原子核の電磁応答に見る核力の性質

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★ $E1$ energy-weighted sum と (有効) 核力の non-locality

★ ^{208}Pb の low-energy $M1$ 分布に見る tensor force の影響

I. Introduction

原子核の電磁応答 $\cdots$ 核データとして重要 (特に low energy part)

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総合的理解 $\rightarrow$ "全体像" ? ($e.g.$ 広い energy 領域での strength 分布)

- transition operator — (ほぼ)clear
- 基底状態の波動関数
  doubly-closed 核 $\rightarrow$ (凡そ) 分かっている
- 励起状態の energy, 波動関数 $\leftrightarrow$ (有効) 核力

逆に，電磁応答から (有効) 核力に関する情報が得られる ?

($\rightarrow$ feedback $\rightarrow$ 電磁応答のより精密な記述へ)

(有効) 核力に基づく電磁応答の "全体像" への微視的 approach

$\rightarrow$ self-consistent HF + RPA

HF + RPA計算

$$\hat{H} = \hat{K} + \hat{V}_N + \hat{V}_C - \hat{H}_{\mathrm{c.m.}}$$

$$\hat{K} = \sum_i \frac{\boldsymbol{p}_i^2}{2M}$$

$\hat{V}_N$: effective NN int. (central + LS + tensor, ρ-dep.)

$\rightarrow$ saturation, shell structure

$\hat{V}_C$: Coulomb int. (including exchange terms exactly)

$\hat{H}_{\mathrm{c.m.}}$: c.m. Hamiltonian (1- + 2-body terms)

$\Rightarrow$ { HF $\rightarrow$ 基底状態, s.p. orbits; RPA $\rightarrow$ $1p$-$1h$励起, 電磁応答 (strength fn.) } $\cdots$ self-consistent !

数値計算 — Gaussian expansion methodを利用

Ref. : H.N. *et al.*, N.P.A in press; arXiv:0904.4285

II. $E1$ energy-weighted sum

Energy-weighted sum rule: $\Sigma_1 \equiv \sum_\alpha (E_\alpha - E_0)\left|\langle\alpha|\hat{\mathcal{T}}|0\rangle\right|^2 = \frac{1}{2}\langle 0|[\hat{\mathcal{T}}^\dagger, [\hat{H}, \hat{\mathcal{T}}]]|0\rangle$

($|0\rangle$: g.s., $\hat{\mathcal{T}}$: transition op.)

→ **励起状態に依存しない！**

$$\hat{\mathcal{T}}^{(E1)} = \frac{N}{A}\sum_{i\in p} r_i Y^{(1)}(\hat{\boldsymbol{r}}_i) - \frac{Z}{A}\sum_{i\in n} r_i Y^{(1)}(\hat{\boldsymbol{r}}_i) \qquad \Sigma_1^{(E1)} \propto \int \sigma_\gamma(E_\alpha)\, dE_\alpha$$

$$\hat{K} \quad \to \quad \Sigma_{\rm TRK} = \frac{1}{2}\langle 0|[\hat{\mathcal{T}}^{(E1)\dagger}, [\hat{K}, \hat{\mathcal{T}}^{(E1)}]]|0\rangle = \frac{1}{2}[\hat{\mathcal{T}}^{(E1)\dagger}, [\hat{K}, \hat{\mathcal{T}}^{(E1)}]]$$

$$= \frac{1}{2}[\hat{\mathcal{T}}^{(E1)\dagger}, [\hat{H} - \hat{V}_N, \hat{\mathcal{T}}^{(E1)}]] = \frac{9}{4\pi}\frac{1}{2M}\frac{ZN}{A}$$

However, non-locality in charge-exchange part of $\hat{V}_N$

$$\to \quad \Sigma_1^{(E1)} = (1+\kappa)\,\Sigma_{\rm TRK} \qquad \kappa = \frac{1}{2}\langle 0|[\hat{\mathcal{T}}^\dagger, [\hat{V}_N, \hat{\mathcal{T}}]]|0\rangle \Big/ \Sigma_{\rm TRK}$$

Note: $H_{\rm c.m.}$

- **1- + 2-body terms** → $[\hat{\mathcal{T}}^{(E1)\dagger}, [\hat{H}_{\rm c.m.}, \hat{\mathcal{T}}^{(E1)}]] = 0$
- **1-body term only** → $\frac{1}{2}[\hat{\mathcal{T}}^{(E1)\dagger}, [\hat{H}^{(1)}_{\rm c.m.}, \hat{\mathcal{T}}^{(E1)}]] = \frac{1}{A}\Sigma_{\rm TRK}$

κ のestimate？ $\rightarrow$ まずnuclear matter $(A = \infty)$

saturation point近傍で

$$\hat{H} \approx E_0 + \sum_{\boldsymbol{k}\sigma\tau} \varepsilon_{\boldsymbol{k}\sigma\tau} :a^\dagger_{\boldsymbol{k}\sigma\tau} a_{\boldsymbol{k}\sigma\tau}: + \hat{V}_{\rm res}$$

$$\varepsilon_{\boldsymbol{k}\sigma\tau} \equiv \frac{\delta\langle\hat{H}\rangle}{\delta n_{\tau\sigma}(\boldsymbol{k})} = \frac{\boldsymbol{k}^2}{2M} + \frac{\delta\langle\hat{V}_N\rangle}{\delta n_{\tau\sigma}(\boldsymbol{k})} \qquad (n_{\tau\sigma}(\boldsymbol{k}): \textbf{ occ. prob.})$$

$$\hat{V}_{\rm res} \equiv \frac{1}{2} \sum_{\boldsymbol{k}\sigma\tau\boldsymbol{k}'\sigma'\tau'} \frac{\delta^2\langle\hat{V}_N\rangle}{\delta n_{\tau\sigma}(\boldsymbol{k})\delta n_{\tau'\sigma'}(\boldsymbol{k}')} :a^\dagger_{\boldsymbol{k}\sigma\tau} a^\dagger_{\boldsymbol{k}'\sigma'\tau'} a_{\boldsymbol{k}'\sigma'\tau'} a_{\boldsymbol{k}\sigma\tau}:$$

$$\approx N_0^{-1}\Omega^{-1} \sum_\ell [f_\ell + f'_\ell(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2) + g_\ell(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2) + g'_\ell(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)] \times P_\ell(\hat{\boldsymbol{k}}_1\cdot\hat{\boldsymbol{k}}_2)$$

$\cdots$ **Landau-Migdal parameters**

$$\frac{1}{2}\langle[\hat{\mathcal{T}}^{(E1)\dagger}, [\hat{V}_N, \hat{\mathcal{T}}^{(E1)}]]\rangle \quad \rightarrow \quad 1 + \kappa_\infty = \frac{M}{M_0^*}(1 + \frac{1}{3}f'_1)$$

κ_∞ の "理論値" の比較　$\leftrightarrow$ 有効核力 $\hat{V}_N$ の性質

$\hat{V}_N \cdots$
- **SLy5** : Skyrme int. の数ある parameter の 1 つ
- **D1S** : Gogny int. の "standard" parameter
- **M3Y-P5′** : semi-realistic int. (G-matrix + modification)

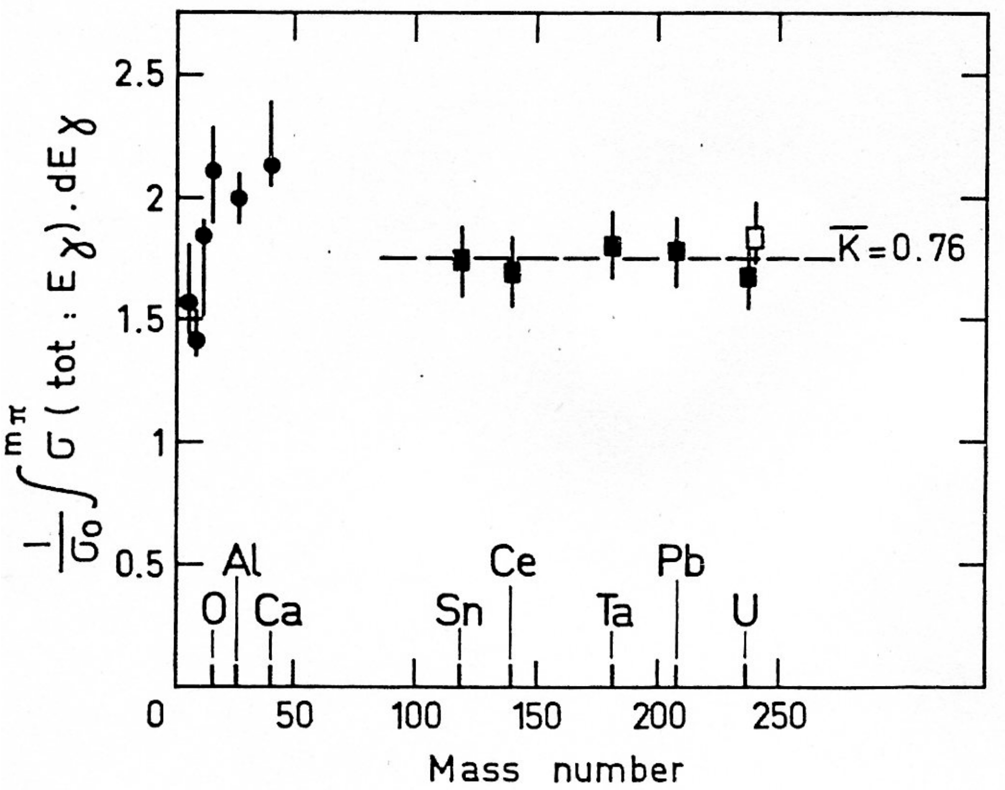
		SLy5	D1S	M3Y-P5′	Exp.
$k_{\mathrm{F}0}$	[fm^{-1}]	1.334	1.342	1.340	1.32 − 1.37
$\mathcal{E}_0$	[MeV]	−15.98	−16.01	−16.14	$\approx$ −16
M_0^*/M		0.697	0.697	0.637	0.6 − 0.8
κ_∞		0.250	0.660	0.884	後述
g_0		1.123	0.466	0.216	$\lesssim$ 0.5 ?
g_0'		−0.141	0.631	1.007	0.8 − 1.2

κの実験値？　$\leftarrow$　**photoabsorption cross section**　(γ, xn),***etc.***

- **GDR — well established**
- **GDR energy以下？** $\cdots$ **核データとして重要**

  GDRのLorentzian fit？ PDR？
- **GDR energy以上 — high energy tailの存在**

  (→ Lorentzian fitはダメ！)



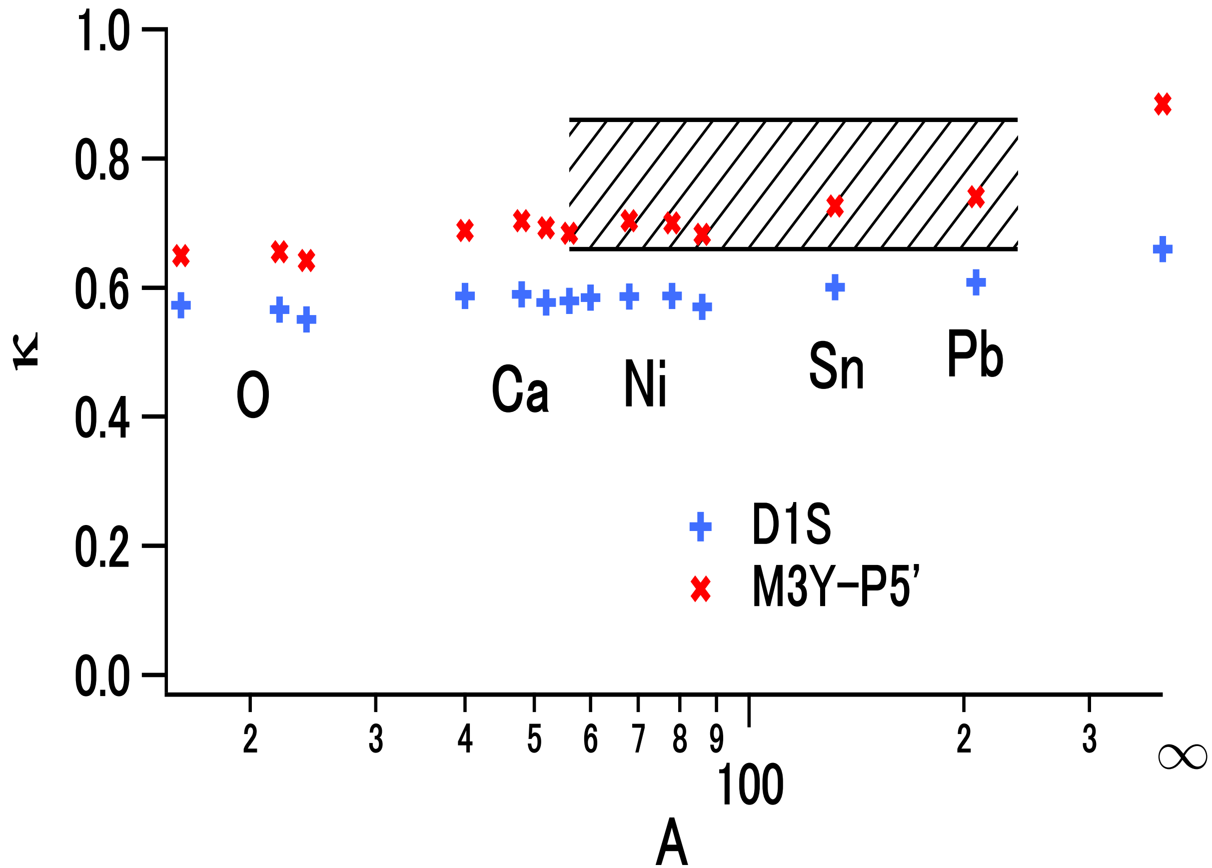
$E_x \leq m_\pi (\approx 140\,\mathrm{MeV})$の積分値

$\Rightarrow \kappa = 0.76 \pm 0.10$

(A-dep. weak)

Ref.: A. Leprêtre *et al.*, N.P.A 367, 237 ('81)

有限核の κ (κ_A) $\leftarrow$ HF + RPA



- $\Sigma_1^{(E1)} \leftrightarrow$ LM parameter f_1' $\cdots$ **有効核力の持つ** non-locality **の** check
- semi-realistic int. (*e.g.* M3Y-P5$'$) — promising

Note： **実験の解析に関する問題点**

- **higher multipole の影響？　→ rel. effect と cancel**
- m_π **以上の components？**
- **finite** q **の影響？　(Siegert's theorem？** $j_1(qr) \approx qr/3$ **？)**

理論計算に関する問題点

- $2p$-$2h$**(以上) の component の影響？**
- **effective int. (+ MEC *etc.*) → effective** $E1$ **op.？**

  (たぶん影響は小さい)

III. $M1$ strength distribution in ^{208}Pb

^{208}Pbのlow energy $M1$ strength distributionの精密実験

Ref.: T. Shizuma *et al.*, P.R.C 78, 061303(R) ('08)

- $1p$-$1h$ 励起 — p: $(0h_{11/2})^{-1}(0h_{9/2})$, n: $(0i_{13/2})^{-1}(0i_{11/2})$
- **歴史的経緯**

  "missing $M1$ problem" $\cdots$ $\left[\sum B(M1)\right]_{\rm exp.} \ll \left[\sum B(M1)\right]_{1p-1h}$!

  $\Rightarrow$ { より精密な測定 $\rightarrow \left[\sum B(M1)\right]_{\rm exp.} \nearrow$; 様々な効果の考慮 $\rightarrow \left[\sum B(M1)\right]_{\rm cal.} \searrow$ }

  ($\Rightarrow$ '90年頃にはほぼ解決？ $\Rightarrow$ 修正)

  理論的approach

  ○ ~'90年以前: RPA + $2p$-$2h$ + *etc.*

  $\leftarrow \hat{V}_N$: LM + tensor, without self-consistency

  — tensor forceが重要！

  ○ ~'80年以降: self-consistent RPA $\leftarrow$ phenomenogical $\hat{V}_N$

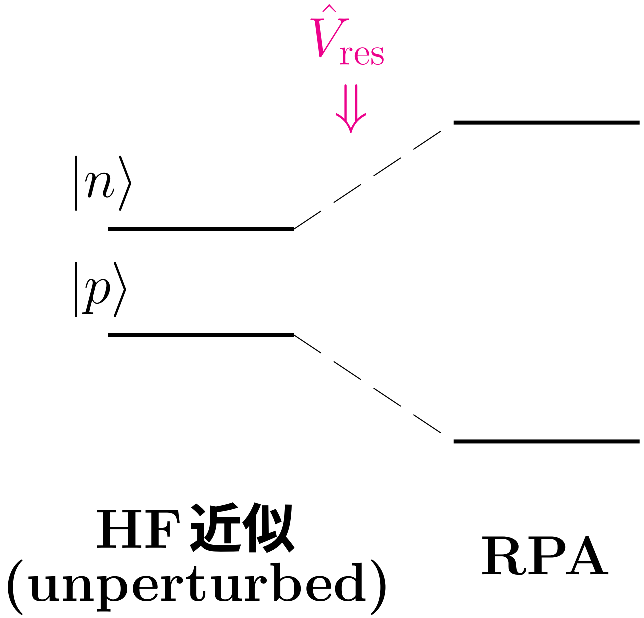
  — LM parameter?, no tensor force

  ○ now: self-consistent RPA with semi-realistic $\hat{V}_N$?

- **excitation energy**

$$|p\rangle \equiv |p(0h_{11/2})^{-1}(0h_{9/2})\rangle \text{ , } |n\rangle \equiv |n(0i_{13/2})^{-1}(0i_{11/2})\rangle$$

$$|\mathbf{IS}\rangle \equiv \frac{1}{\sqrt{2}}(|p\rangle + |n\rangle) \text{ , } |\mathbf{IV}\rangle \equiv \frac{1}{\sqrt{2}}(|p\rangle - |n\rangle)$$



$$|\text{“}\mathbf{IV}\text{”}\rangle = -c_2|p\rangle + c_1|n\rangle$$
$$= -c_2'|\mathbf{IS}\rangle + c_1'|\mathbf{IV}\rangle$$

$$(c_1 > c_2 > 0)$$

$$|\text{“}\mathbf{IS}\text{”}\rangle = c_1|p\rangle + c_2|n\rangle$$
$$= c_1'|\mathbf{IS}\rangle + c_2'|\mathbf{IV}\rangle$$

$(c_1.c_2)$ **or** $(c_1', c_2') \leftrightarrow \hat{V}_{\text{res}}$

- $\hat{\mathcal{T}}^{(M1)} \neq \hat{\mathcal{T}}^{(M1,\mathrm{br})}$!

$$\hat{\mathcal{T}}^{(M1,\mathrm{br})} = \sum_{i\in p}\left\{g_{\ell,p}\,\hat{\boldsymbol{l}}_i + g_{s,p}\,\hat{\boldsymbol{s}}_i\right\} + \sum_{i\in n}\left\{g_{\ell,n}\,\hat{\boldsymbol{l}}_i + g_{s,n}\,\hat{\boldsymbol{s}}_i\right\}$$
$$= \sum_{i}\left\{g_{\ell,\mathrm{IS}}\,\hat{\boldsymbol{l}}_i + g_{s,\mathrm{IS}}\,\hat{\boldsymbol{s}}_i\right\} + \sum_{i}\left\{g_{\ell,\mathrm{IV}}\,\hat{\boldsymbol{l}}_i + g_{s,\mathrm{IV}}\,\hat{\boldsymbol{s}}_i\right\}\tau_{z,i}$$

($\tau_z = +1$ for p, -1 for n)

$g_{\ell,\mathrm{IS}} \equiv \frac{1}{2}(g_{\ell,p} + g_{\ell,n})$, $g_{\ell,\mathrm{IV}} \equiv \frac{1}{2}(g_{\ell,p} - g_{\ell,n})$; $g_{s,\mathrm{IS}}$, $g_{s,\mathrm{IV}}$ も同様

core polarization, meson exchange current, Δ-h, *etc.*

shell model の立場からは $1p$-$1h$ の CP が最も重要

$\rightarrow$ (HF +) RPA では自然に入る

他の効果 $\rightarrow$ Towner の table から引用 $\rightarrow$ $\hat{\mathcal{T}}^{(M1)}$

Ref. : I.S. Towner, P.Rep. 155, 263 ('87)

$\rightarrow$ $g^{\mathrm{eff}}_{\ell,\mathrm{IS}} \approx g^{\mathrm{eff}}_{s,\mathrm{IS}}$ $\rightarrow$ $\langle\alpha|\hat{\mathcal{T}}^{(M1)}_{\mathrm{IS}}|0\rangle \approx g^{\mathrm{eff}}_{\ell,\mathrm{IS}}\,\langle\alpha|\hat{J}|0\rangle = 0$!

$\rightarrow$ $\left|\langle\alpha|\hat{\mathcal{T}}^{(M1)}|0\rangle\right|^2 \approx \left|\langle\alpha|\hat{\mathcal{T}}^{(M1)}_{\mathrm{IV}}|0\rangle\right|^2$

$\cdots$ $\left.\begin{array}{l}\left|\langle\text{“IS”}|\hat{\mathcal{T}}^{(M1)}|0\rangle\right|^2 : \ |c'_2|^2 \\ \left|\langle\text{“IV”}|\hat{\mathcal{T}}^{(M1)}|0\rangle\right|^2 : \ |c'_1|^2\end{array}\right\}$ を直接反映

HF + RPA *vs.* Exp.

			M3Y-P5		Exp.
			$\hat{V}-\hat{V}^{(\mathrm{TN})}$	$\hat{V}$	
"IS"	E_x	(MeV)	6.87	5.85	5.85
	$B(M1)\uparrow$	(μ_N^2)	4.7	2.4	2.0
"IV"	E_x	(MeV)	9.2 – 10.9	9.2 – 10.9	7.1 – 8.7
	$(\bar{E}_x)$		(9.9)	(9.6)	
	$\sum B(M1)\uparrow$	(μ_N^2)	16.3	19.4	16.3 **or** 18.2

(D1Sによる結果 $\cdots$ "$\hat{V}-\hat{V}^{(\mathrm{TN})}$" の結果と類似)

- "IS" 状態 — low energy → $2p$-$2h$ 状態の影響小さい
  "IV" 状態 — $2p$-$2h$ 状態とのcoupling → fragmentation, energy shift ?
  (RPAでは入らない効果)
- $\hat{V}^{(\mathrm{TN})}$ ⇒ $E(\text{“IS”})\searrow$, $E(\text{“IV”})\nearrow$ ⇒ $c_1'\approx 1$, $c_2'\approx 0$
  (IS component とIV component の分離が進む)
  ⇒ 適切な $E_x(\text{“IS”})$ & $\left|\langle\text{“IS”}|\hat{\mathcal{T}}^{(M1)}|0\rangle\right|^2$

IV. Summary & future prospect

- $E1$ **energy-weighted sum** → $\hat{V}_N$ **の性質**

  — **non-locality in charge-exchange part**

- **low-energy** $B(M1)$ **distribution (in ^{208}Pb)**

  → **role of tensor force reconfirmed**

- **semi-realistic** $\hat{V}_N$ **(↔ micro. & phenom. の適切な融合)** ··· **promising**

- **課題** ··· $2p$-$2h$ **自由度の考慮　(— 容易でないが重要！)**

  shell model との融合？　QPM？　extended RPA？