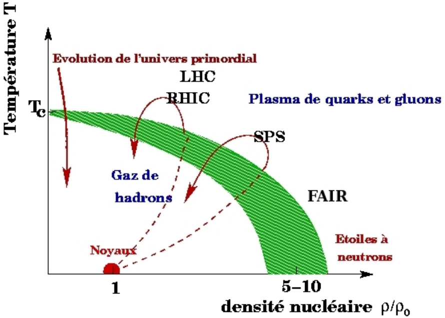

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- Problème à N corps ;
- Contraintes de QCD : symétrie chirale, confinement.

Lagrangien de Walecka

Lagrangien de type Walecka :

$$\begin{aligned}\mathcal{L} &= \bar{\psi}(i\partial_\mu\gamma^\mu - M)\psi + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - g_\sigma\bar{\psi}\sigma\psi \\ &\quad - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - g_\omega\bar{\psi}\gamma_\mu\omega^\mu\psi\end{aligned}$$

où $F_{\mu\nu}F^{\mu\nu} = (\partial_\mu\omega_\nu - \partial_\nu\omega_\mu)(\partial^\mu\omega^\nu - \partial^\nu\omega^\mu)$.

[Walecka 1973]

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[Walecka 1973]

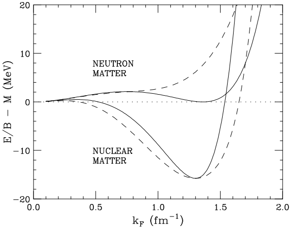
Mécanisme de Saturation

$$\frac{E}{A} = \frac{1}{\rho}\int_0^{p_F} \frac{4d^3p}{(2\pi)^3}\left(\frac{p^2+MM^*}{E^*} - M\right) + Vs + Vv$$

où $Vs = -\frac{1}{2}\frac{g_\sigma^2}{m_\sigma^2}\rho_S^2$ et $Vv = \frac{1}{2}\frac{g_\omega^2}{m_\omega^2}\rho^2$ avec $\rho_S =< \bar{\psi}\psi >, \rho =< \psi^\dagger\psi >$

Résultat :

- $m_\sigma = 500\text{MeV}$, $g_\omega = 13.8$
- $K = 545\text{MeV}$



[B. D. Serot and J. D. Walecka, Int. J. Mod. Phys. **E6** (1997) 515-631]

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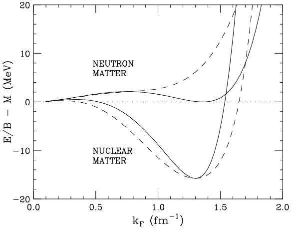

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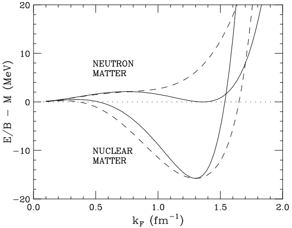

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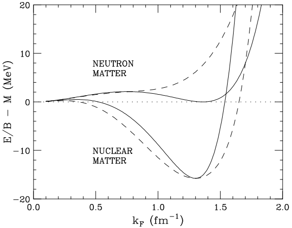

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Extension du modèle de Walecka

Autres mésons :

$$\begin{aligned}
\mathcal{L}_\rho &= -g_\rho \rho_{a\mu}\bar{\psi}\gamma^\mu \tau_a \psi - g_\rho \frac{\kappa_\rho}{2M}\partial_\nu \rho_{a\mu}\bar{\psi}\sigma^{\mu\nu}\tau_a\psi \\
&\quad + \frac{1}{2}m_\rho^2 \rho_{a\mu}\rho_a^\mu - \frac{1}{4}G_a^{\mu\nu}G^{a\mu\nu} \\
\mathcal{L}_\delta &= -g_\delta \delta_a \bar{\psi}\tau_a\psi - \frac{1}{2}m_\delta^2 \delta_a^2 + \frac{1}{2}\partial_\mu \delta_a \partial^\mu \delta_a \\
\mathcal{L}_\pi &= \frac{g_A}{2f_\pi}\partial_\mu \phi_{a\pi}\bar{\psi}\gamma^\mu\gamma^5\tau_a\psi - \frac{1}{2}m_\pi^2\phi_{a\pi}^2 + \frac{1}{2}\partial_\mu\phi_{a\pi}\partial^\mu\phi_{a\pi}
\end{aligned}$$

[A. Bouyssy, J. F. Mathiot, V. G. Nguyen and S. Marcos, Phys. Rev. C **36**, 380 (1987)]

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Lagrangien de QCD

$$\mathcal{L}_{QCD} = \sum_{i=u,d} \left(i\bar{\psi}_i \gamma^\mu \partial_\mu \psi_i - m_i \bar{\psi}_i \psi_i \right)$$

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où $\psi = \begin{pmatrix} \psi_u \\ \psi_d \end{pmatrix}$

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Symétries de QCD

- Symétrie vectorielle :

$$\textit{Transformation de } SU(2) \;:\; \psi \rightarrow e^{i\alpha_k \frac{\tau_k}{2}} \psi$$

$-\frac{m_u - m_d}{2} \bar{\psi} \tau_3 \psi$ brise explicitement la symétrie ;
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- Symétrie axiale :

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$-\frac{m_u + m_d}{2}\bar{\psi}\psi$ brise explicitement la symétrie ;
$m_u \simeq m_d \neq 0$ mais petites : symétrie légèrement brisée explicitement.

Symétrie Chirale
$SU(2)_L \times SU(2)_R$

$$P_L : \psi \rightarrow \frac{(1-\gamma^5)}{2}\psi, \ P_R : \psi \rightarrow \frac{(1+\gamma^5)}{2}\psi$$

$$SU(2)_L : \psi_L \rightarrow e^{i\alpha_k \frac{\tau_k}{2}}\psi_L, \psi_R \rightarrow \psi_R$$
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Lagrangien chiral :

$$\mathcal{L}_{QCD} = i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R - m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

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Bosons de Goldstone = pions.

Modèle σ

$$\mathcal{L}_H = i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R - M(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$$

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$$M\bar{\psi}\psi = M(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \to g(\bar{\psi}_L W(x)\psi_R + \bar{\psi}_R W^\dagger(x)\psi_L)$$

où $W(x) = \sigma(x) + i\vec{\tau}\cdot\vec{\phi}(x)$

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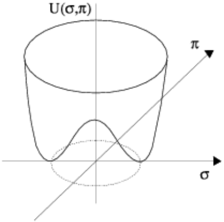
Contenu dynamique :

$$\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \frac{1}{2}\partial_\mu\vec{\phi}\partial^\mu\vec{\phi} - U(\sigma,\vec{\phi}) + c\sigma$$



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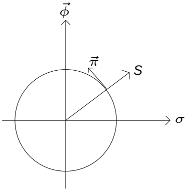
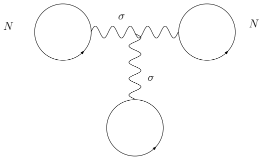
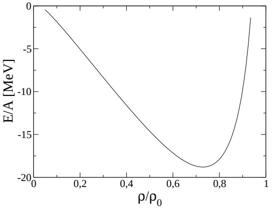


$$\mathcal{L}_{s,\vec{\pi}} = \frac{1}{2}\partial_\mu s\partial^\mu s + \frac{1}{2}\partial_\mu\vec{\pi}\partial^\mu\vec{\pi} - g_s s\bar{\psi}\psi + \frac{g_A}{2f_\pi}\partial_\mu\vec{\pi}\bar{\psi}i\gamma^\mu\gamma^5\vec{\tau}\psi - U(s) + c\sigma.$$

[C. Chanfray, M. Ericson, P. A. M. Guichon, Phys. Rev. C **63**, 055202 (2001)]

Limites du Modèle σ





Masse du sigma :

$$m_s^{*2} = \frac{\partial^2 \epsilon}{\partial \bar{s}^2} \simeq m_\sigma^2 - \frac{3g_s}{2f_\pi}\rho_S$$

Masse du nucléon :

$$M(m_\pi^2) = a_0 + a_2 m_\pi^2 + a_4 m_\pi^4 + \Sigma_\pi(m_\pi, \Lambda)$$

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Réponse Nucléonique

κ_{NS} = réponse scalaire du nucléon [P. A. M. Guichon]

$$M^* = M(s) = M - g_s s + \frac{1}{2}\kappa_{NS} s^2 + ...$$

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Modification du lagrangien :

$$\delta\mathcal{L} = -\frac{1}{2}\kappa_{NS}\bar{\psi}s^2\psi$$

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Constante de couplage et masse du s :

$$g_s^*(\bar{s}) = \frac{\partial M^*}{\partial \bar{s}} = g_s + \kappa_{NS}\bar{s}$$

$$m_s^{*2} = \frac{\partial^2 \epsilon}{\partial \bar{s}^2} \simeq m_\sigma^2 - \left(\frac{3g_s}{f_\pi} - \kappa_{NS}\right)\rho_S$$

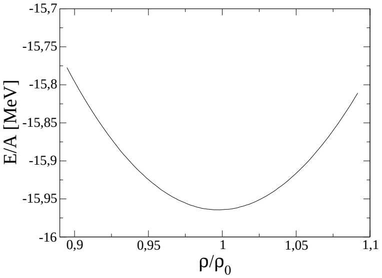
Résultats dans la Matière Symétrique

m_s	g_s	C	g_δ	g_ω	g_ρ	g_A
800	10	1,25	1	8	2,65	1,25

$$C = \frac{f_\pi^2}{2M}\kappa_{NS}$$

$$\kappa_\rho = 3.7$$
$$g_\omega = 7.775$$
$$C = 1,33$$

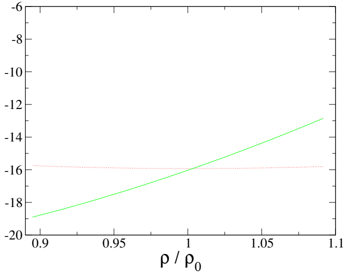
$$\rho/\rho_0 = 1,00$$
$$E/A = -15,96 \text{ MeV}$$
$$K = 315 \text{ MeV}$$
$$m_s^* = 841 \text{ MeV}$$
$$g_s^* = 6.01$$



[É. Massot and C. Chanfray, Phys. Rev. C **78**, 015204 (2008)]

Potentiel Chimique

$$\mu = \frac{\partial \epsilon}{\partial \rho} = E^*(p_F) + \Sigma^0(p_F) \stackrel{?}{=} \frac{E}{A}$$



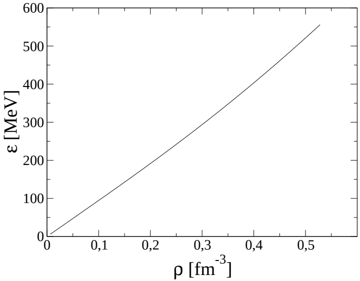
Résultats dans la Matière Asymétrique

- Matière presque symétrique :

κ_ρ	$3,7$	5	$6,6$
a_s(MeV)	$26,6$	$29,8$	$35,9$

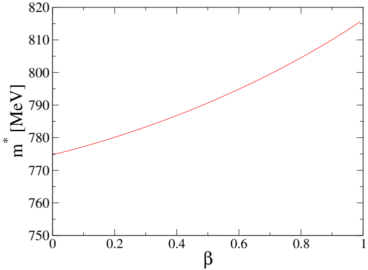
- Étoiles à neutrons :

$$\epsilon = \frac{< H >}{V} + \epsilon_{e^-}$$



Masses Effectives

$$\frac{1}{m^*} = \frac{1}{k}\frac{de}{dk}, m^*_{Landau} = m^*(p_F)$$



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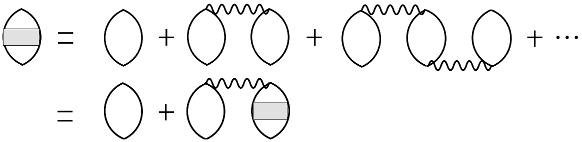
Excitations Particule-trou



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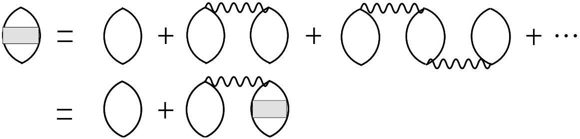

$$\Pi = \Pi^0 + \Pi^0 V \Pi^0 + \Pi^0 V \Pi^0 V \Pi^0 + \cdots$$
$$= \frac{\Pi^0}{1 - \Pi^0 V}$$

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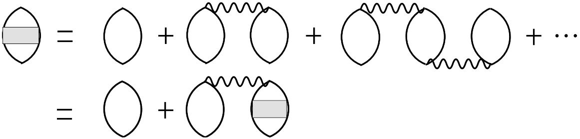
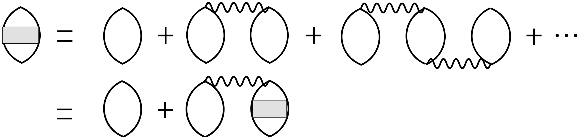


$$\Pi = \Pi^0 + \Pi^0 V \Pi^0 + \Pi^0 V \Pi^0 V \Pi^0 + \cdots$$
$$= \frac{\Pi^0}{1 - \Pi^0 V}$$

$$\frac{E}{A} = \int \frac{i d^4 q}{(2\pi)^4} V_{\mu\nu}(q) \Pi^{\mu\nu}(q)$$

Excitations Particule-trou



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$$= \frac{\Pi^0}{1 - \Pi^0 V}$$

$$\frac{E}{A} = \int \frac{id^4q}{(2\pi)^4} V_{\mu\nu}(q)\Pi^{\mu\nu}(q) = \int \frac{id^4q}{(2\pi)^4} \frac{d\lambda}{\lambda} \lambda^2 V_{\mu\nu}(q)\Pi^{\mu\nu}(q)$$

Canal Axial

$$\mathcal{L}_\pi = -\frac{g_A}{2f_\pi}\bar{\psi}\gamma^\mu\gamma^5\vec{\tau}\psi\partial_\mu\vec{\pi}$$

$$\mathcal{L}_c = g' g_{\mu\nu}\left(\frac{g_A}{2f_\pi}\right)^2\bar{\psi}\gamma^\mu\gamma^5\vec{\tau}\psi\bar{\psi}\gamma^\nu\gamma^5\vec{\tau}\psi$$

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$$V_{\mu\nu}(q) = \left(\frac{q_\mu q_\nu}{\omega^2-\omega_q^2} - g' g_{\mu\nu}\right)v^2(q)$$

$$\Pi^{0\mu\nu}_{aa}(q) = -2i\int\frac{d^4p}{(2\pi)^4}tr\left[\gamma^\mu\gamma^5 G(p)\gamma^\nu\gamma^5 G(p+q)\right]$$

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$$G(p) = \frac{1}{p^2 - M_N^{*2} + i\eta} + 2i\pi N_p\delta(p^2 - M_N^{*2})\theta(p^0)$$

Projections

$$\hat{\eta}^\mu = \eta^\mu - \frac{\eta \cdot q}{q^2} q^\mu$$

$$\begin{aligned} T_T^{\mu\nu} &= g_{\mu\nu} - \frac{\hat{\eta}^\mu \hat{\eta}^\nu}{\hat{\eta}^2} - \frac{q^\mu q^\nu}{q^2} \\ T_R^{\mu\nu} &= \frac{\hat{\eta}^\mu \hat{\eta}^\nu}{\hat{\eta}^2} \\ T_L^{\mu\nu} &= \frac{q^\mu q^\nu}{q^2} \end{aligned}$$

[L.S. Celenza, A. Pantziris and C.M. Shakin, Phys. Rev. C **45**, 205 (1992)]

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$$\Pi_i = \Pi_i^0 + \Pi_i^0 V_i \Pi_i, \qquad i = T, R, L$$

Résultats Canal Axial

$$E_{loop} = -\frac{3V}{2}\int_{-\infty}^{+\infty}\frac{id\omega}{(2\pi)}\int\frac{d\mathbf{q}}{(2\pi)^3}\left[2\,ln\left(1 - V_T\Pi_T^0\right) + 2V_T\Pi_T^0 + \ln\left(1 - V_R\Pi_R^0\right) + V_R\Pi_R^0 + \ln\left(1 - V_L\Pi_L^0\right) + V_L\Pi_L^0\right]$$

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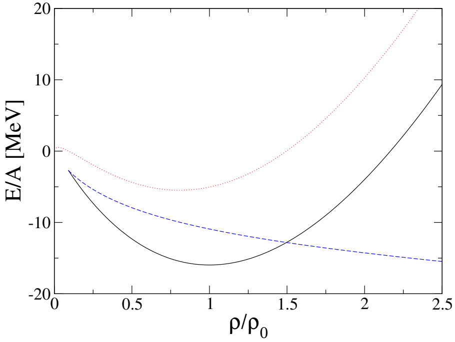
g'	$0,0$	$0,1$	$0,2$	$0,3$	$0,4$	$0,5$	$0,6$	$0,7$
E_T	0,0	-0,3	-1.0	-2,3	-3,9	-6,0	-8,4	-11,1
E_R	0,0	-0,0	-0,0	-0,01	-0,01	-0,02	-0,03	-0,04
E_L	-17,7	-12,3	-8,7	-6,0	-3,9	-2,4	-1,3	-0,6

Avec le Rho



$g_\omega = 7.6$
$C = 1,15$
$\rho/\rho_0 = 0,99$
$E/A = -15,9$ MeV
$K = 251$ MeV

[É. Massot and C. Chanfray, à venir]

Résumé

Symétrie chirale, effets de confinements, corrélations.

- Symétrie chirale : nécessité d'introduire un effet de confinement, par exemple la réponse nucléonique ;
- Corrélations : meilleures valeurs de C et K.