原子核の励起状態の研究から考える今後理解したいこと

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関西核多体セミナー, 2023年8月4日, 阪大中之島センター

slide: https://www.rcnp.osaka-u.ac.jp/~tamii →頁の下の方

Outline

Methods

spin-M1 excitation

E1 excitation

decay-coincidence

quasi-free at 0deg

Physics

photo-nuclear reactions

E1 polarizability
spin susceptibility

decay
damping
width
viscosity

EoS

PDR
E1 toroidal

n-skin

d-like correlation
np-pairing

level density
characteristic scale

an image of

Nuclear ground states

=

mean-field like component (low-momentum) ← single particle orbit occupation

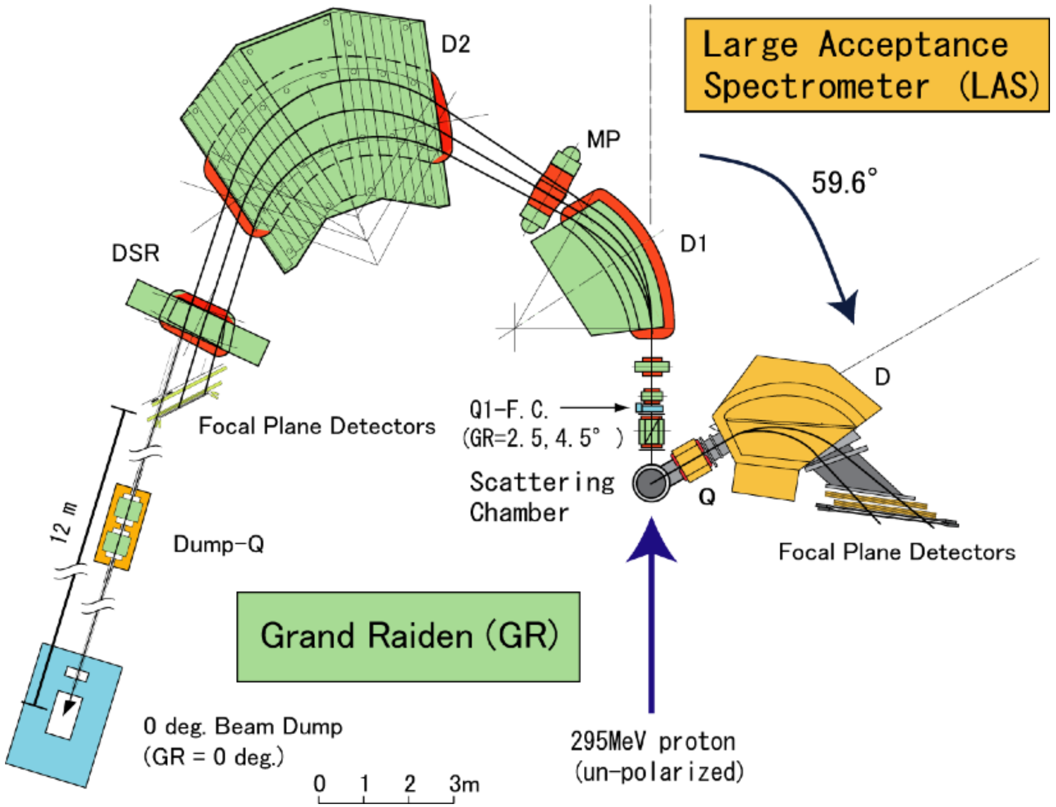
⊕

d-like correlation (inc. high-momentum) ← α-cluster も含まれる

?

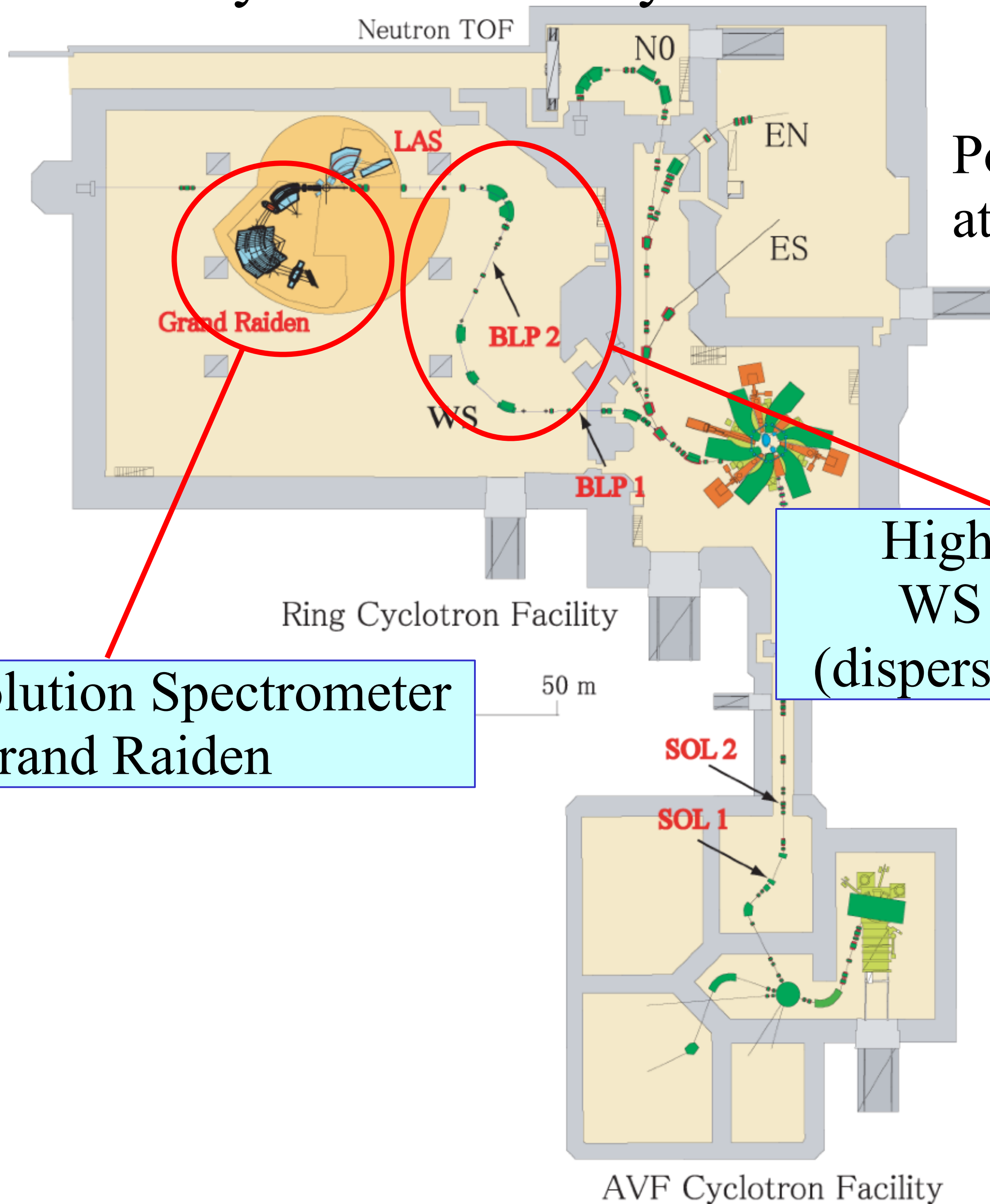
d-like correlation の定量的記述

Experimental Methods Briefly



Cyclotron Facility at RCNP

Polarized p beam at 295 MeV



High-resolution Spectrometer
Grand Raiden

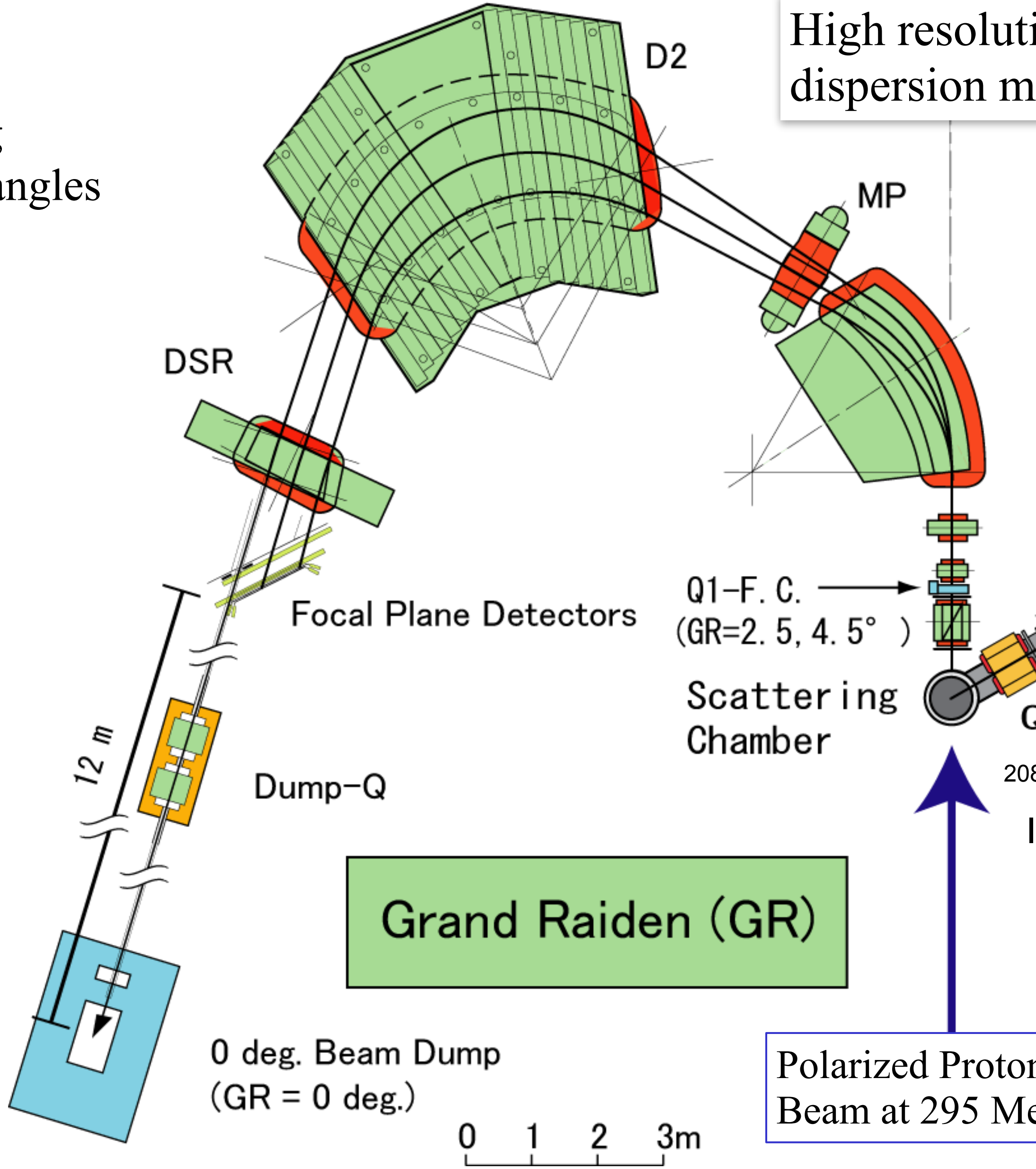
High-resolution
WS beam-line
(dispersion matching)

High-Resolution Spectrometer “Grand Raiden”

RCNP

Proton scattering
at very forward angles

High resolution of 20-30 keV:
dispersion matching.



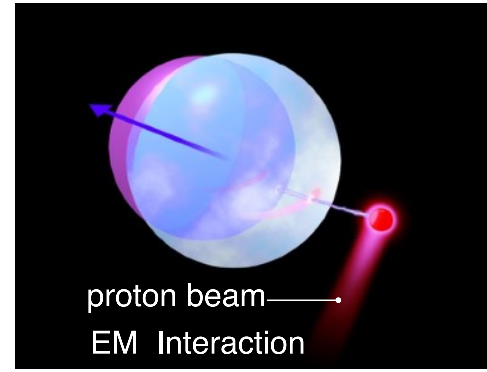
^{208}Pb target: 5.2 mg/cm^2
Intensity : 1-8 nA

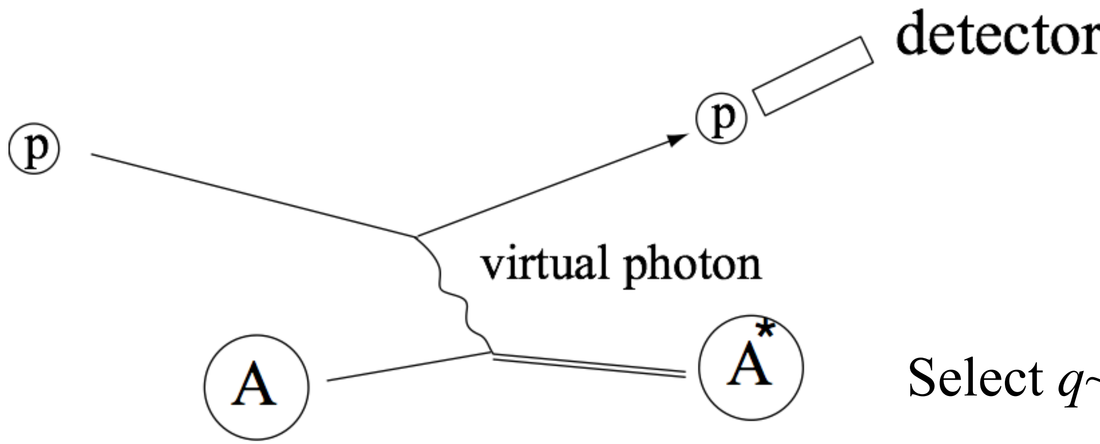
Polarized Proton
Beam at 295 MeV

AT et al., NIMA605, 326 (2009)

Probing the E1 Response by Proton Scattering

Missing Mass Spectroscopy by Virtual Photon Excitation



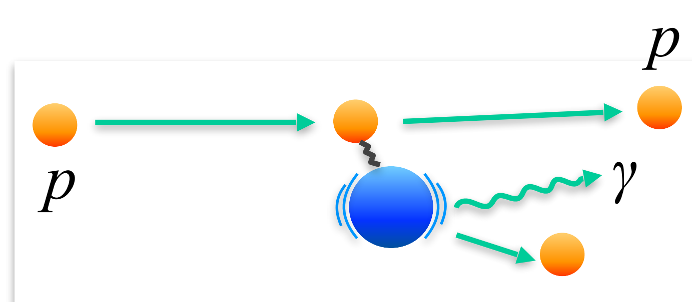


Select q~0 (~0 deg.)

- **Missing mass spectroscopy**:
  Total strength is measured independently from the decaying channels.
- **Multipole decomposition** of the strength in the continuum:
  Includes the contribution of unresolved small states
- **Coulomb excitation**: EM Interaction
  Absolute determination of the transition strength.

Probes for the Electric Dipole Response of Nuclei

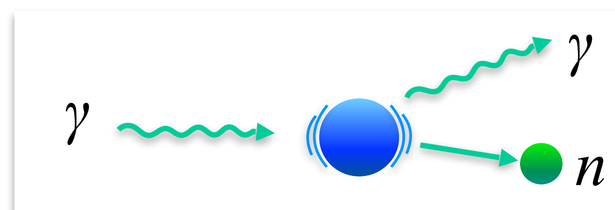
1. Virtual photon excitation
   (Coulomb excitation)
   - proton inelastic scattering at 0 deg.



Proton beams at RCNP and iThemba LABS

E_x distribution in one shot measurement
total photo-absorption c.s.
up to 32 (24) MeV at RCNP (iThemba)

2. Real photon absorption
   - (γ,γ') Nuclear Resonance Fluorescence
   - (γ,n), (γ,2n), (γ,p), … photodisintegrations



Real γ-beam at ELI-NP

pure EM probe
precise absolute c.s.
partial strength including *n*
up to 20 MeV at ELI-NP

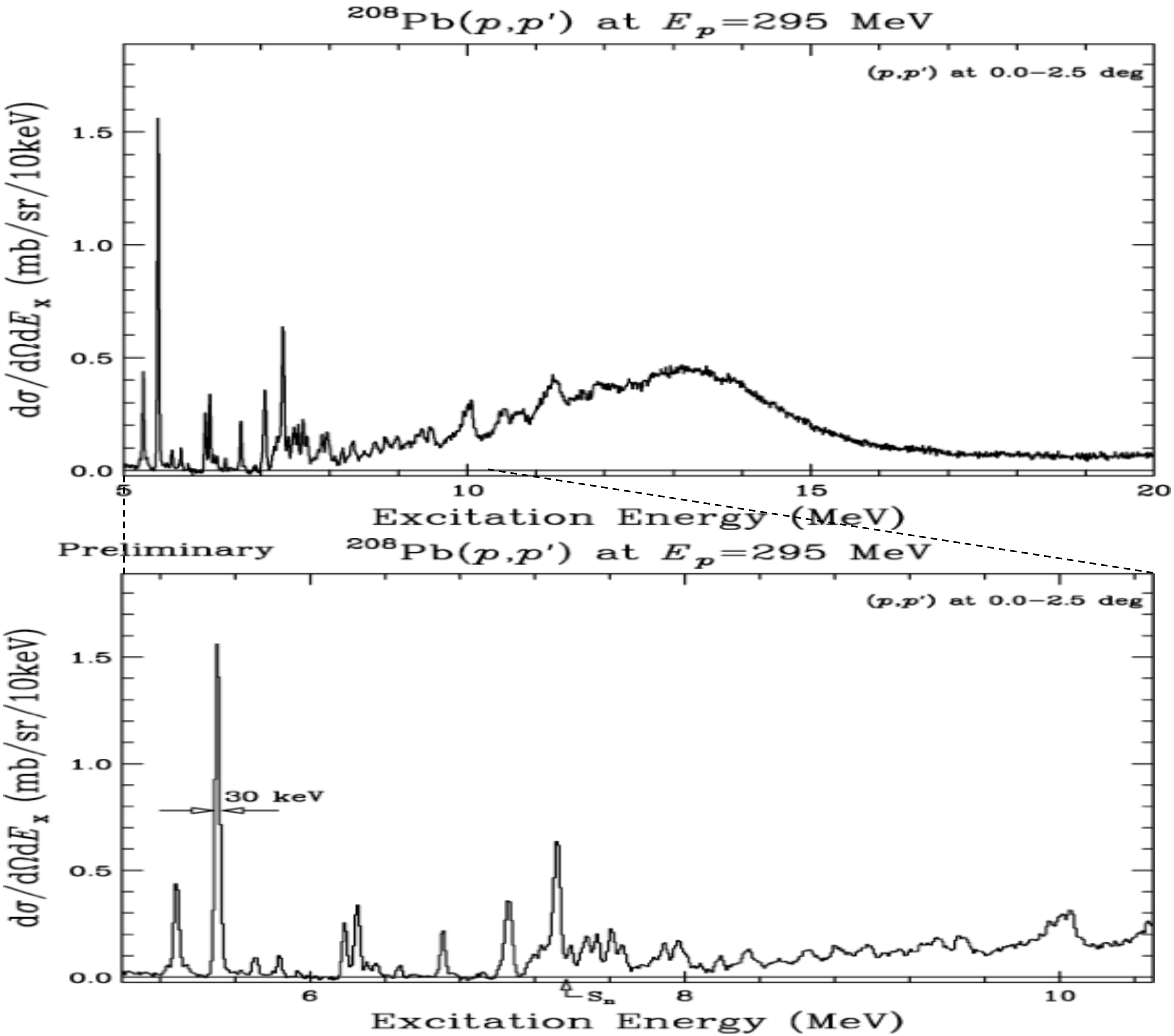
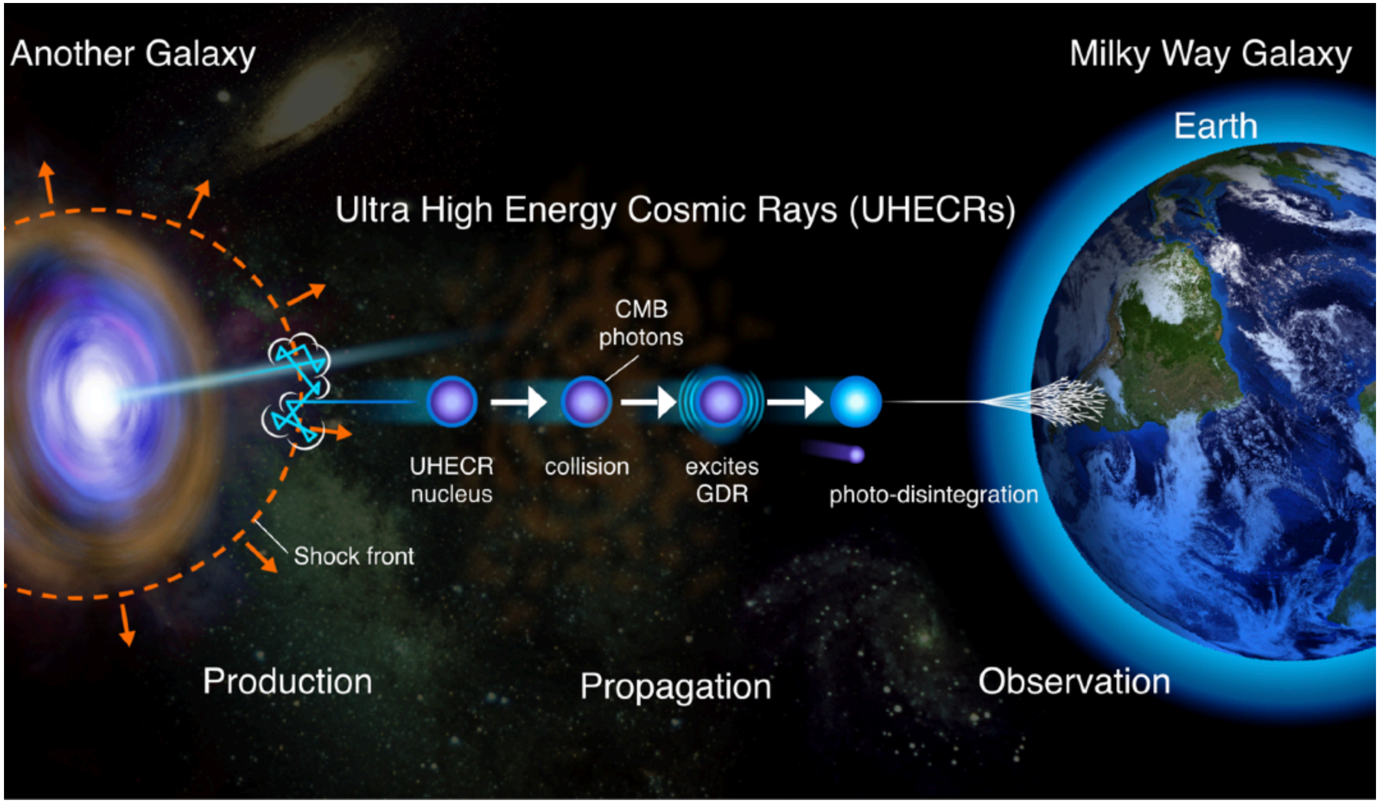

208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0−2.5 deg
dσ/dΩdEx (mb/sr/10keV)
0.0
0.5
1.0
1.5
5
10
15
20
Excitation Energy (MeV)
Preliminary
208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0−2.5 deg
dσ/dΩdEx (mb/sr/10keV)
30 keV
Sn
6
8
10
Excitation Energy (MeV)

Photo-Nuclear Reaction

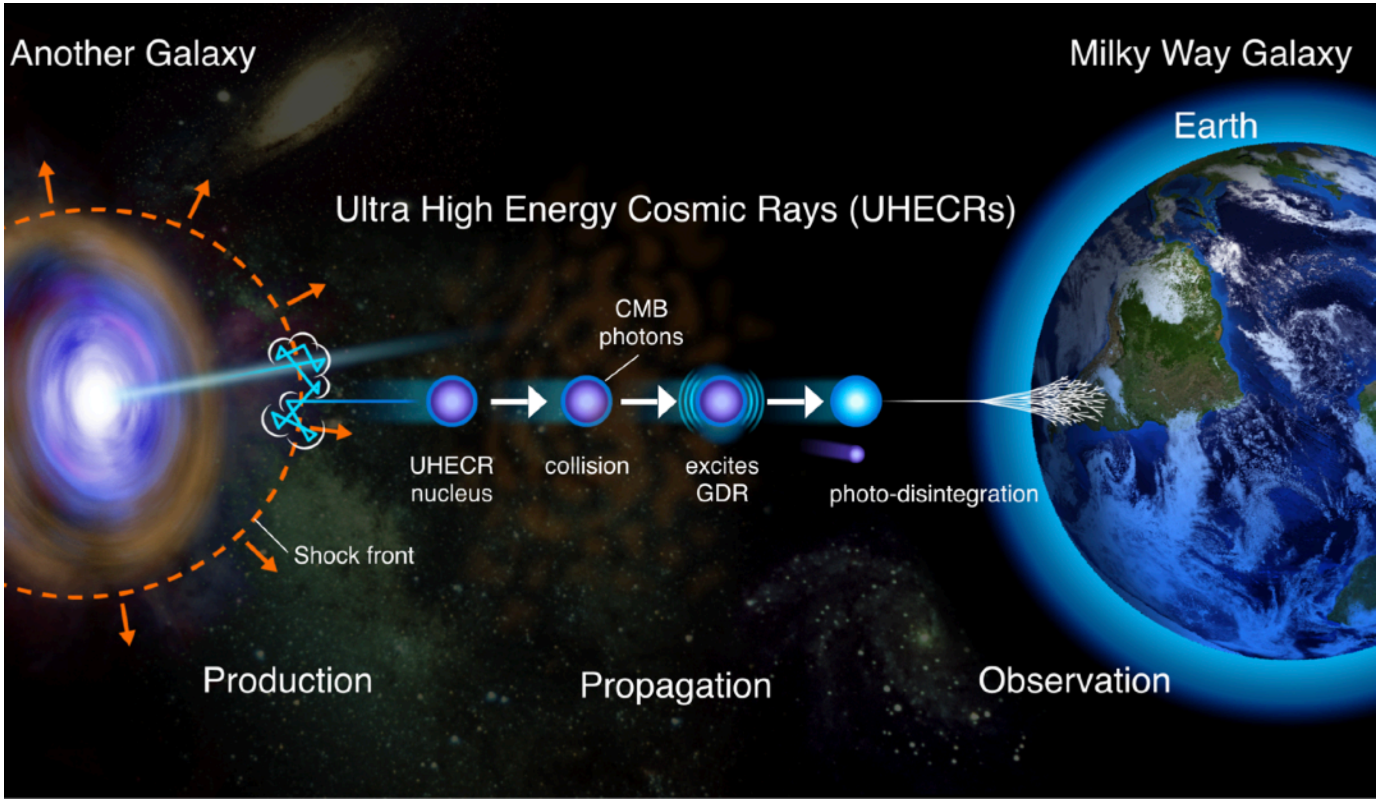


PANDORA Project

Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Systematic Measurement on E1 Strength Distribution and n,p,α,γ decays up to A=60

inter-galactic propagation of UHECRs



PANDORA Project

Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Systematic Measurement on E1 Strength Distribution and n,p,α,γ decays up to A=60

Understanding of photo-nuclear reactions for light nuclei

- photo-absorption c.s. $\simeq$ B(E1) distribution
- decay process

軽核の光核反応を精度よく記述したい

E1遷移

崩壊計算も重要

統計崩壊計算では不十分

PANDORA White paper, AT *et al.*, to be published in EPJA

軽い核の光核反応の記述の重要性

宇宙核物理・素粒子物理:

元素合成

超高エネルギー宇宙線のエネルギー損失過程

中性カレントニュートリノ検出: 巨大共鳴のγ放出、(n,γ)反応

放射線遮蔽、放射線施設のdecomissioning、原子炉内の核反応

光放射化分析、非破壊検査

γ-イメージング、CT診断、生体物質の放射線への影響

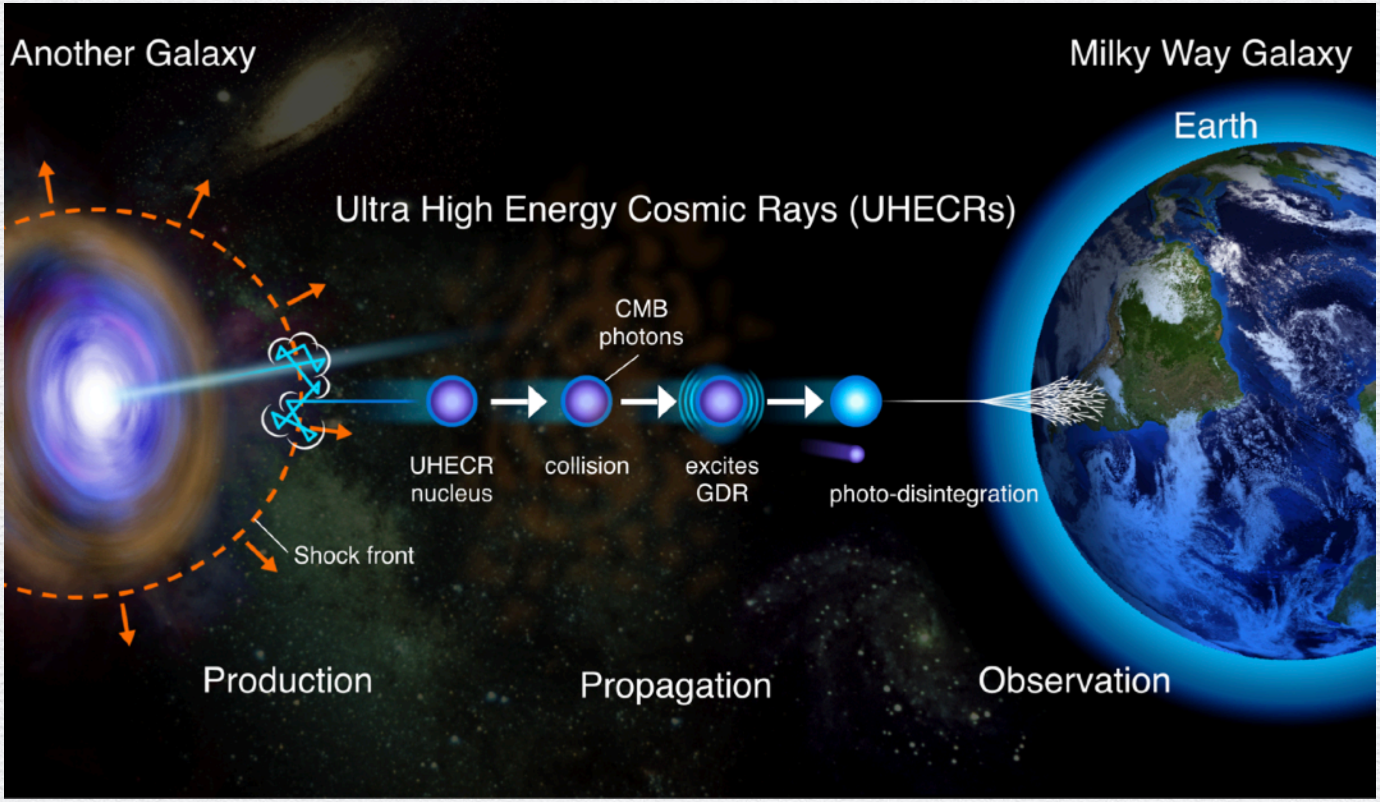
Home-Land Security、核分裂物質・爆発性物質の探査

光照射による医療用RI製造

雷雲内の核反応、ガンマ放射

宇宙の元素の99.99999%は
A=60以下の原子核から成る

Extragalactic Propagation of UHECR Nuclei



Cosmic Microwave Background (CMB)

WMAP
T=2.73 K

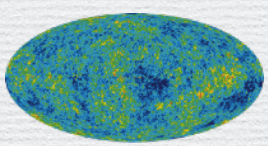
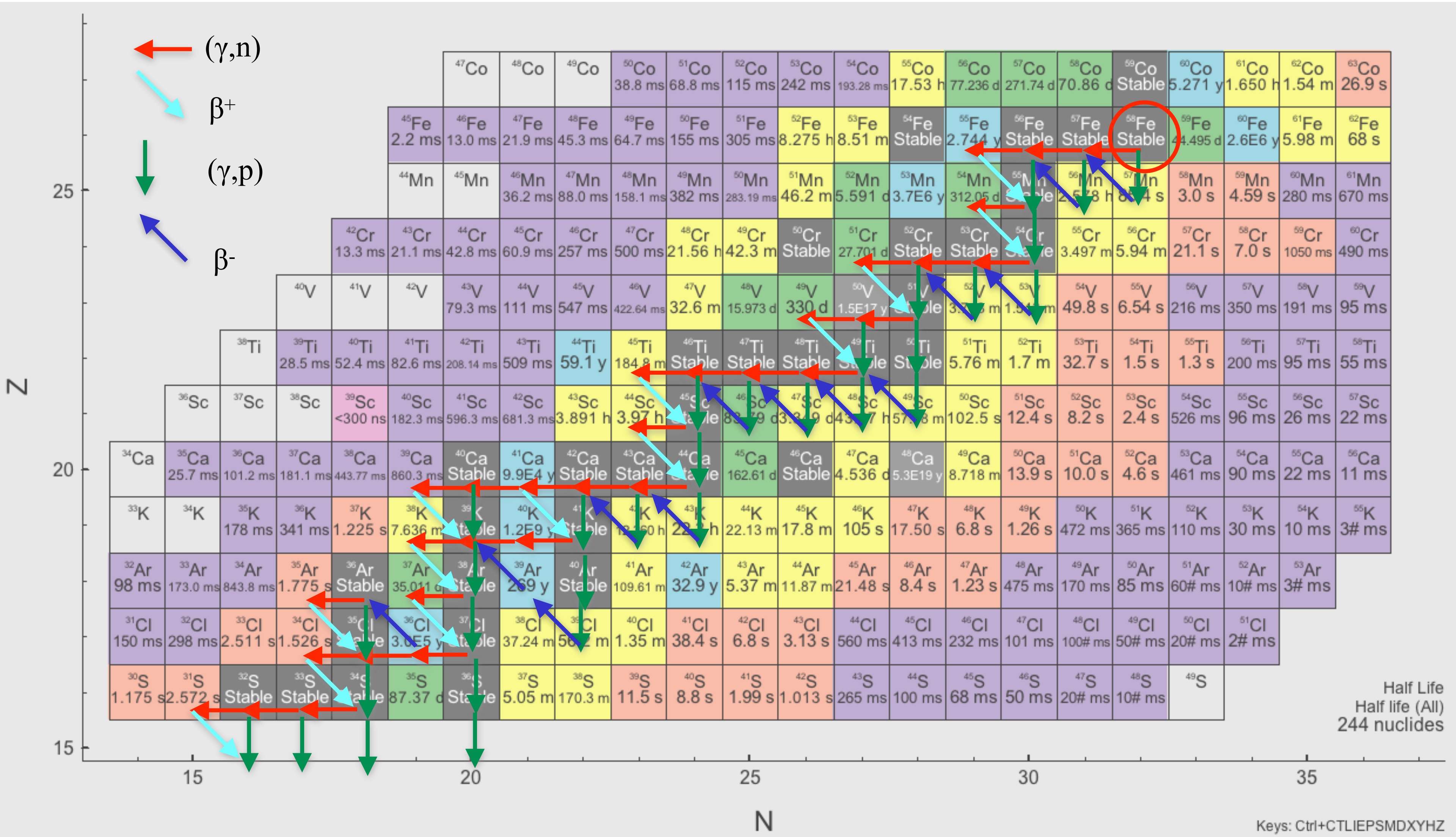


Photo-nuclear reactions determine the maximum travel distance of UHECRs nuclei and their composition/ energy modification in extra-galactic propagation.

GZK cut-off

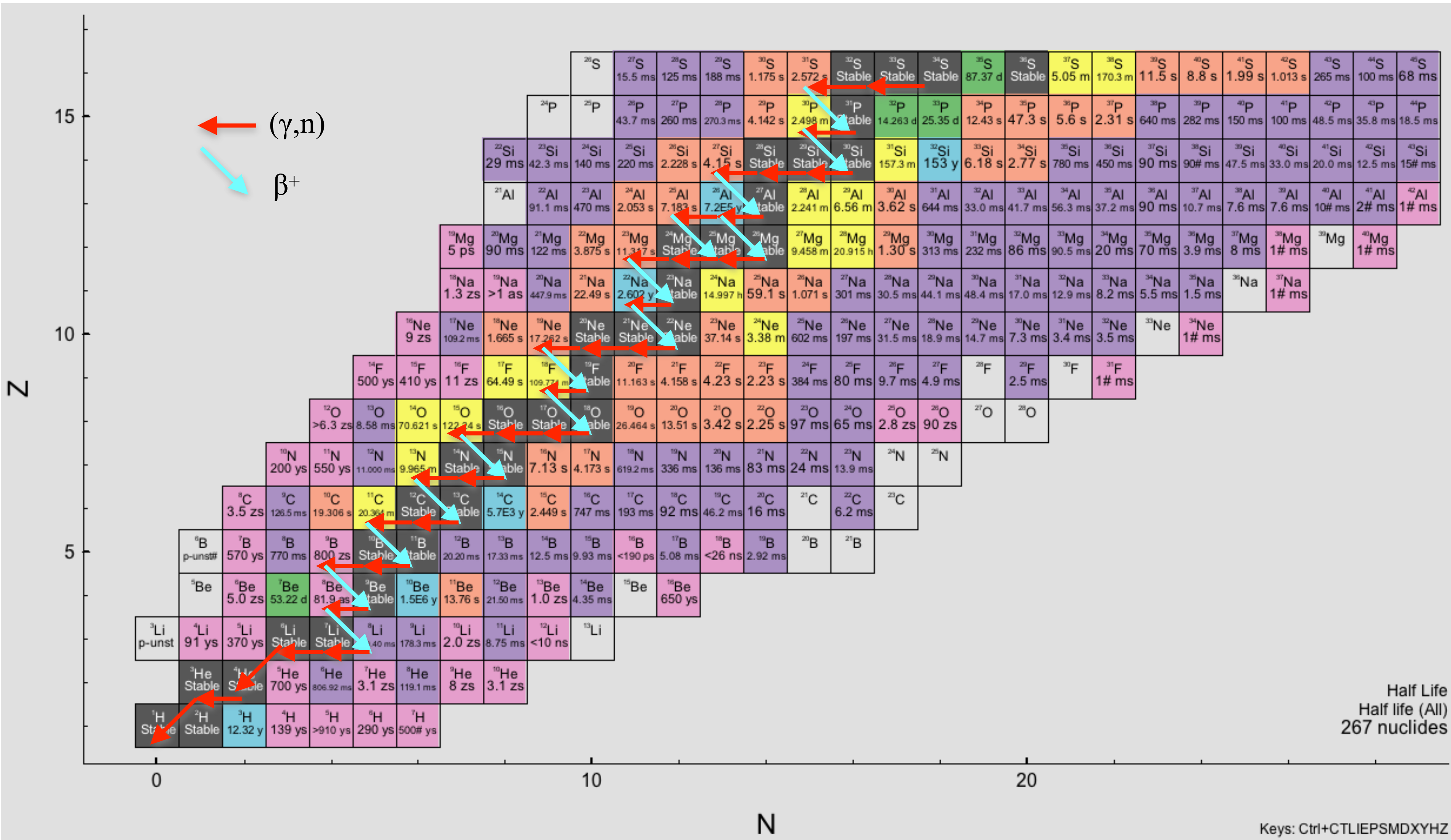
Photo-disintegration Pass of ^{56}Fe



(γ,xn), (γ,α) reactions also take place.

Several unstable nuclei also contribute.

Photo-disintegration Pass of ^{56}Fe



PANDORA Project: Collaborator

Nuclear Experiments

RCNP

ELI-NP

iThemba LABS

Osaka Univ.

A. Tamii, N. Kobayashi, T. Sudo, M. Murata, A. Inoue, **R. Niina**, T. Kawabata, T. Furuno, S. Adachi, K. Sakanashi, K. Inaba, Y. Fujikawa, S. Okamoto

Y

ELI-NP

P.-A. Söderström, D. Balabanski, L. Capponi, A. Dhal, T. Petruse, D. Nichita, Y. Xu

iThemba LABS, Univ. Witwatersland, Stellenbosh Univ.

L. Pellegri, R. Neveling, F.D. Smit, **J.A.C. Bekker**, S. Binda, H, Jivan, T. Khumal, M. Wiedeking, P. Adsley, L.M. Donaldson, E. Sideras-Haddado, K.L. Malatji, S. Jongile, A. Netshiya

TU-Darmstadt — P. von Neumann-Cosel, N. Pietralla, J. Isaak, J. Kleemann, M. Spall

U. Milano/INFN — A. Bracco, F. Camera, F. Crespi, O. Wieland

Shanghai — H. Utsunomiya

U. Oslo — K.C.W. Li, S. Siem, …

Nuclear Theory

AMD — **M. Kimura, Y. Taniguchi**, H. Motoki

NRFT — **E. Litvinova**, P. Ring, H. Wibowo

RPA/DFT — RPA by **T. Inakura, QPM by N. Tsoneva**

TALYS — **S. Goriely**, **E. Khan**

Large Scale Shell Modle — Y. Utsuno, N. Shimizu

UHECR Theory

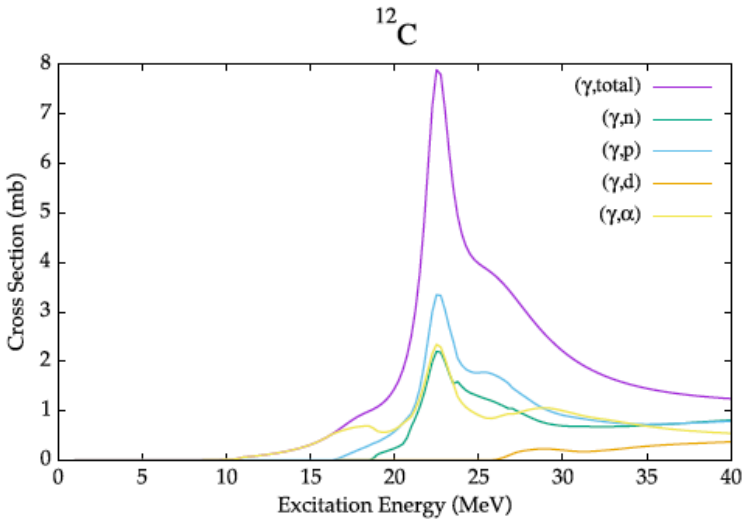
Propagation and production

D. Allard, B. Baret, I. Deloncle, J. Kiener, E. Parizot, V. Tatischeff

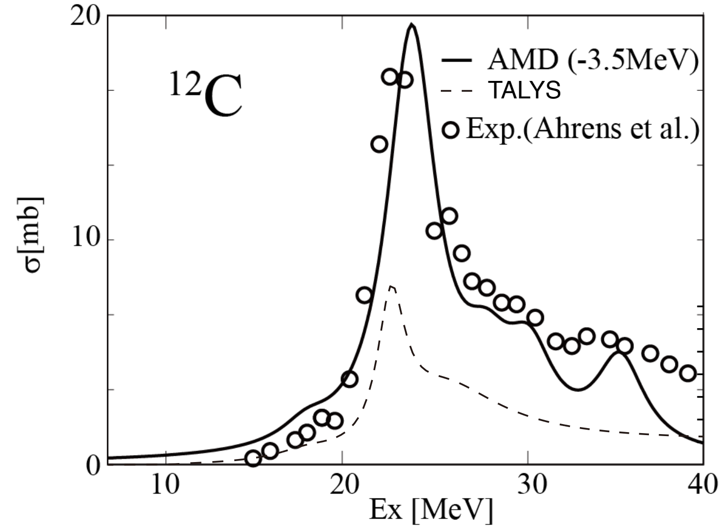
S. Nagataki, **E. Kido**, J. Oliver, H. Haoning

Predictions

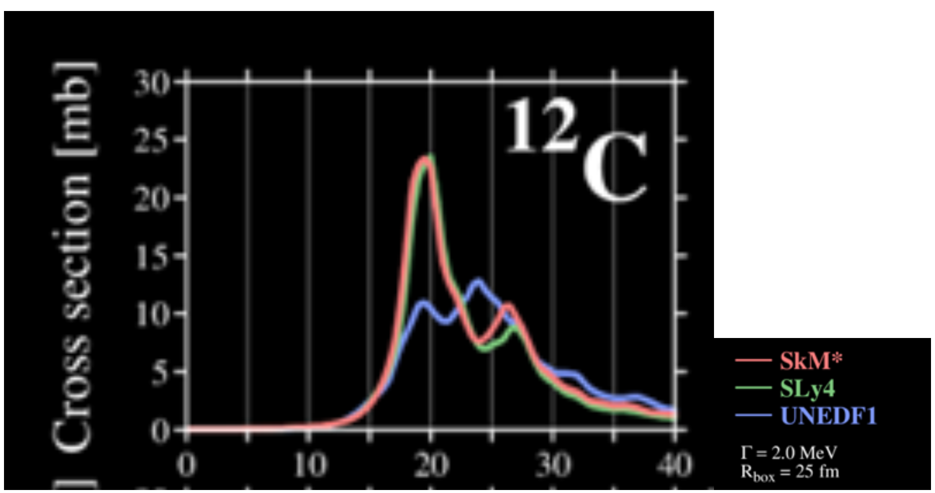
TALYS

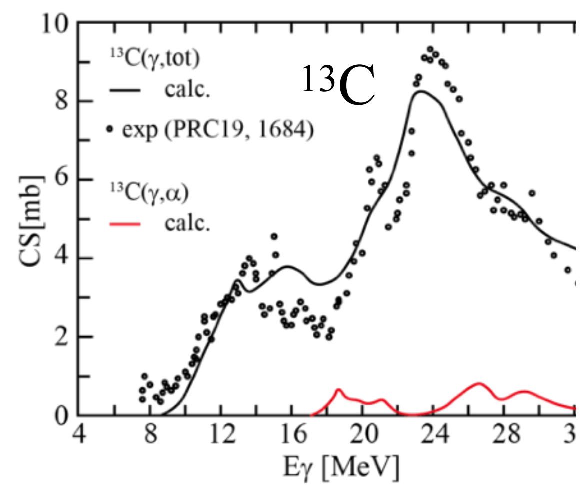


AMD + Laplace Expansion (M. Kimura et al.,)



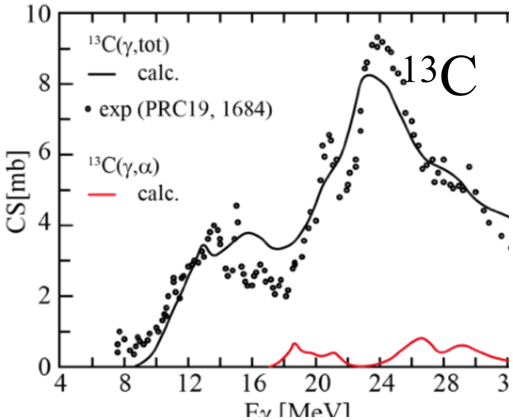
RPA (T. Inakura)

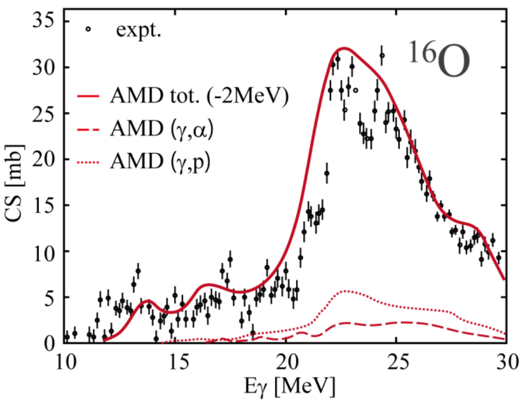




Theoretical Model Developments

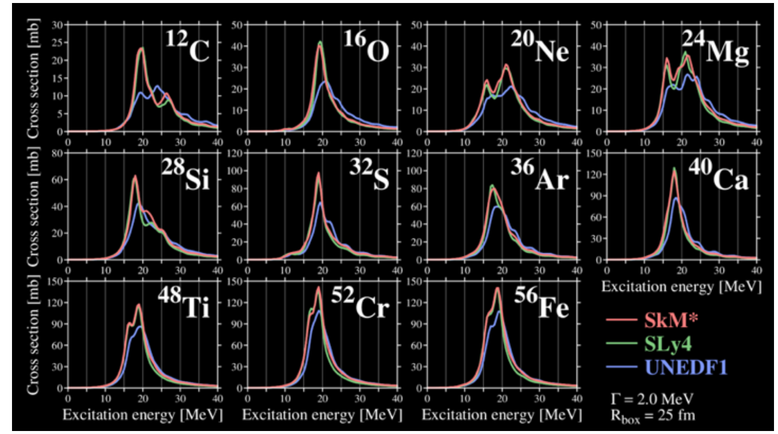
AMD + Laplace Expansion (M. Kimura et al.,)



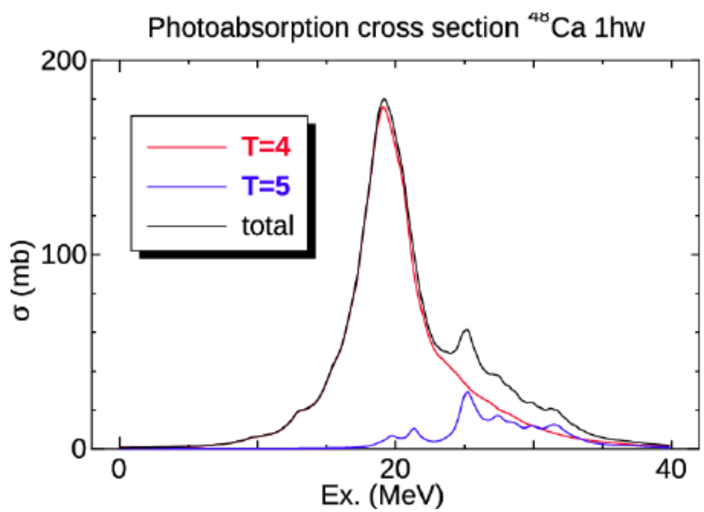


Isospin selection rule

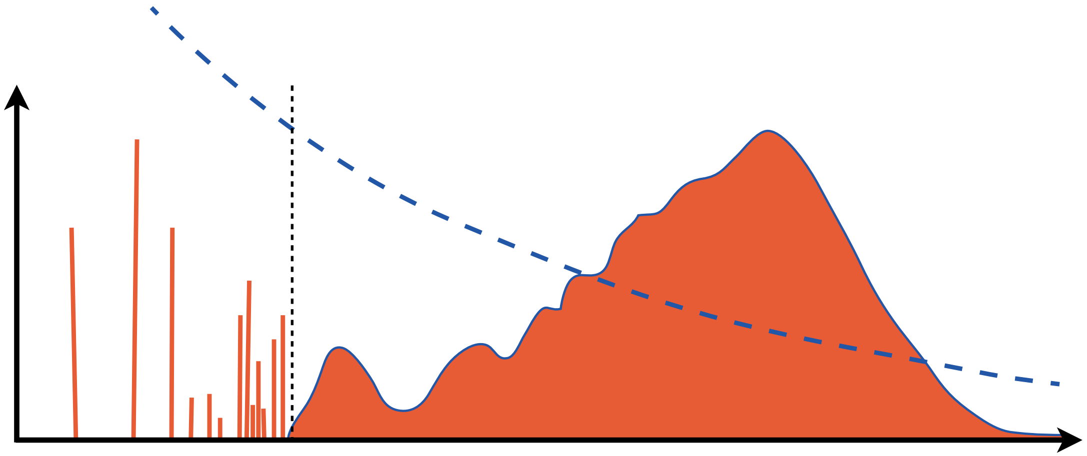
RPA by T. Inakura



N. Shimizu, Y. Utsuno, et al.,



E1 Polarizability

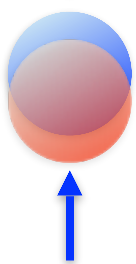


Static Electric Dipole Polarizability (α_D)

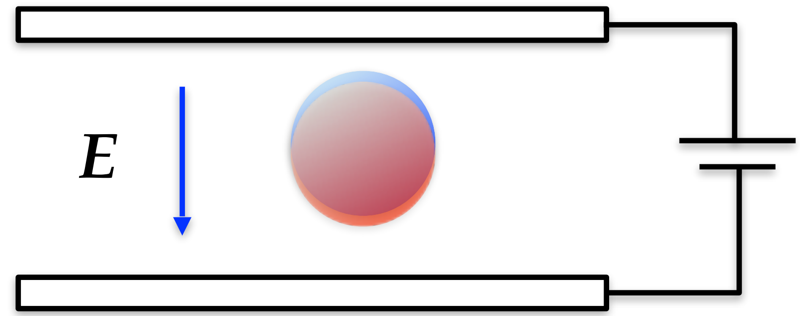
Electric dipole moment

$$p = \alpha_D \times E$$

α_D: electric dipole polarizability



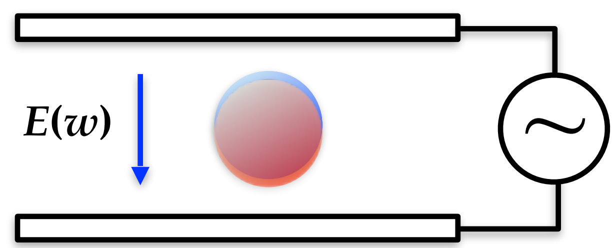
The **restoring force** originates from the **symmetry energy.**



nucleus
in a static electric field
with fixing the c.m. position

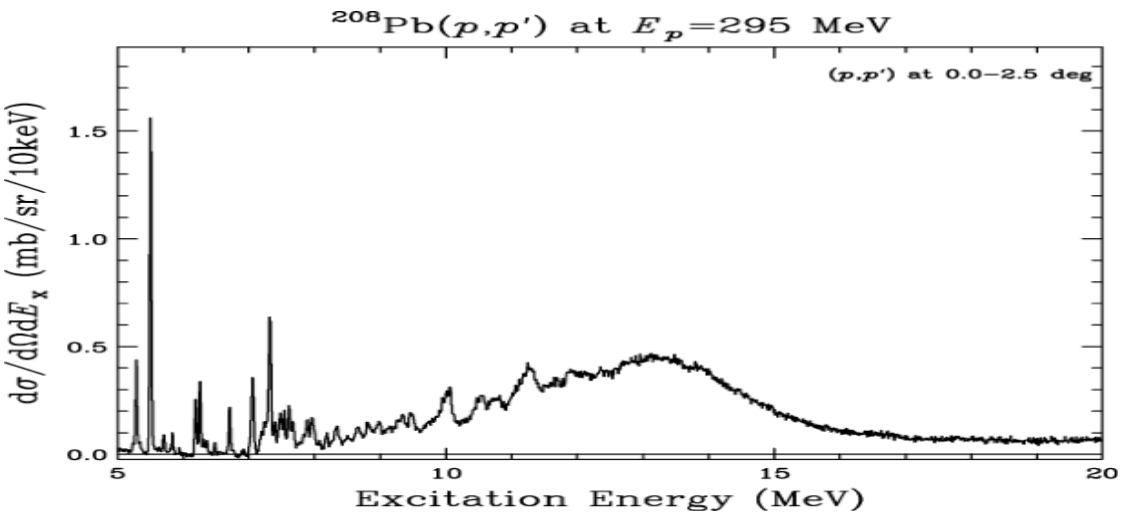
Inversely energy-weighted sum-rule of B(E1)

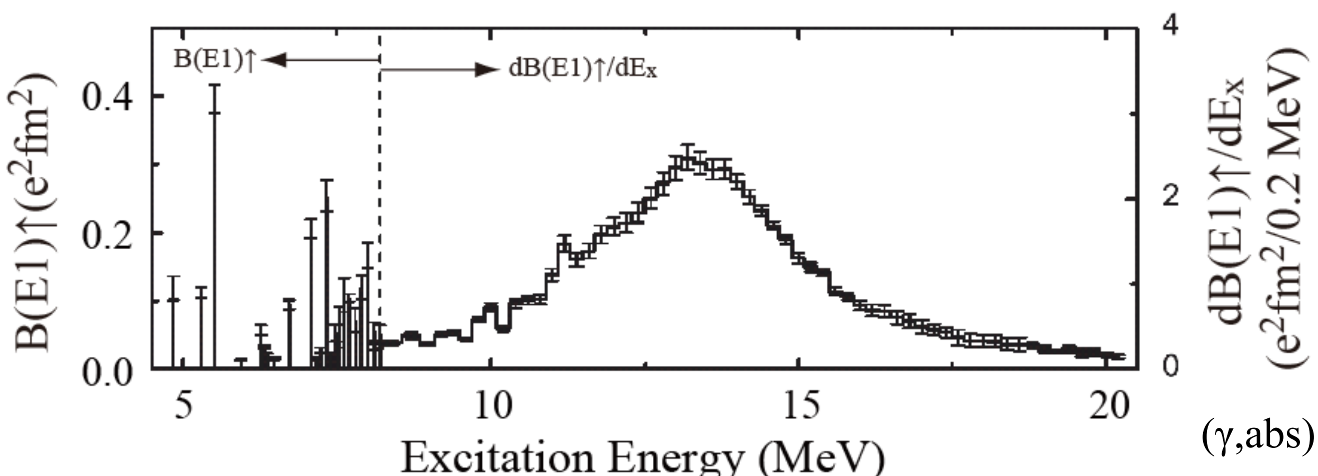
$$\alpha_D = \frac{8\pi e^2}{9} \int \frac{dB(E1)}{E_x}$$



first order perturbation calc. A.B. Migdal: 1944
dielectric theorem

Electric Dipole Polarizability: ^{208}Pb, ^{120}Sn

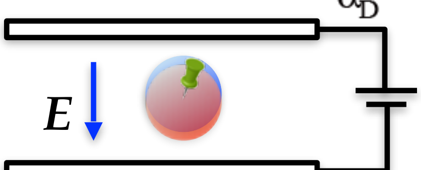




(γ,abs) at Mainz

E_x	0	10	20	130 MeV
α_D	2.7	16.2	1.2 fm³	

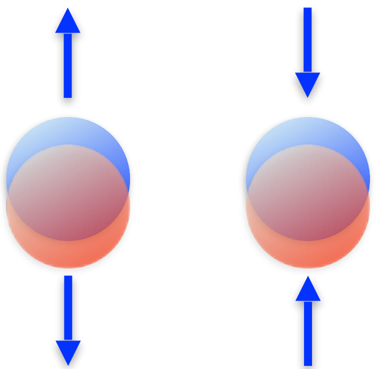
total 20.1±0.6 fm³



AT et al., PRL107, 062502(2011)

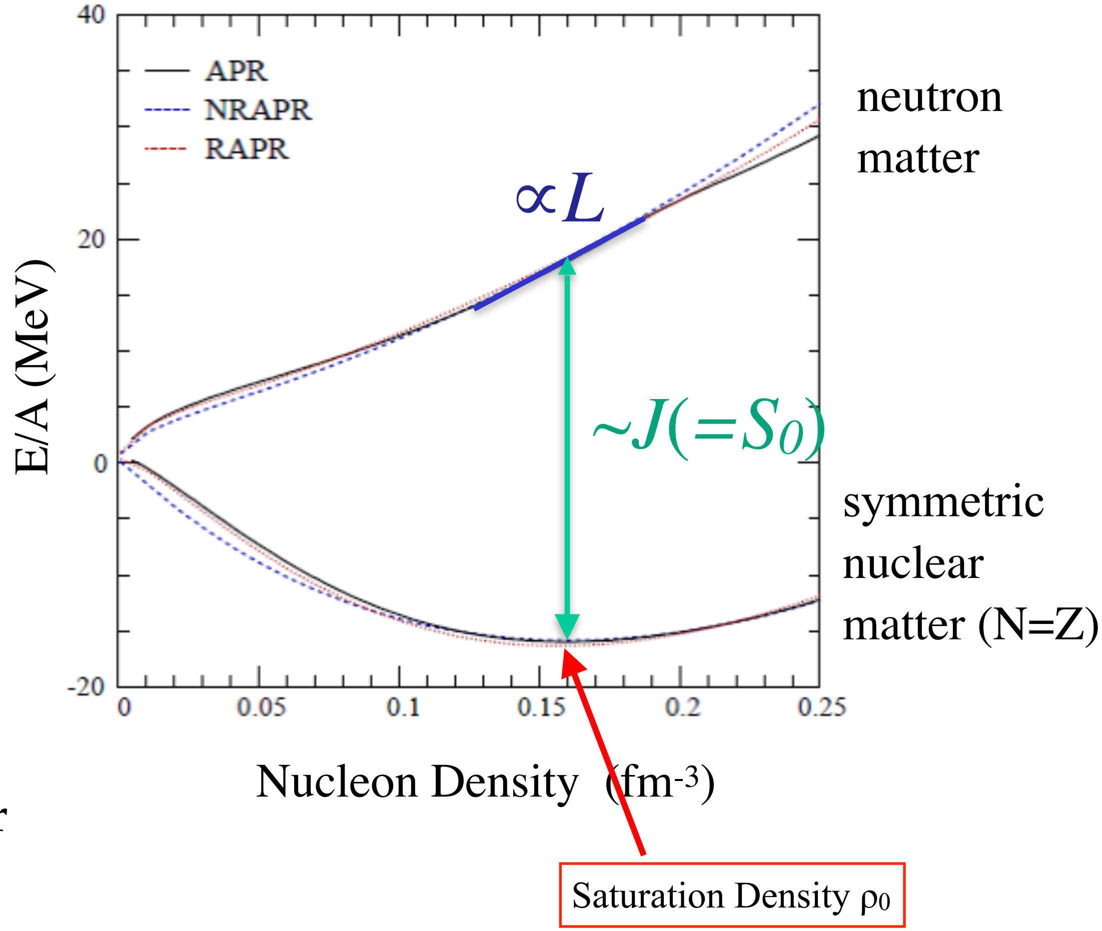
Symmetry Energy (J and L parameters)
Keys to Understand the Neutron Matter Equation of State (EOS)

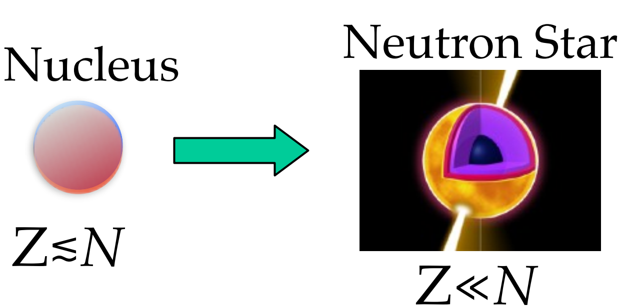
Electric Force   Symmetry Energy



α_D is determined by the balance between the two.

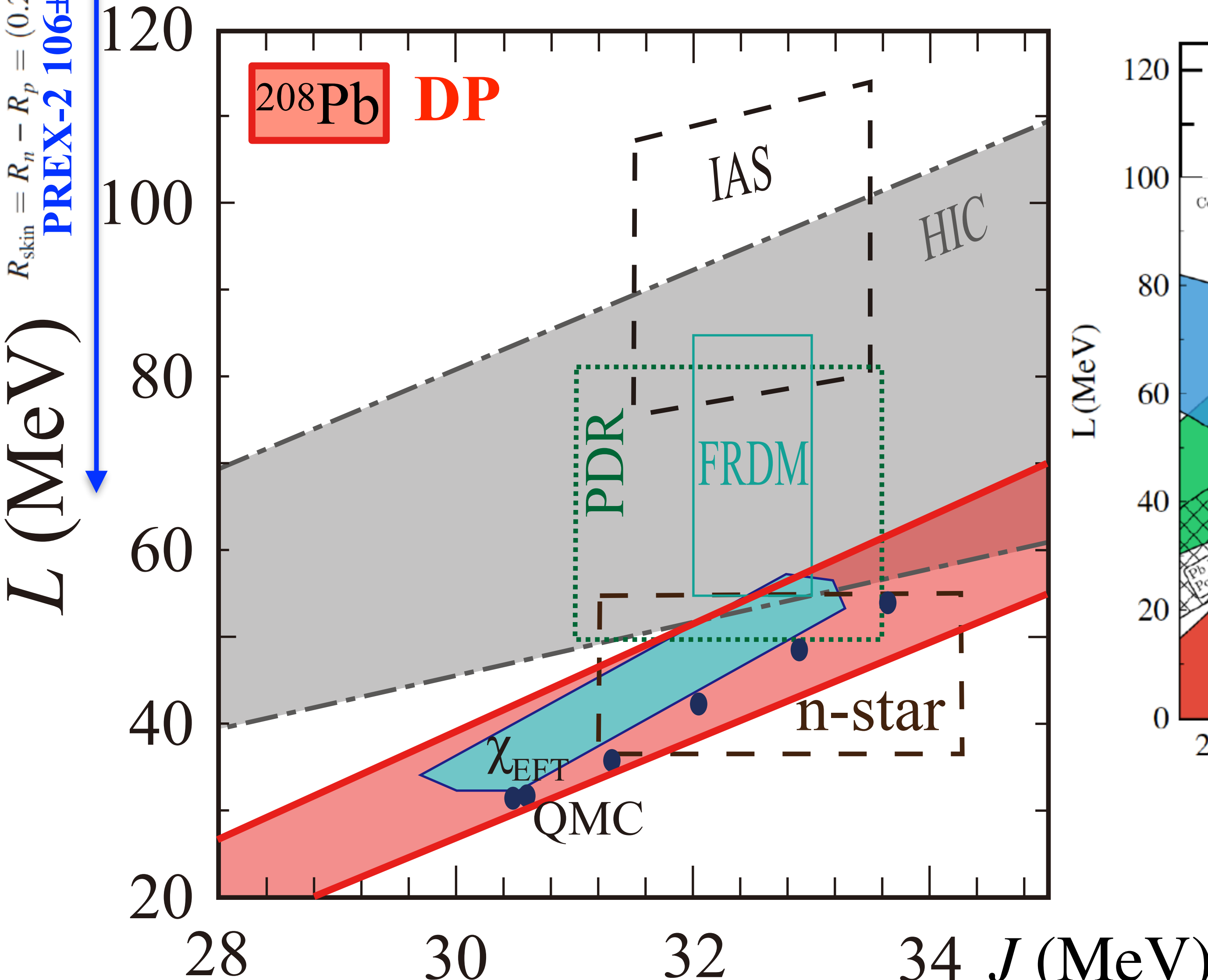
Nuclear Equation of State

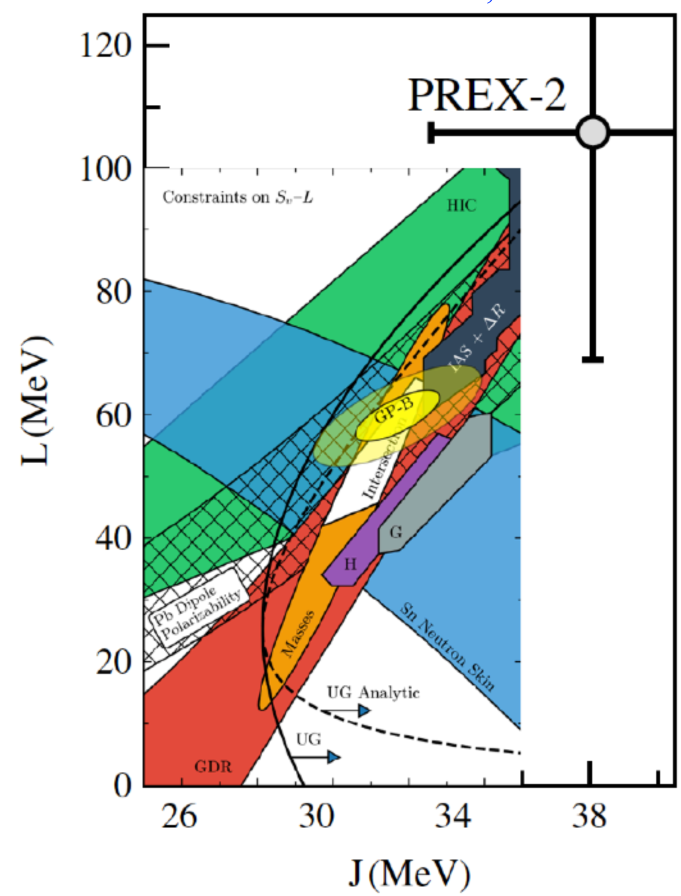




$R_{skin} = R_n - R_p = (0.283 \pm 0.071)$ fm.
PREX-2 106±37 MeV
B.T.Reed et al., PRL2021

Constraints on Symmetry Energy (*J* and *L*)



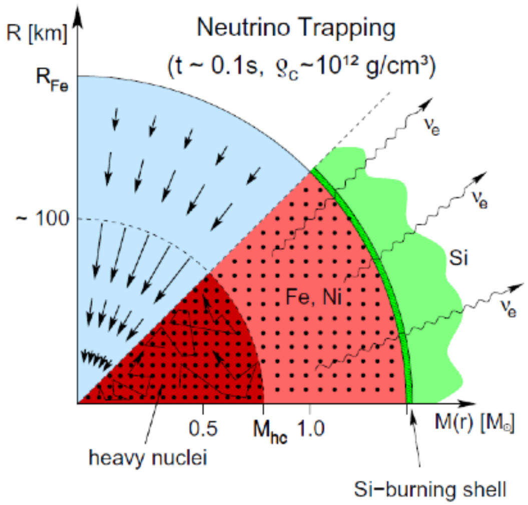


DP: Dipole Polarizability
^{208}Pb AT PRL2011

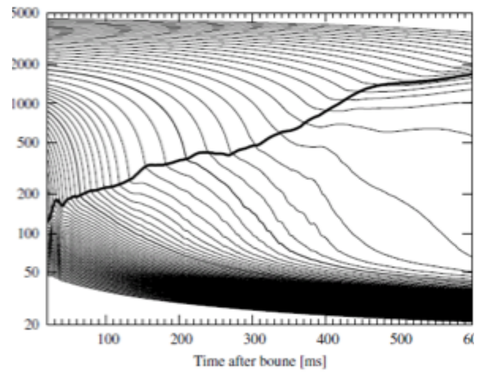
Symmetry Energy of the Nuclear EOS

is fundamental information for stellar processes

Core-collapse supernova

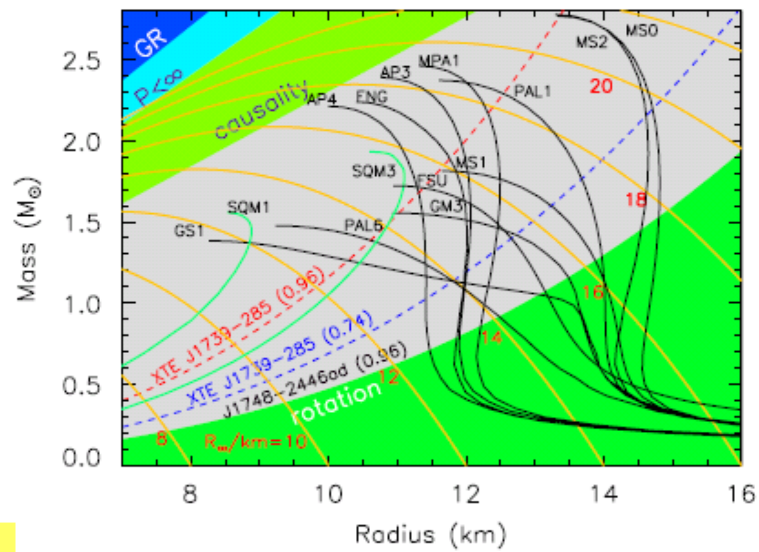


Langanke and Martinez-Pinedo



Y. Suwa et al., ApJ764, 99 (2013).

Neutron star mass vs radius



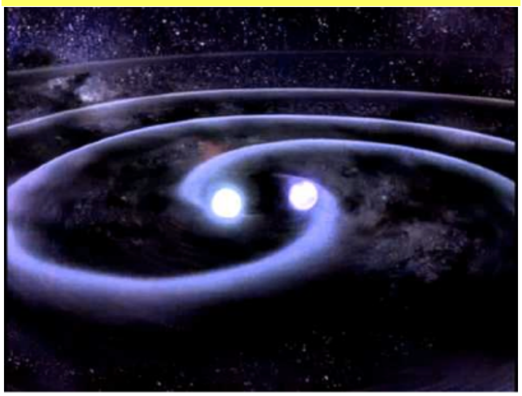
Lattimer et al., Phys. Rep. 442, 109(2007)

Nucleosynthesis

Neutron star structure

Neutron Star Merger
Gravitational Wave

Neutron star cooling



Symmetry Energyの理解: neutron-skin, n-star radius, n-star merger GW, …

広く訴えられているので、今回は強調しない

ρ(fm)

https://www.youtube.com/watch?v=IZhNWh_lFuI

Lattimer and Prakash, Science 304, 536 (2004).

http://www.astro.umd.edu/~miller/nstar.html

Quasi-Deuteron Excitation Contribution

Photon absorption by a virtual deuteron in the nucleus

Needs to be subtracted for comparison with EDF calculations.

^{208}Pb

$\alpha_D(^{208}\text{Pb})$: 20.1 ± 0.6 fm^3

quasi-*d*: 0.51 ± 0.15 fm^3

w/o quasi-*d*: 19.6 ± 0.6 fm^3

~2.5%

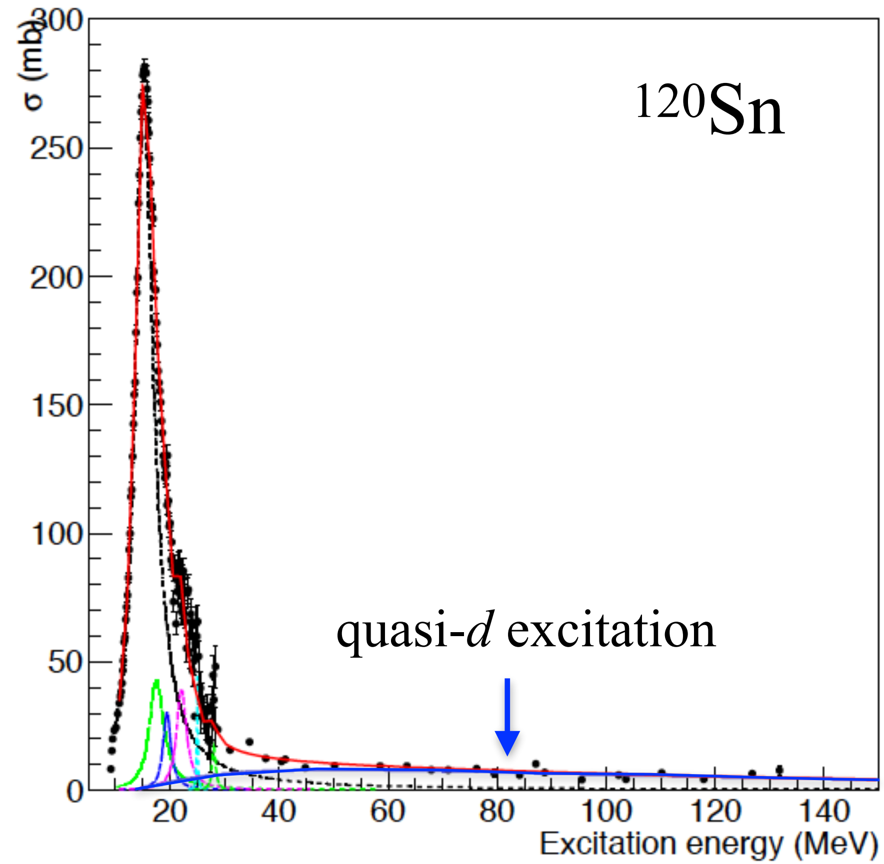
^{120}Sn

$\alpha_D(^{120}\text{Sn})$: 8.93 ± 0.36 fm^3

quasi-*d*: 0.34 ± 0.08 fm^3

w/o quasi-*d*: 8.59 ± 0.37 fm^3

~4%



quasi-deuteron excitation の理解:

d-like correlation in nuclei

Quasi-Deuteron Excitation Contribution

Levinger constant

Levinger, PR84, 43(1951).

Tavares and Terranova, JPG18, 521 (1992)

$$\sigma^{t}_{qd}(E_\gamma, A) = L\frac{NZ}{A}\sigma^{t}_{d}(E_\gamma)$$

現象論的?

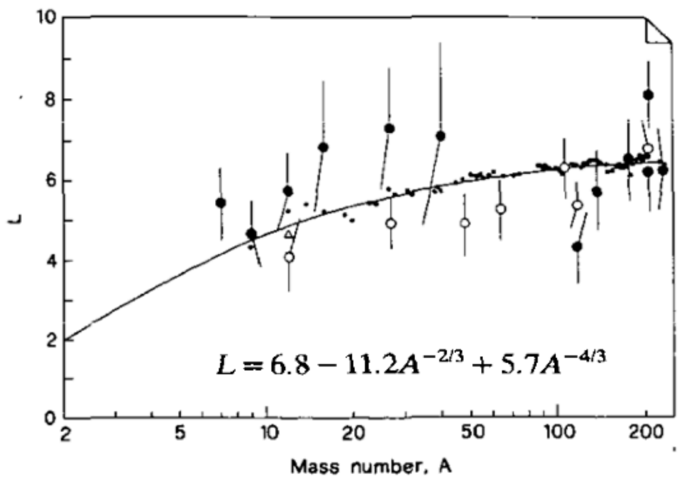
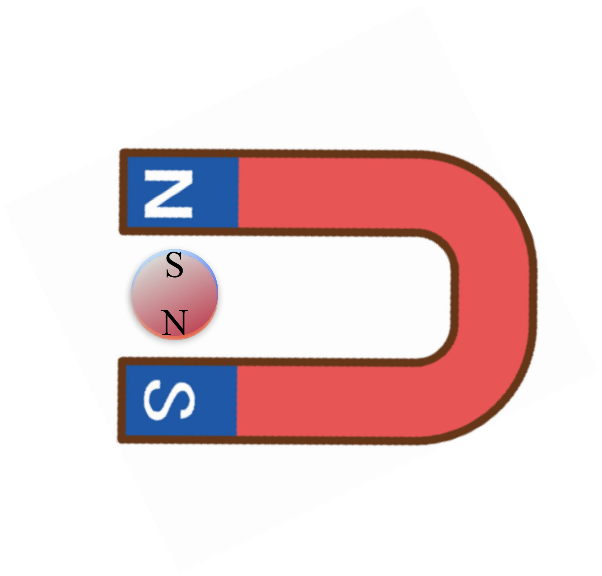
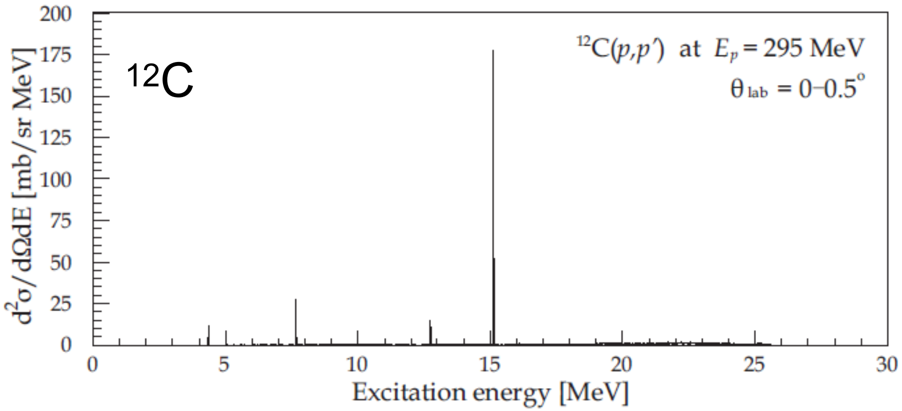


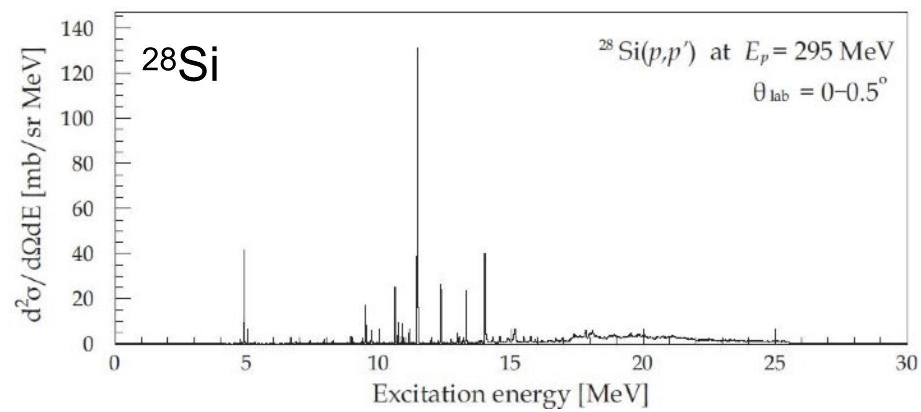
Figure 1. Levinger's constant L plotted against mass number A. The dots represent L values calculated according to Levinger's model as explained in the text. The line is the trend obtained by least-squares fitting of the calculated L values (equation (9)). Full circles represent L values obtained from total nuclear photoabsorption cross section data [14]. Open symbols represent L values deduced from: ○, data by Stibunov [16]; △, data by Homma *et al* [17, 18].

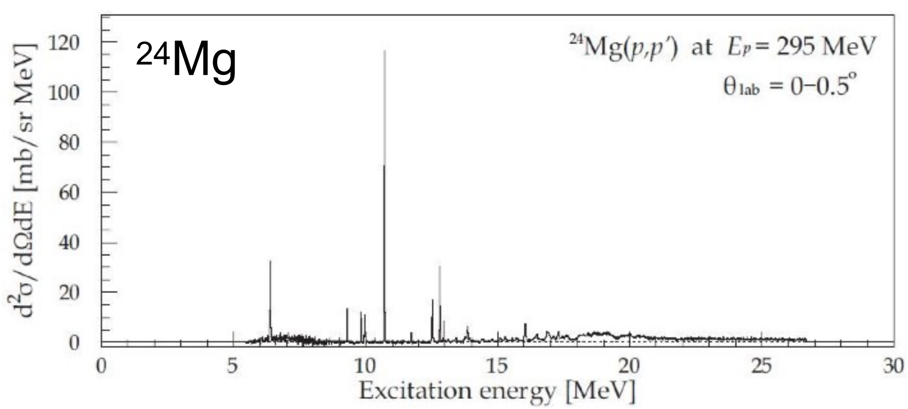
spin-Magnetic Excitation

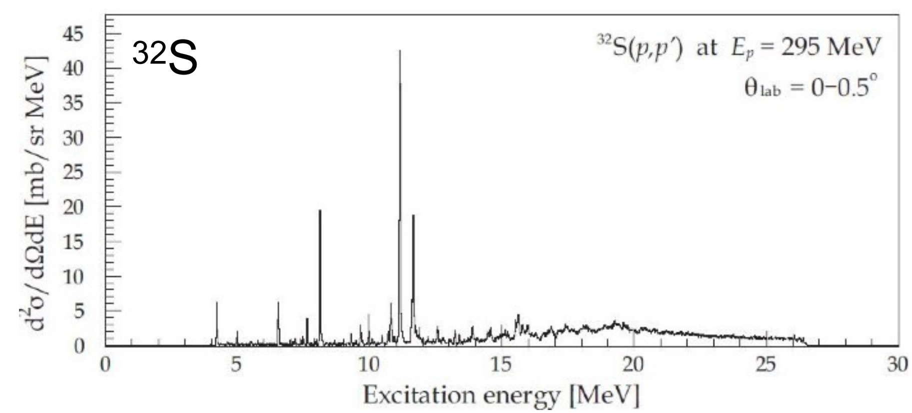


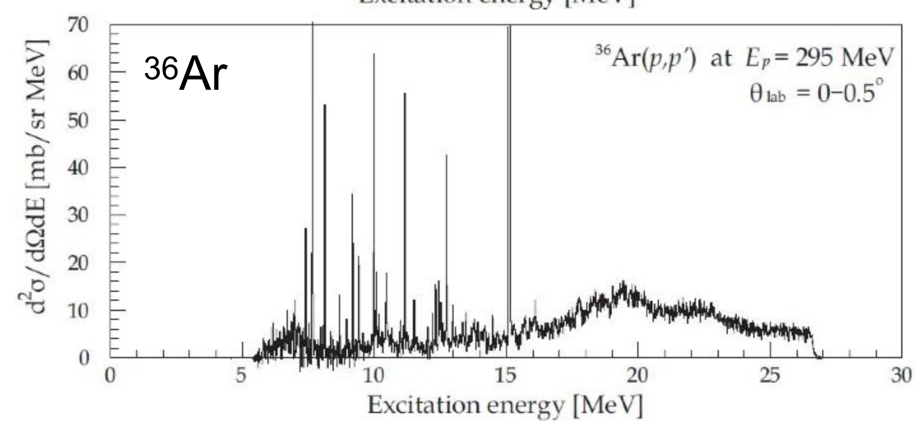
Energy spectra at 0-degrees



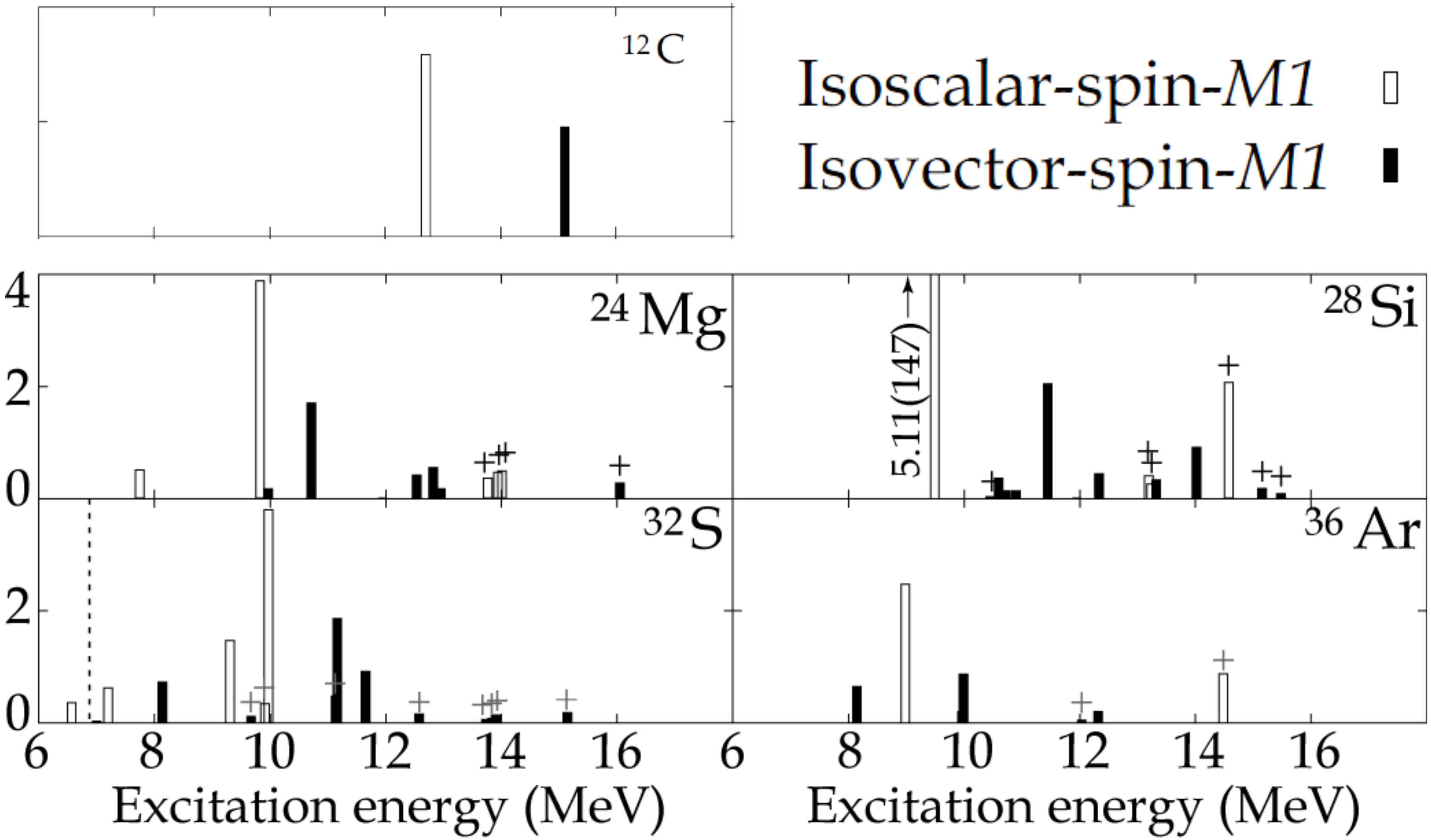








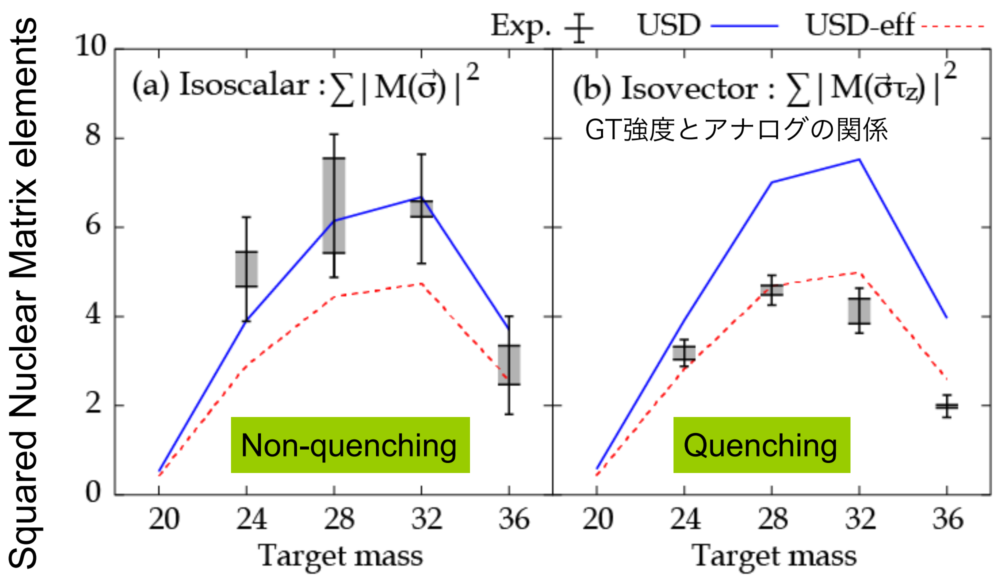
IS / IV-spin-M1 distribution



スピンM1遷移行列要素

H. Matsubara et al., PRL115, 102501 (2015)

eff: correction with $\frac{g^{eff}}{g^{bare}}$



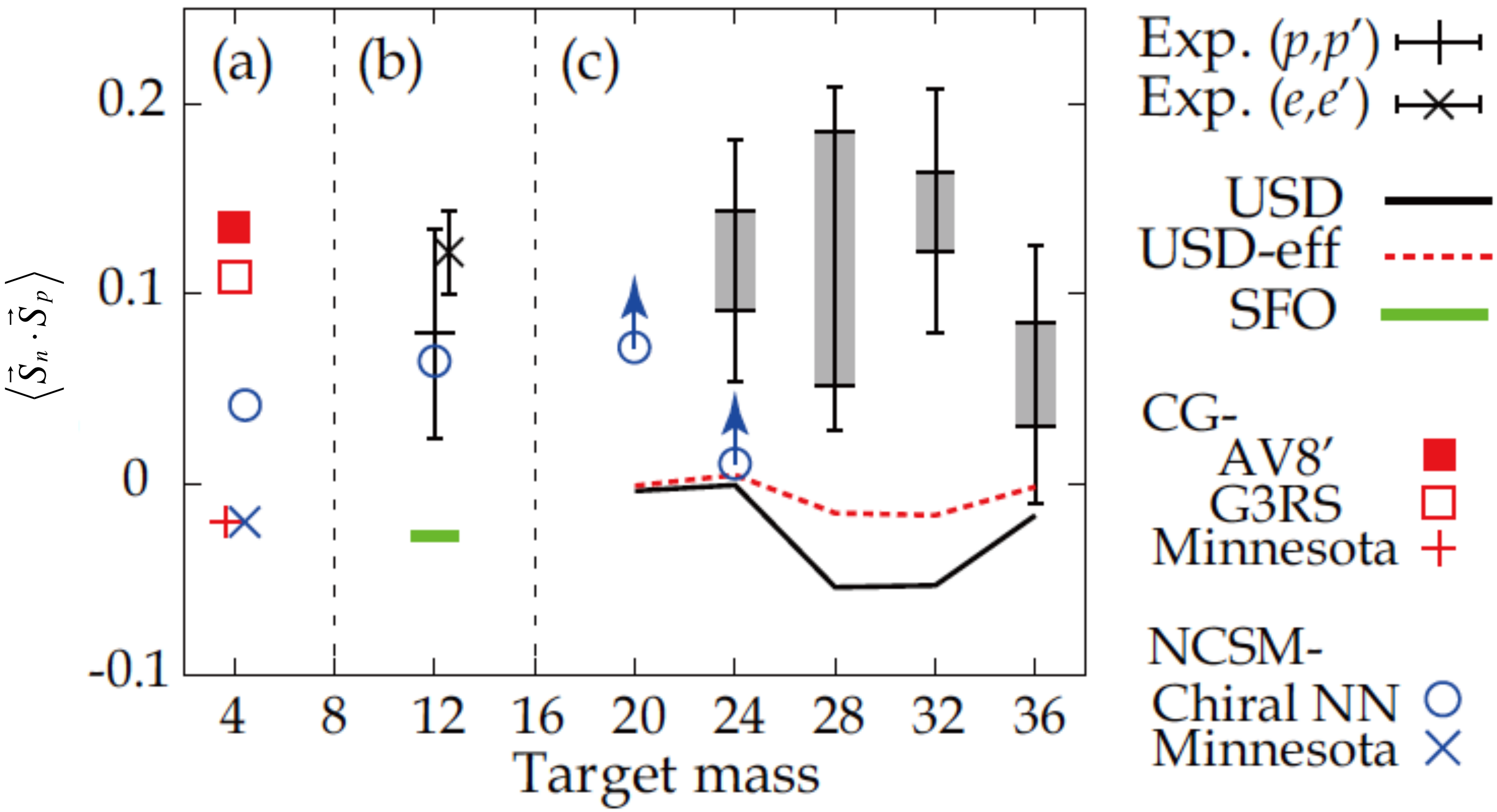
IV spin-M1遷移行列要素にquenching があるが
IS spin-M1遷移行列要素には quenching が見られない

(IS/IV spin-M1) Quenching機構の理解

GTなど他のmultipolarity遷移も
“ab initio” couple-cluster model etc.

スピンM1遷移行列要素

H. Matsubara et al., PRL115, 102501 (2015)



npスピン相関関数(基底状態)

$$\langle \vec{S}_n \cdot \vec{S}_p \rangle = \frac{1}{16}\left(\sum \left|M\left(\vec{\sigma}\right)\right|^2 - \sum \left|M\left(\vec{\sigma}\tau_z\right)\right|^2\right)$$

IS - IV

model *dependent* sum-rule

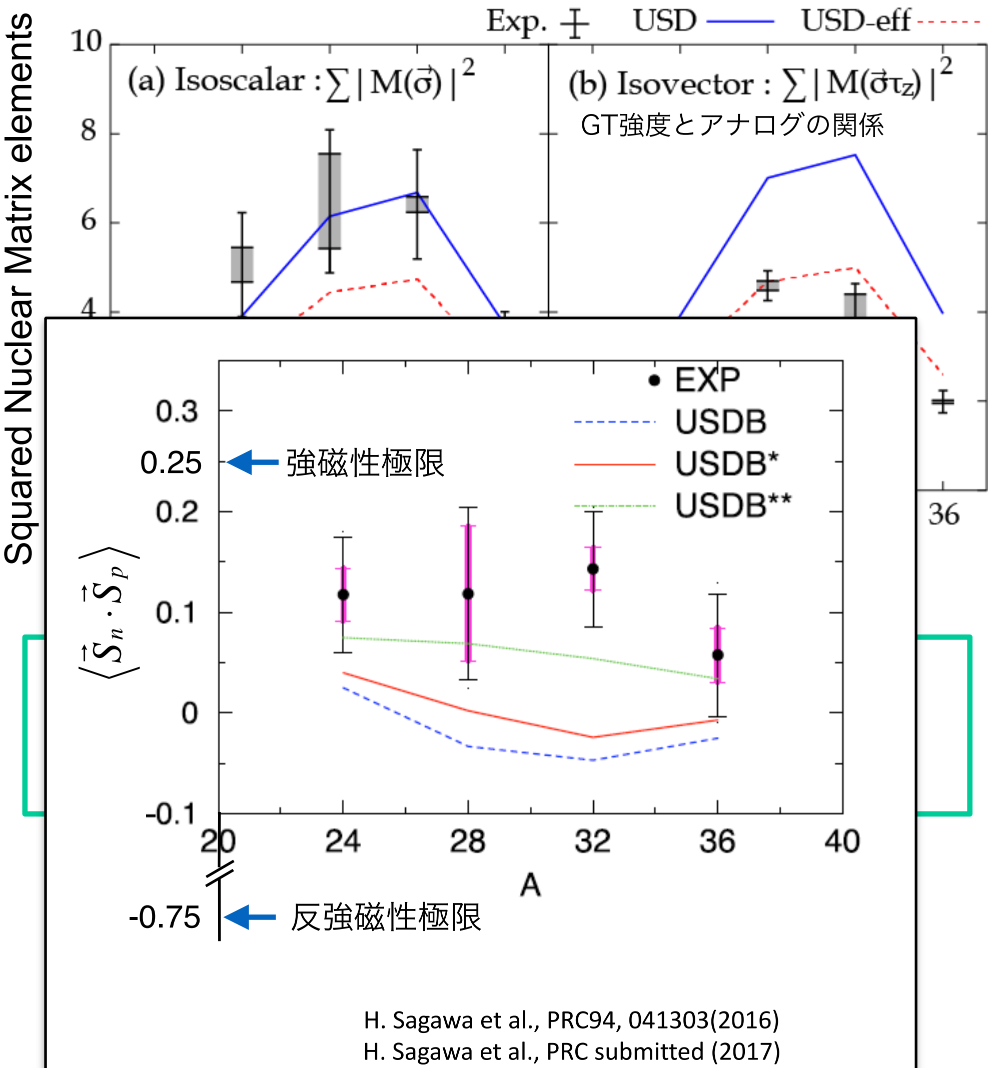
基底状態の*np*-spin相関の理解

d-like correlation in nuclei

スピンM1遷移行列要素

H. Matsubara et al., PRL115, 102501 (2015)

eff: correction with $\frac{g^{eff}}{g^{bare}}$

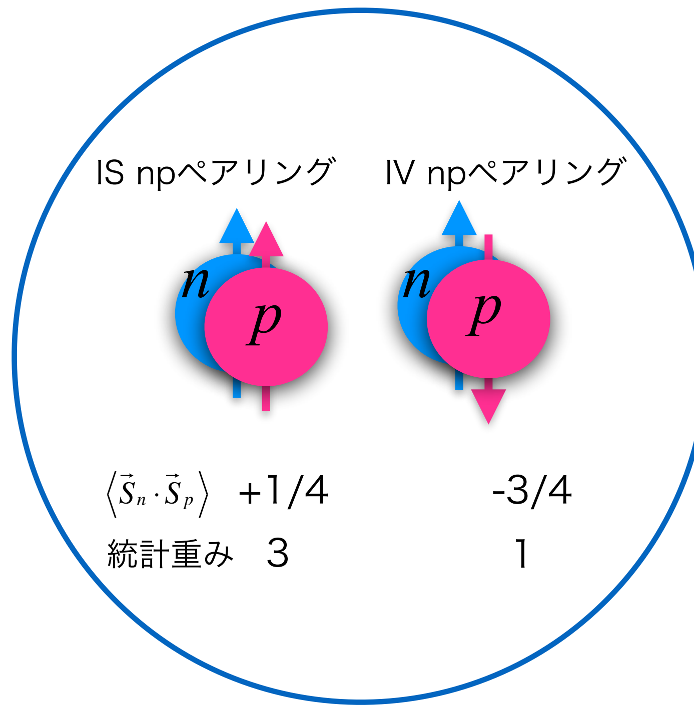


npスピン相関関数(基底状態)

$$\left\langle \vec{S}_n \cdot \vec{S}_p \right\rangle = \frac{1}{16}\left(\sum \left| M(\vec{\sigma}) \right|^2 - \sum \left| M(\vec{\sigma}\tau_z) \right|^2 \right)$$

IS - IV

> 0



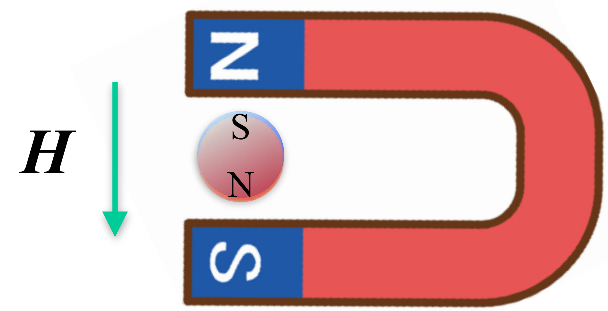
原子核の磁気的応答: スピン磁化率

Magnetic dipole (*M1*) operator

$$O(M1) = g_\ell^{IS}\ell + g_s^{IS}\boldsymbol{\sigma} + g_\ell^{IV}\ell\cdot\boldsymbol{\tau} + g_s^{IV}\boldsymbol{\sigma}\cdot\boldsymbol{\tau}$$

IS(1) and IV(τ) terms

$$\chi_\sigma^{spin} = \frac{8}{3N}\sum_f \frac{1}{\omega}\left|\langle f|\sum_i \boldsymbol{\sigma}_i|0\rangle\right|^2$$



$$\mathbf{M} = \chi_\sigma \mathbf{H}$$

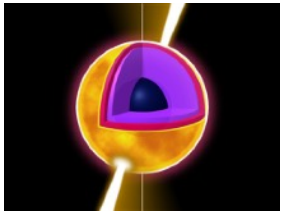
χ_σ: magnetic susceptibility 磁化率

核物質のスピン磁化率の理解

- 核物質の磁化率のスピン成分
- 強磁場中の核物質の応答(マグネターなど)
- 超新星爆発コア中でのニュートリノ閉じ込め・透過度
- 中性子星の強磁性体状態発現の可能性

S. Fantoni et al., PRL87, 181101 (2001)

S. Reddy et al., PRC59, 2888 (1999)



マグネター $10^{14\text{-}16}$ Gauss

スピン磁化率

Magnetic dipole (*M1*) operator

$$O(M1) = g_\ell^{IS}\ell + \underline{g_s^{IS}\boldsymbol{\sigma}} + g_\ell^{IV}\ell\cdot\boldsymbol{\tau} + \underline{g_s^{IV}\boldsymbol{\sigma}\cdot\boldsymbol{\tau}}$$

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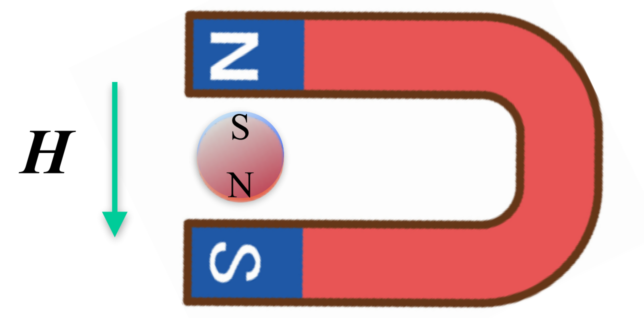
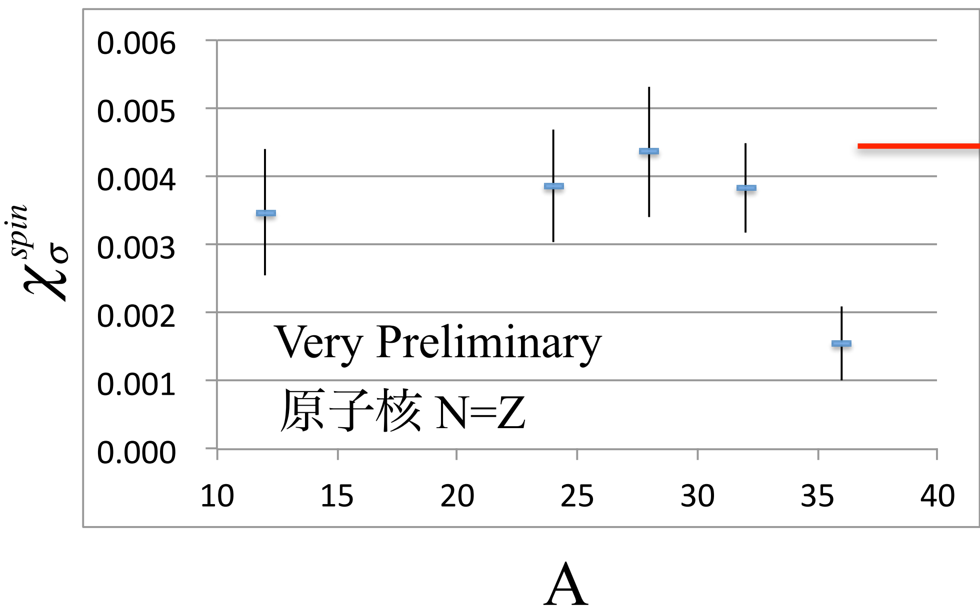
$$\chi_\sigma^{spin} = \frac{8}{3N}\sum_f \frac{1}{\omega}\left|\langle f|\sum_i \boldsymbol{\sigma}_i|0\rangle\right|^2$$



$$\mathbf{M} = \chi_\sigma \mathbf{H}$$

χ_σ: magnetic susceptibility 磁化率



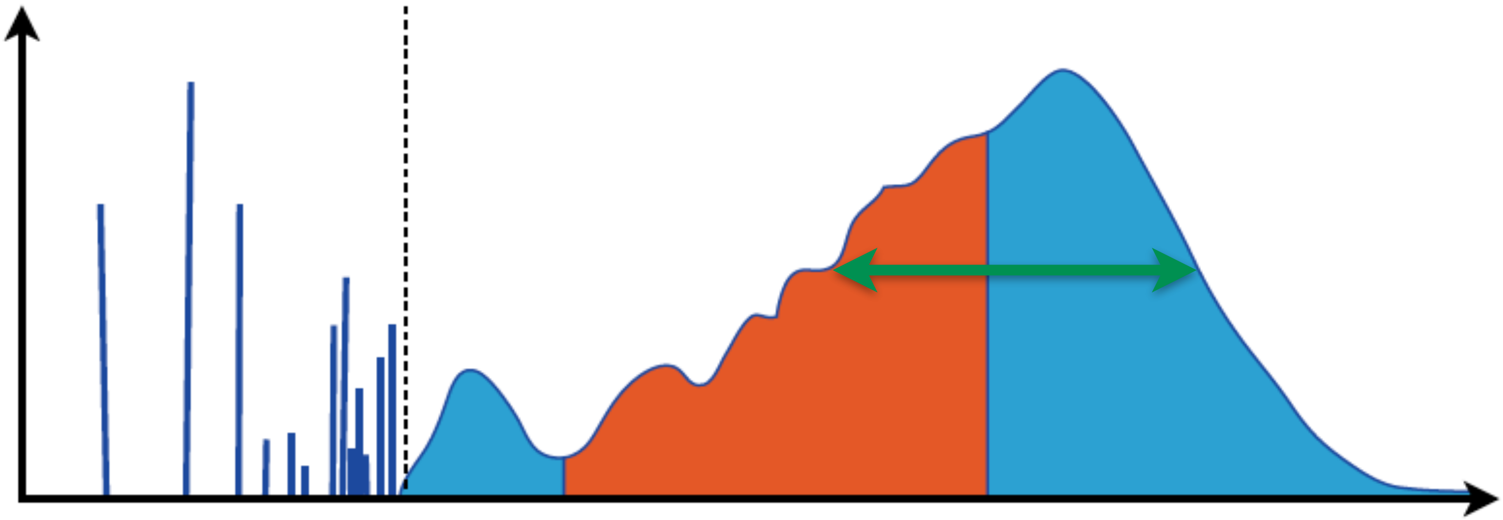
0.0044(7) MeV^{-1} at ρ=0.16 fm^{-3}

中性子物質計算 AFDMC model

G. Shen et al., PRC**87**, 025802 (2013)

→ 重い原子核、同位体依存性、...

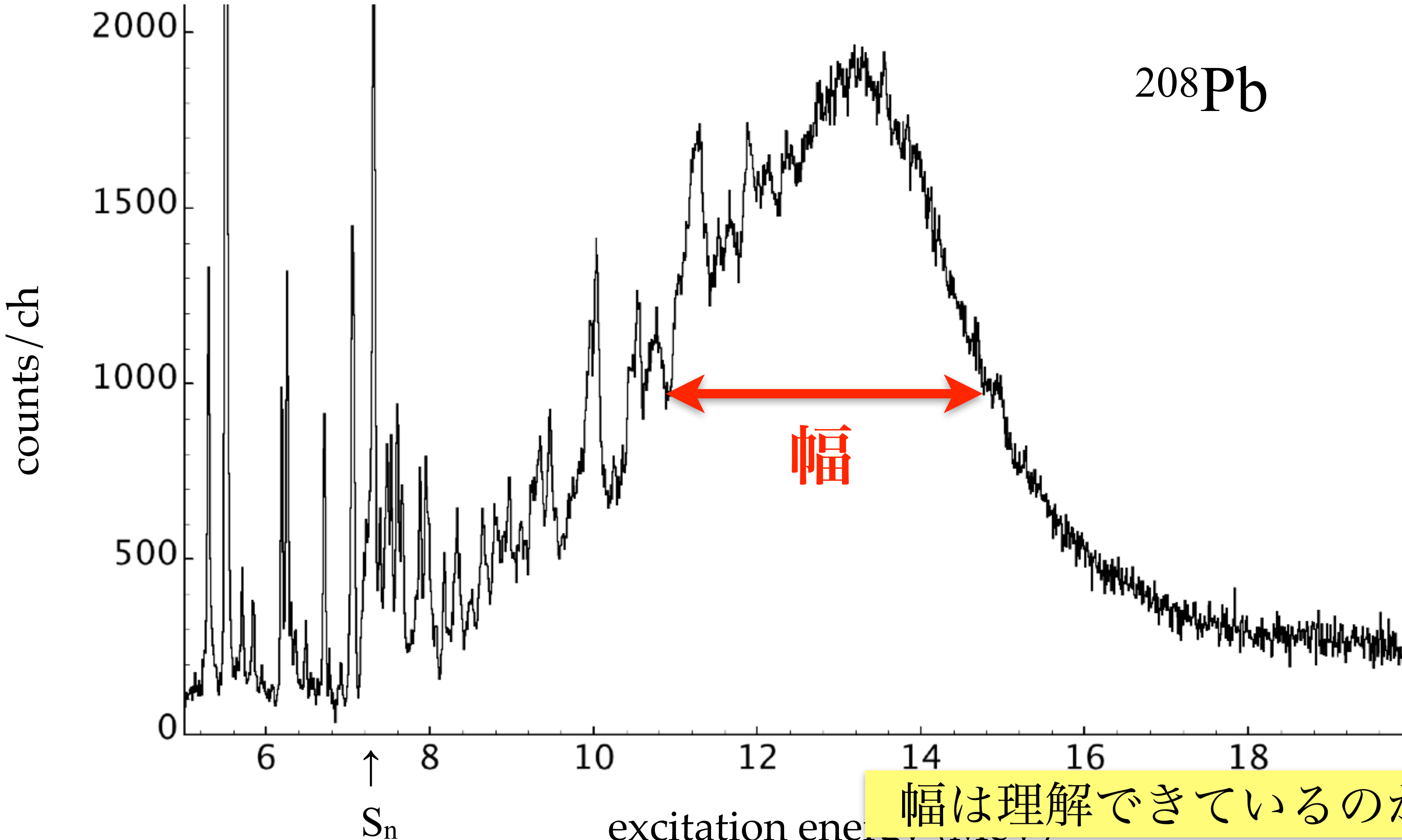
Damping of Giant Resonances



原子核の電気双極(E1)応答

PDR ピグミー共鳴

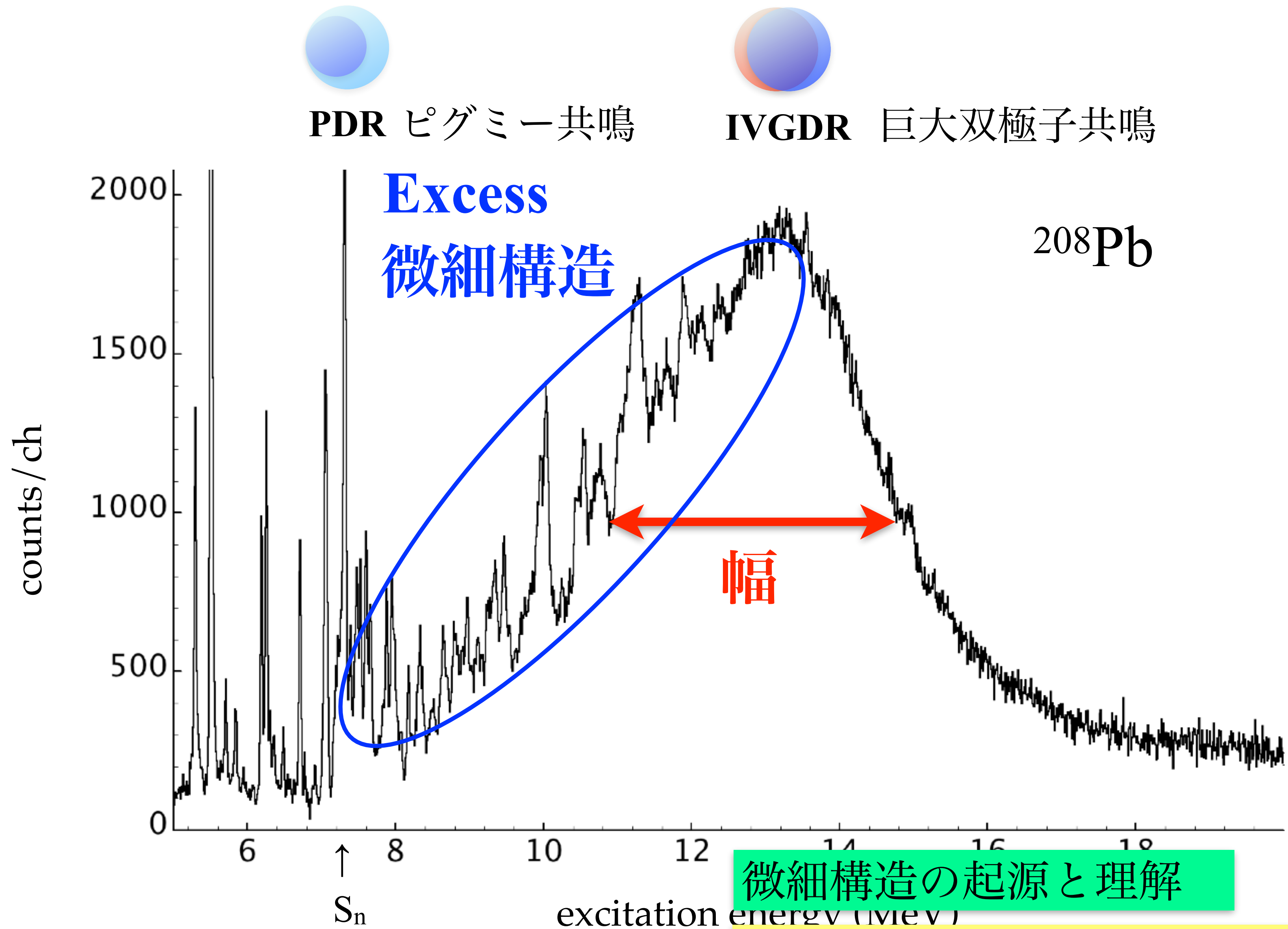
IVGDR 巨大双極子共鳴



幅は理解できているのか？

巨大共鳴の崩壊の記述

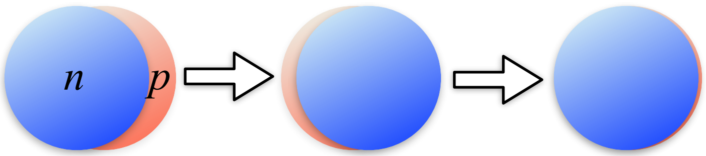
原子核の電気双極(E1)応答



微細構造の起源と理解

特徴的な幅を持つのではないか？

巨大共鳴の減衰



巨大双極子共鳴(IVGDR)

巨視的な集団運動描像

→陽子と中性子の相対双極振動

振動の減衰は、陽子中性子流体間の粘性によって引き起こされる

wikipedia

減衰（共鳴幅）の生成機構　　（教科書的説明）

$$\Gamma = \Delta\Gamma + \Gamma\downarrow + \Gamma\uparrow$$

$\Delta\Gamma$　ランダウ減衰: 戸口状態の1p1h配位分布

複数の1p1h共鳴モードの合成

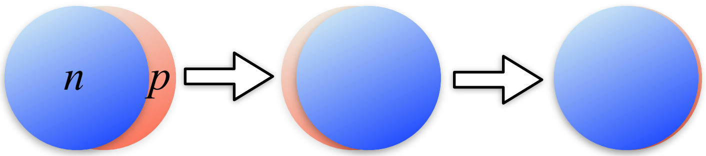
$\Gamma\uparrow$　エスケープ幅: 戸口状態からの粒子・光子放出による直接崩壊過程

エネルギーを放出して別の状態へ遷移する

$\Gamma\downarrow$　分散幅：戸口状態からより複雑な配位(複合核）への遷移

共鳴がコヒーレンスを失っていく過程

巨大共鳴の減衰：微視的理解



巨大双極子共鳴(IVGDR)

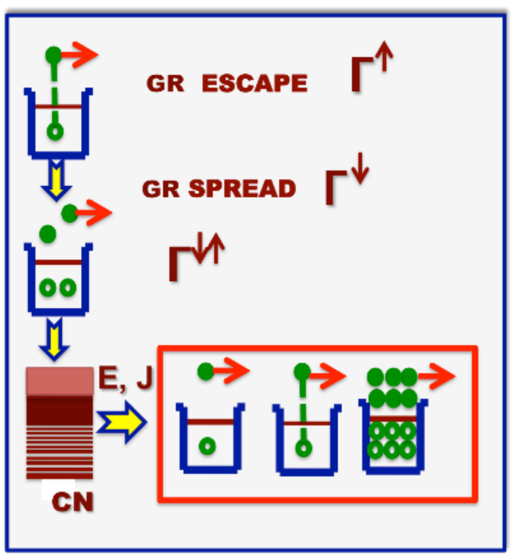
分散幅:

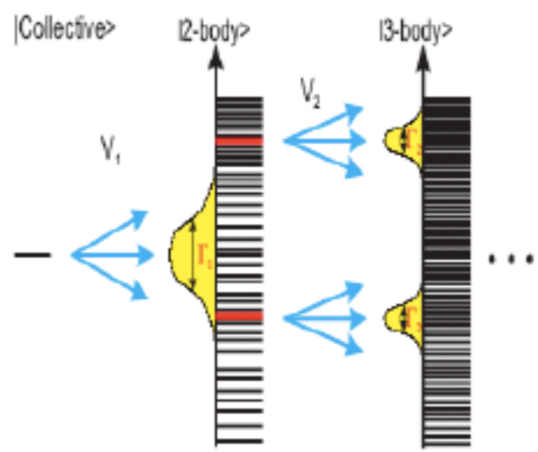
中重核の分散幅の主成分

励起状態のW.F.

$$|\psi\rangle = \sum_i |1p1h\rangle_i + \sum_i |1phonon + 1p1h\rangle_i + \sum_i |2p2h\rangle_i + \cdots + \sum_i |CN\rangle_i$$

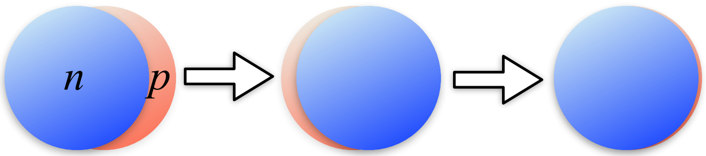
→ コヒーレンスを失うことによる減衰





total width = Σ partial width
∝ Σ partial transition rate
∝ Σ (partial life time)$^{-1}$

巨大共鳴の減衰：実験からの観点



IVGDR

巨大共鳴は最終的にはエネルギーを失って別の形態へ崩壊する。

崩壊チャンネルは放出粒子（光子）とそのエネルギーによって分類される

$$\Gamma = \sum \Gamma_n + \sum \Gamma_p + \sum \Gamma_\gamma + \ldots$$

実験では、各崩壊チャンネル毎に分岐比を測定することが可能

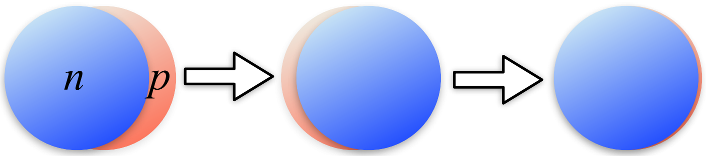
分岐比： $b_i = \dfrac{\Gamma_i}{\Gamma}$　　全幅： $\Gamma = \sum \Gamma_i$

今回の研究では<u>**基底状態へのγ崩壊**</u>に着目

Γ_{γ_0}　分岐比~1%

なぜか？

巨大共鳴の減衰



IVGDR

基底状態へのγ崩壊は、基底状態からの**クーロン励起の逆過程**にあたる。

基底状態からのクーロン励起断面積から

→ B(E1)↑

→ B(E1)↓ (微細平衡)

→ Γ_{γ_0}

が決まる。

崩壊同時測定

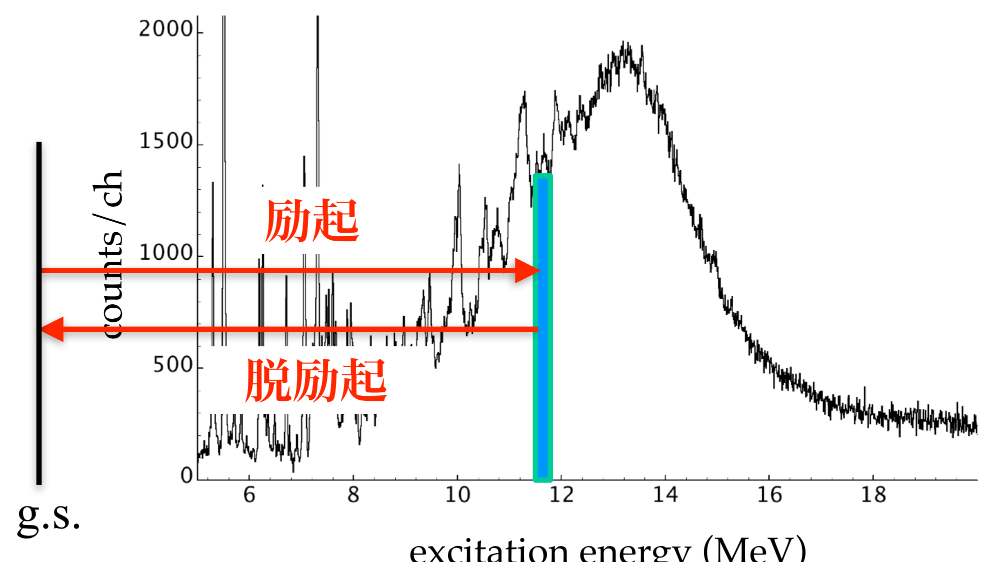
→ 分岐比 $b_{\gamma_0} = \frac{\Gamma_{\gamma_0}}{\Gamma}$

が決まる。

→ Γが決まる

どうなる？

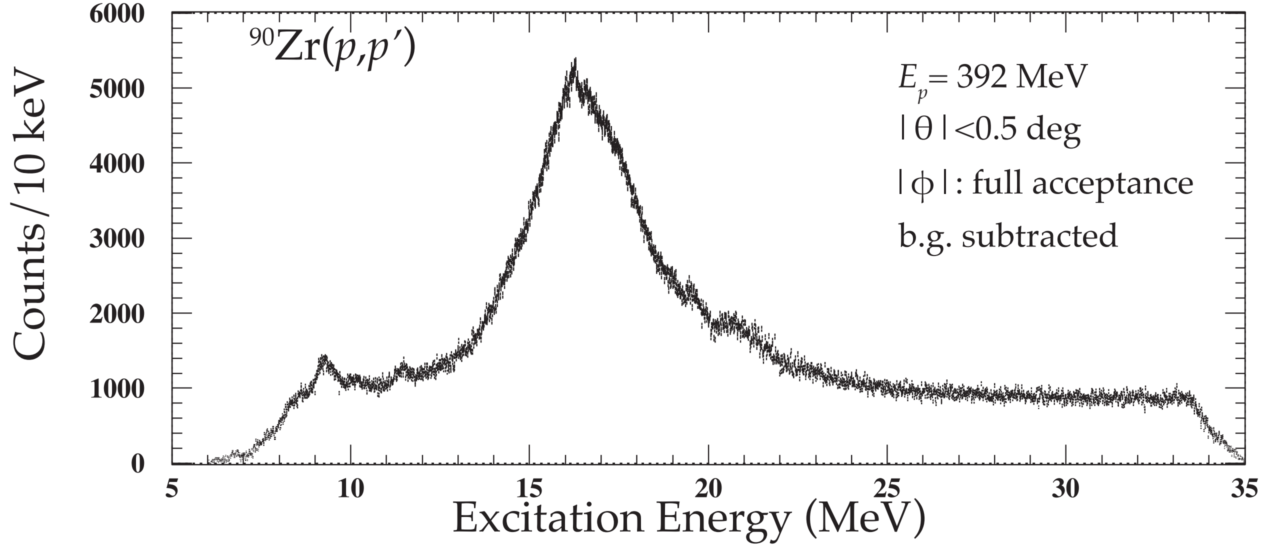
Γを励起エネルギーの関数として求められる

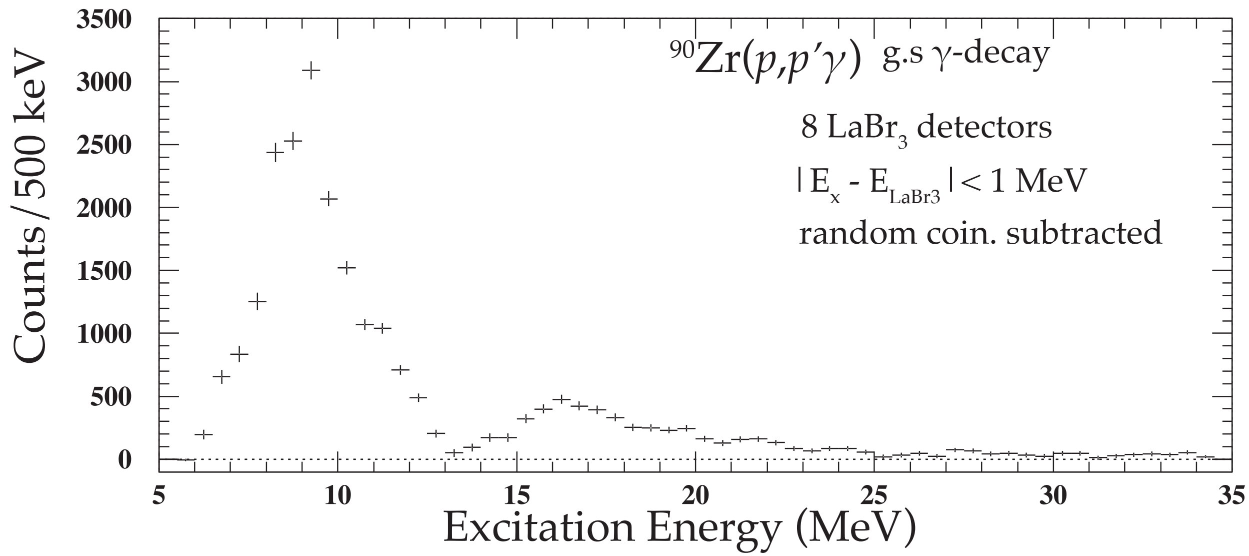


Semi-online analysis

$^{90}Zr(p,p')$ at 0 deg

RCNP-E498
semi-online analysis
2018/07/27 Run #1100-1199

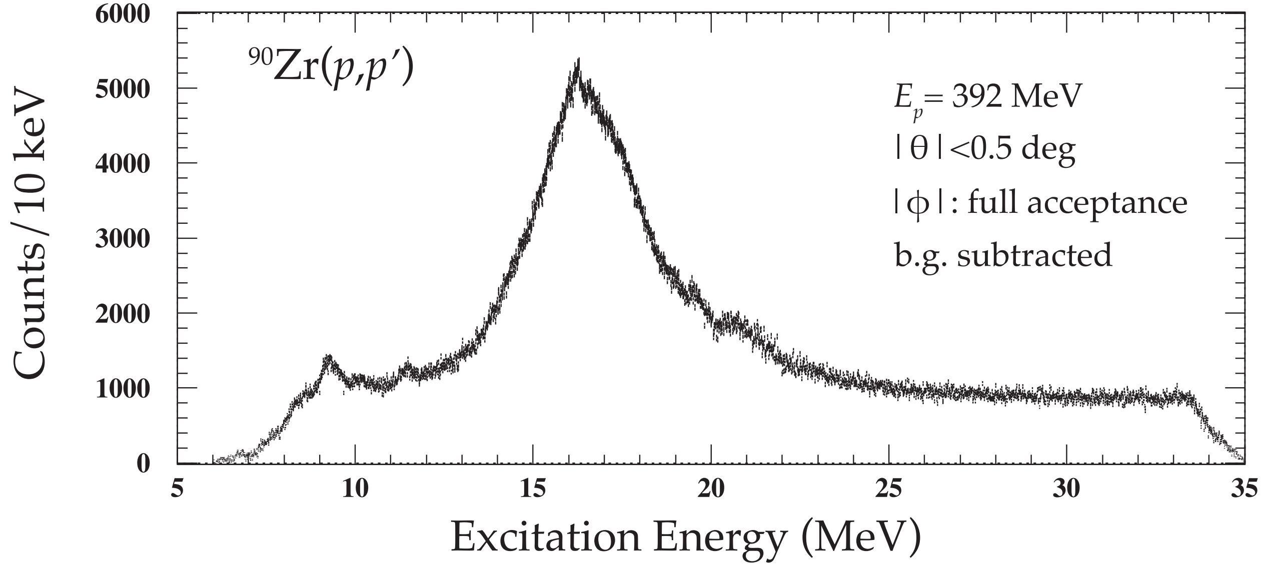


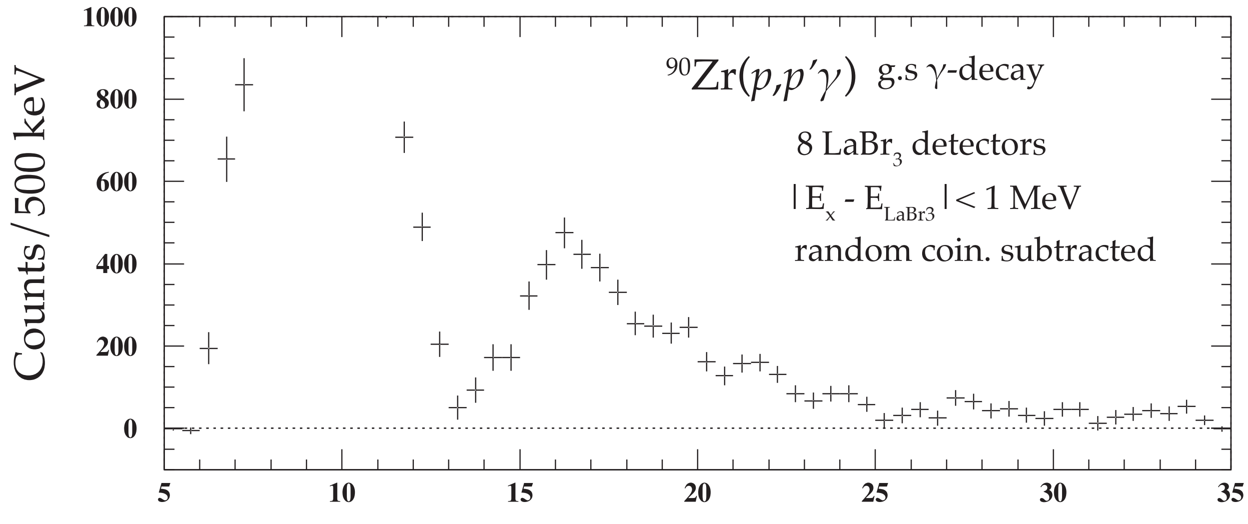


preliminary

^{90}Zr(p,p') at 0 deg

RCNP-E498
semi-online analysis
2018/07/27 Run #1100-1199

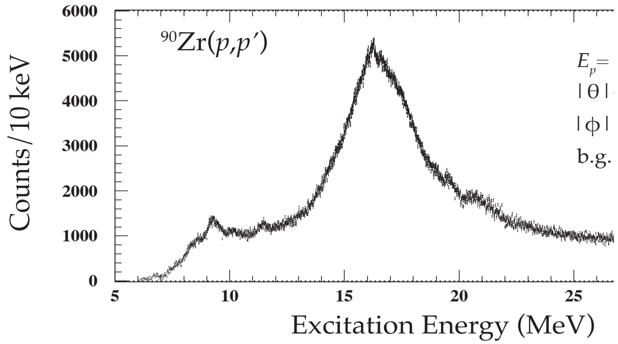


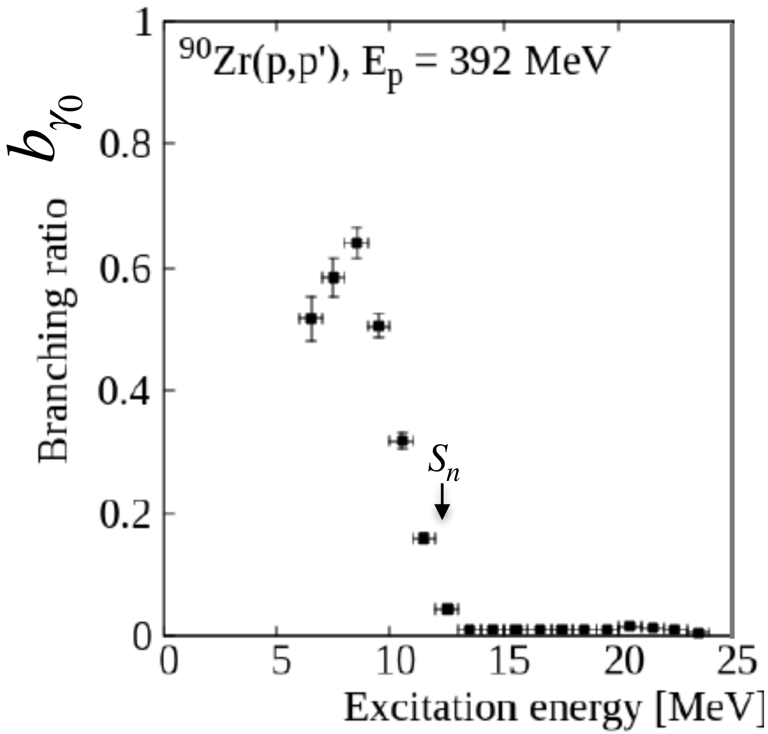


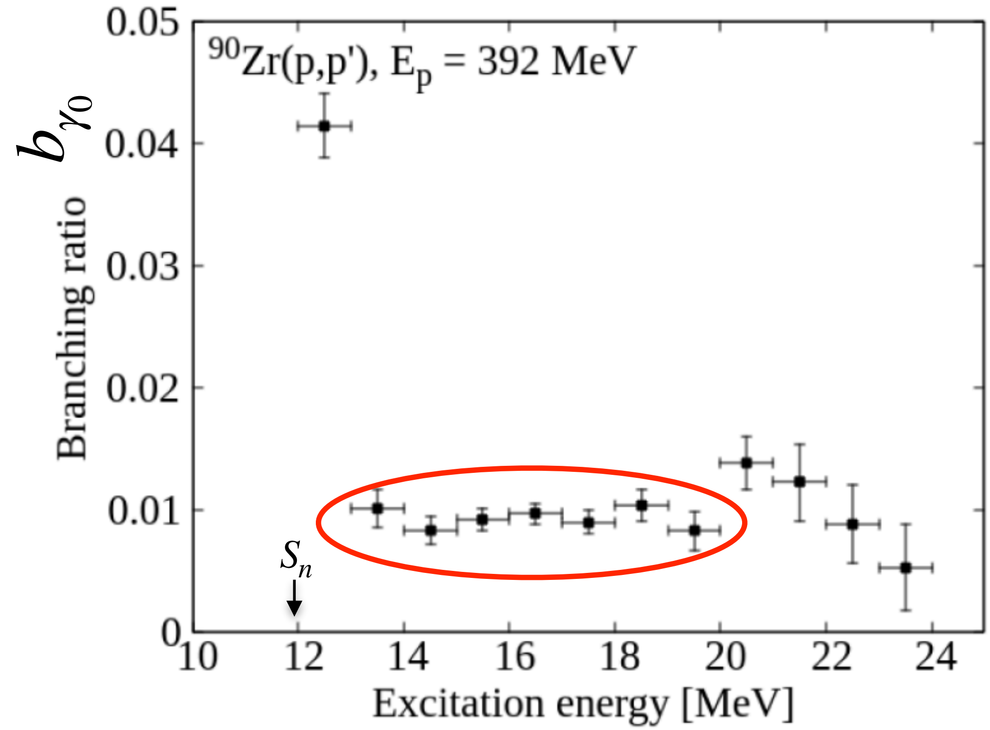
GDR領域のγ崩壊が精度よく測れた

g.s.γ崩壊: 分岐比

Preliminary







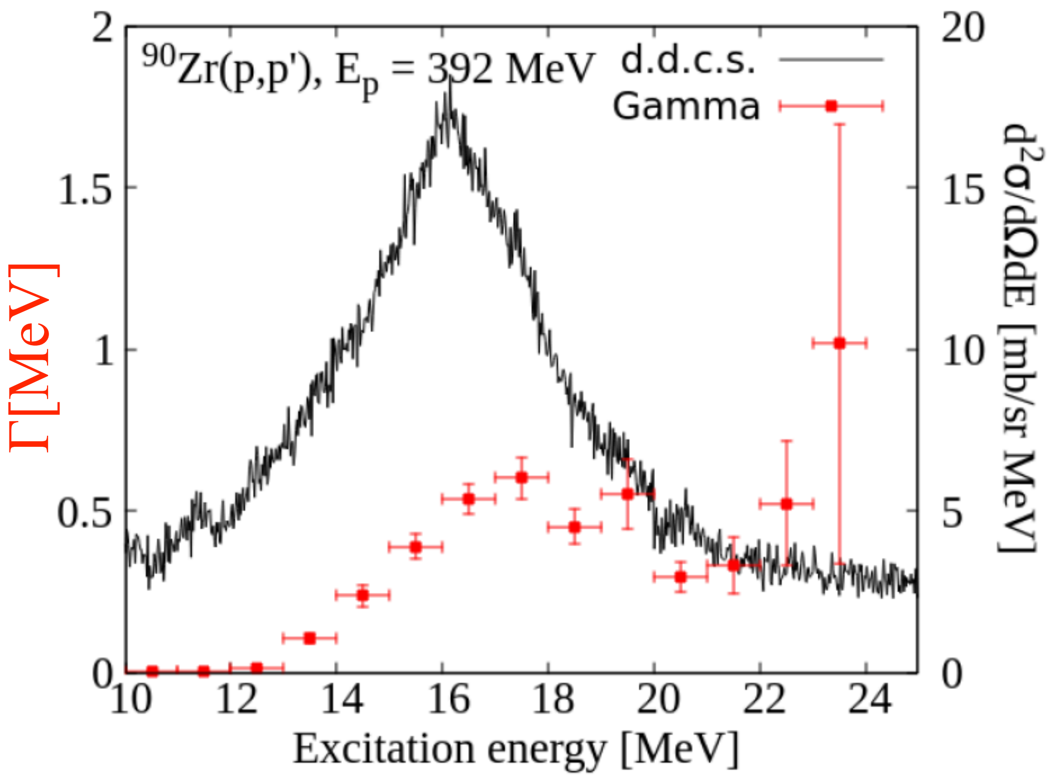
g.s.γ崩壊比はGDR領域でほぼフラット

S. Nakamura, master thesis

Γの励起エネルギー依存性

Preliminary

$$\Gamma = \frac{\Gamma_{\gamma_0}}{b_{\gamma_0}} \qquad \Gamma_{\gamma_0} = \frac{16\pi}{9}\left(\frac{E_x}{\hbar c}\right)^3 \frac{2J_0+1}{2J_x+1} B(E1)\uparrow$$



どう解釈するのか？

測られた「Γ」は
Γなのか、Γ↑なのか？

$\Gamma = \varDelta\Gamma + \Gamma\downarrow + \Gamma\uparrow$

「Γ」を積算した値がIVGDRの幅に対応するのか？

E_x→大で、「Γ」→大

中性子崩壊の位相空間体積効果？

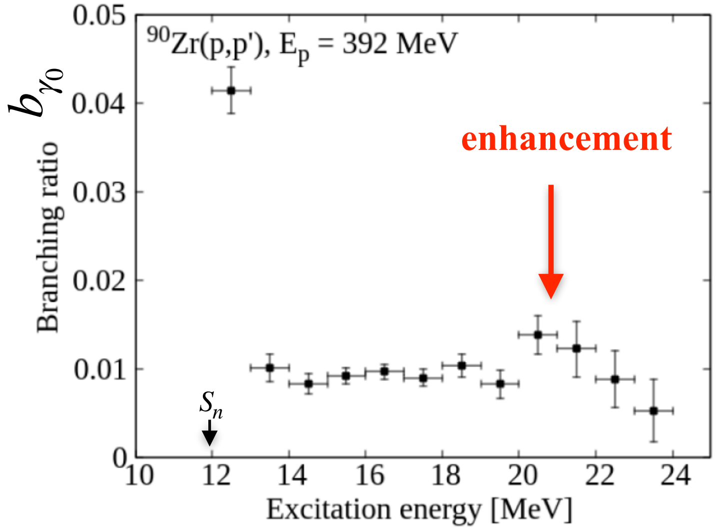
IVGDRの低E_x側に見られる微細構造に対応？

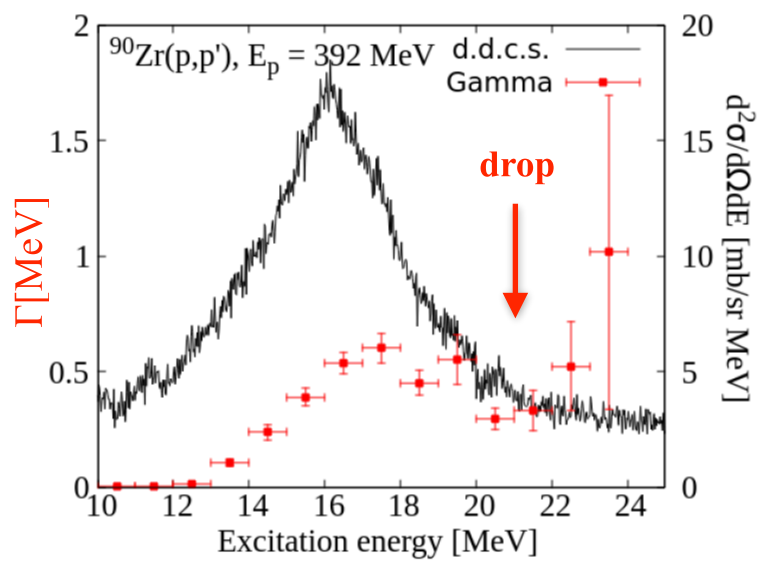
open questions…

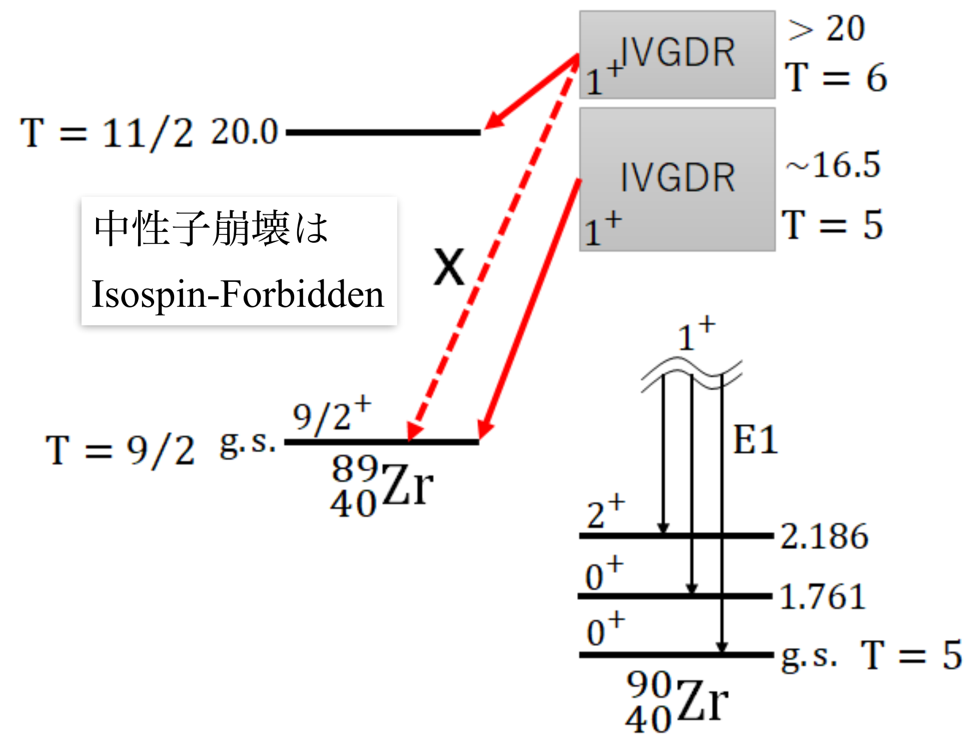
S. Nakamura, master thesis 46

Isospin Upper IVGDR の影響

Preliminary

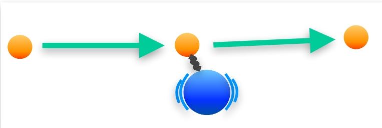






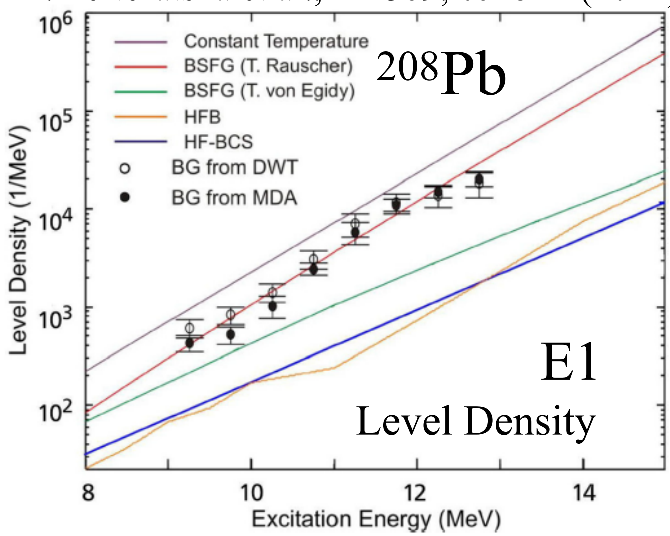
S. Nakamura, master thesis

Nuclear Level Densities

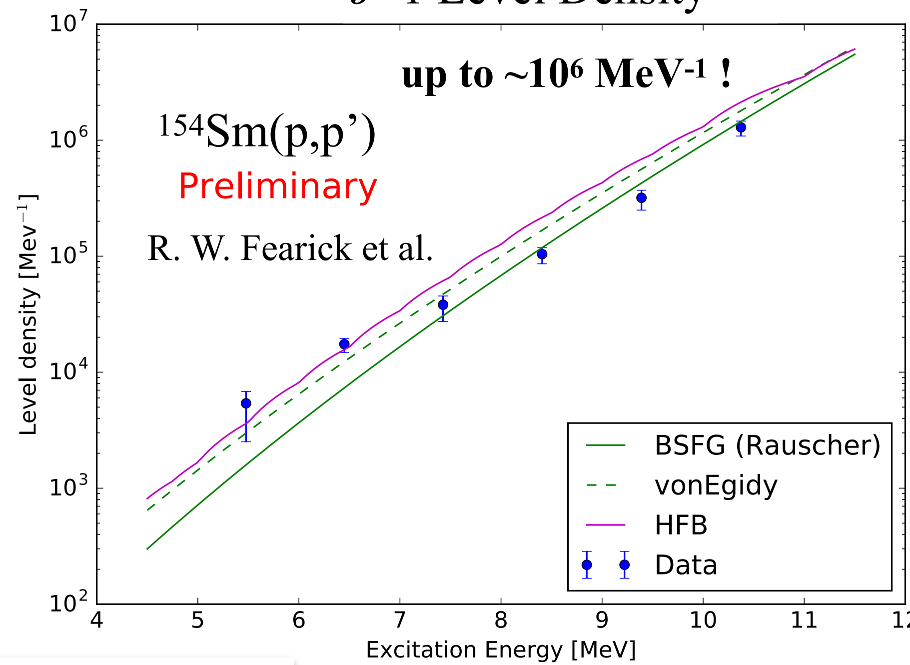


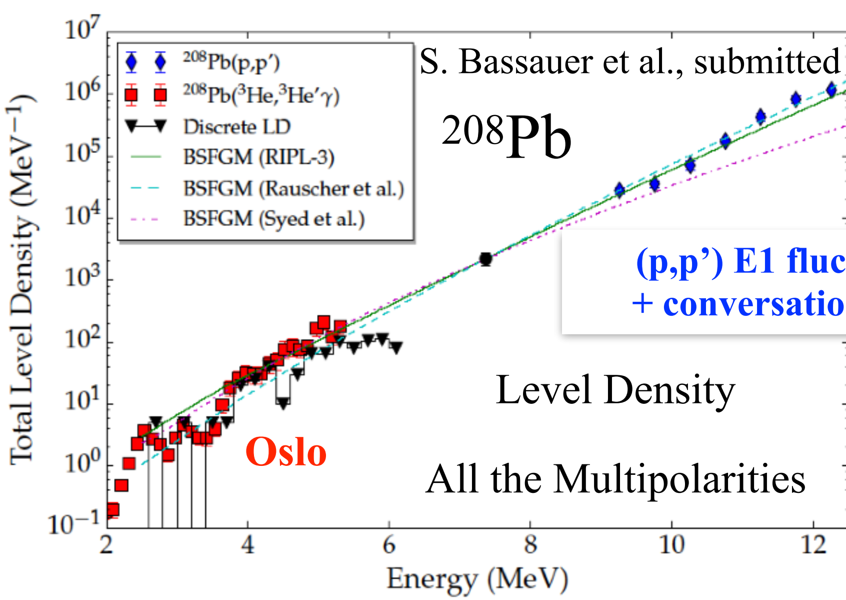
extracted by fluctuation analysis using auto-correlation function

I. Poltoratska et al., PRC89, 054322 (2014)



J=1 Level Density

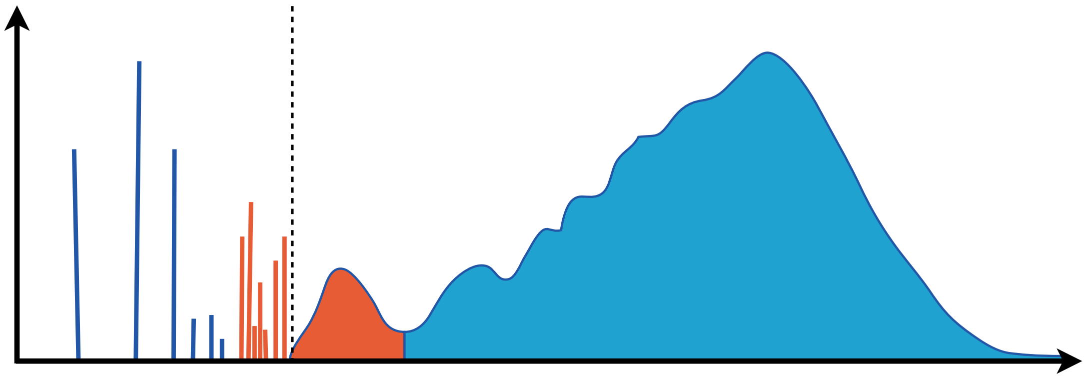




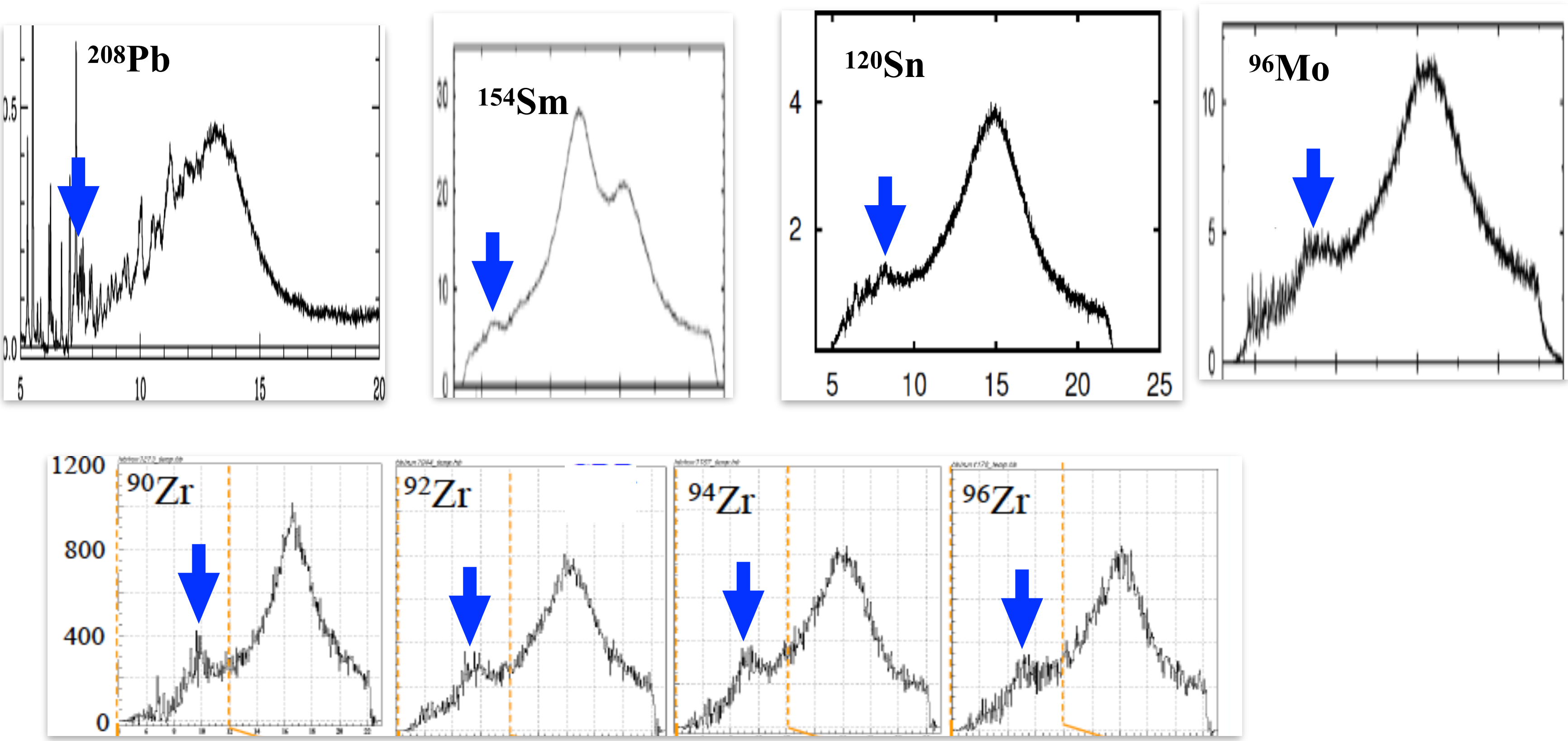
(p,p') E1 fluctuation analysis
+ conversation to total (theo.)

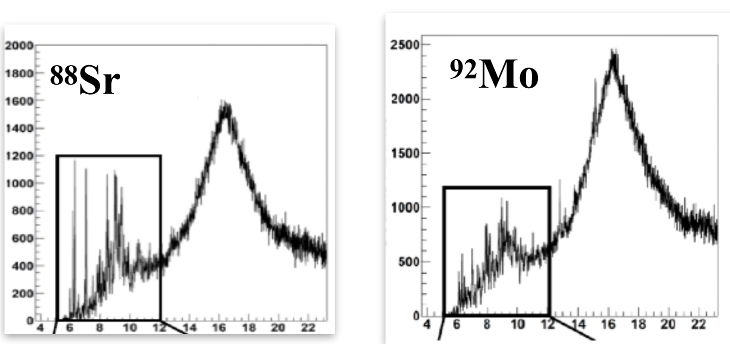
準位密度の定量的記述

Pygmy Dipole Resonance



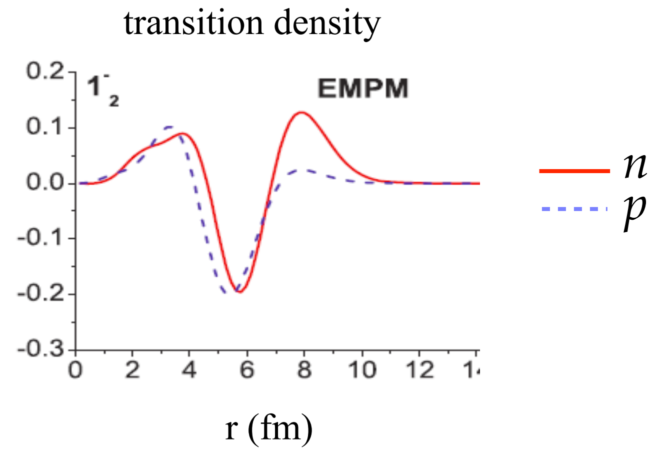
Universal Existence of PDR in Nuclei with A > ~90 ?





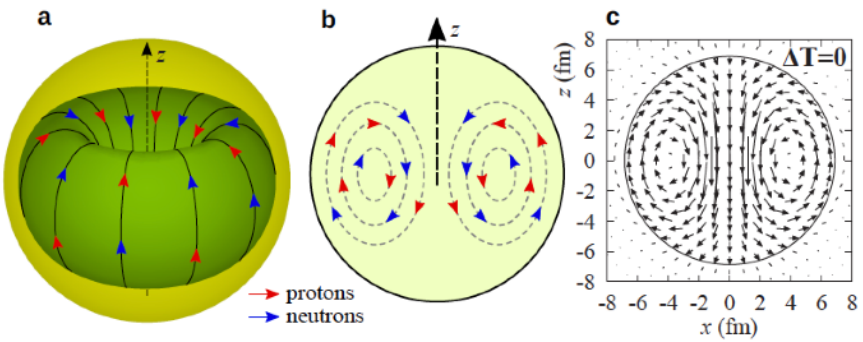
There must be a common reason of the existence.

Pygmy Dipole Resonance (PDR)



How is the relation to the IS-E1 mode?

How is the relation to the E1 toroidal mode?



(e,e') transverse excitation?

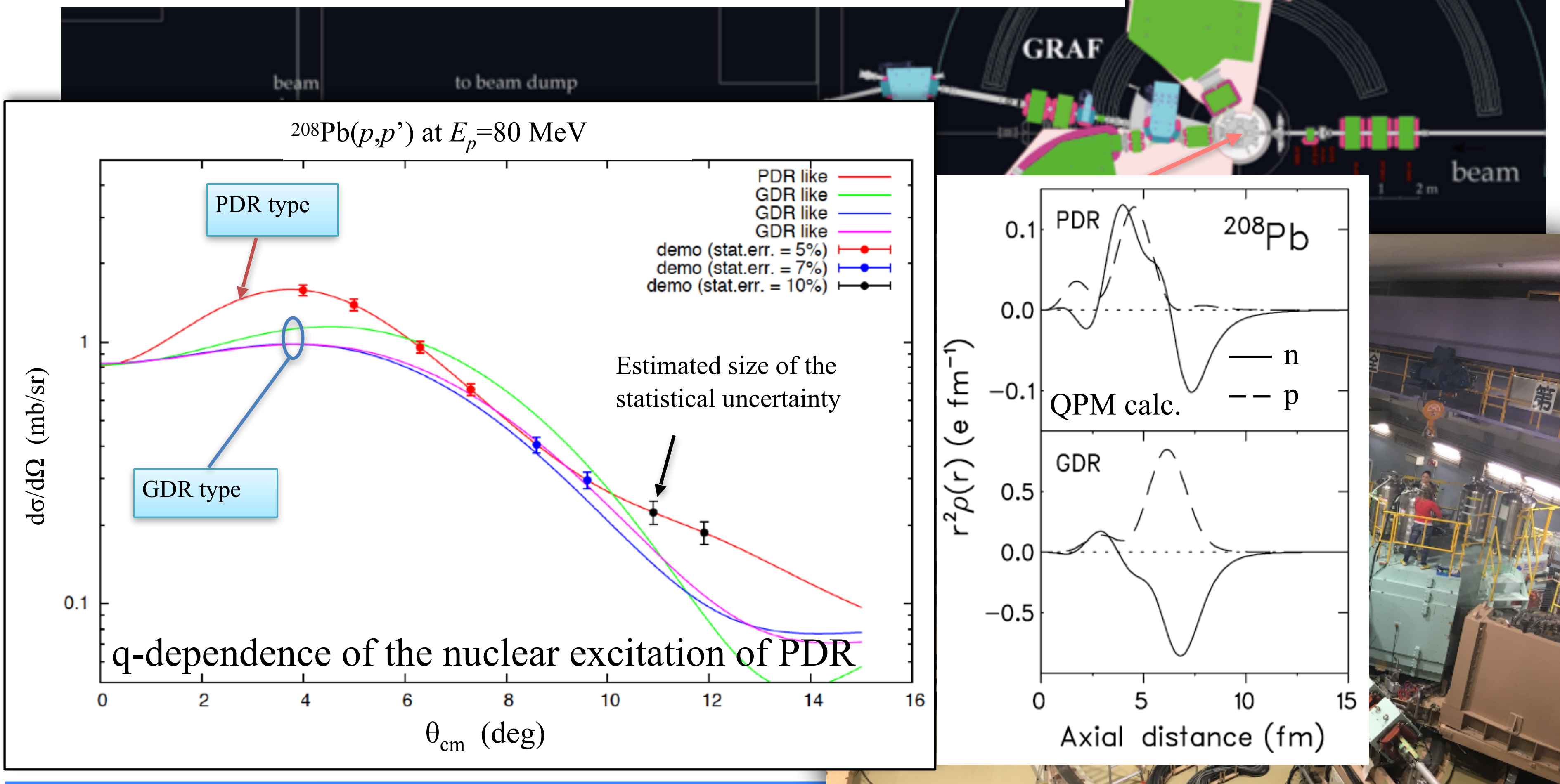
What is the signature of PDR?

PDRの実験的証拠は何か?

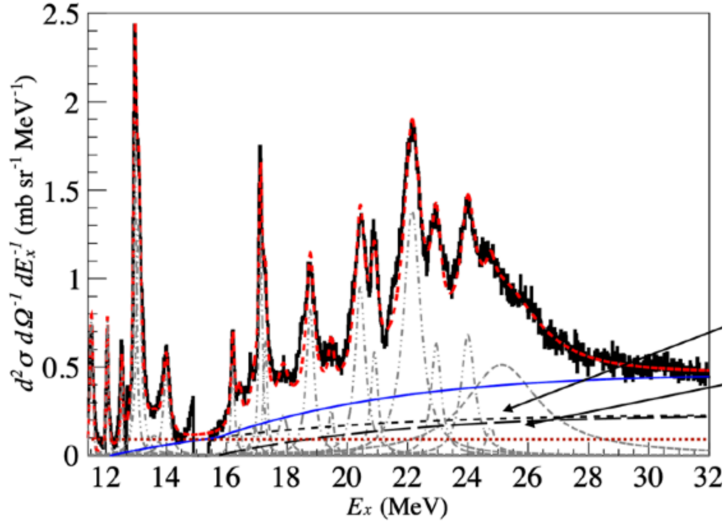
(p,pγ) in CAGRA+GR Campaign

Structure of the PDR *1

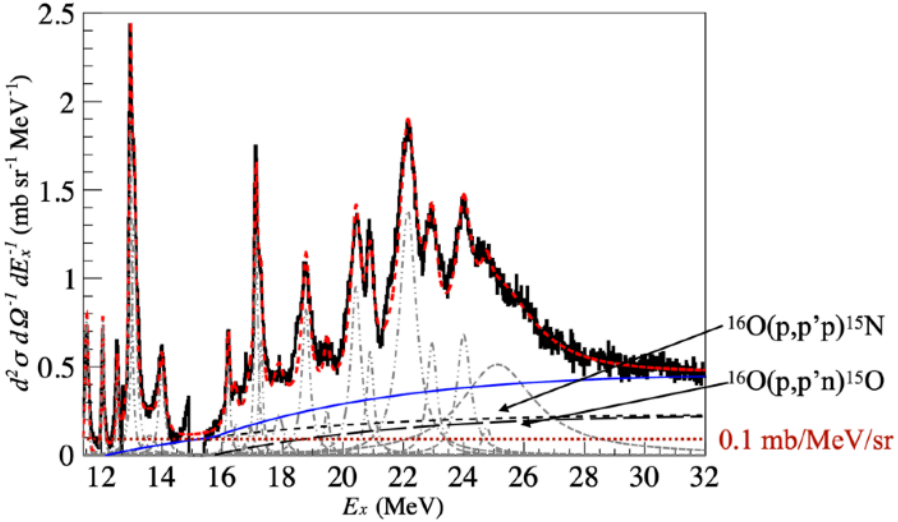
A. Bracco, F. Crespi, V. Derya, M.N. Harakeh, T. Hashimoto, C. Iwamoto,
P. von Neumann-Cosel, N. Pietralla, D. Savran, A. Tamii, V. Werner, and A. Zilges *et al.*



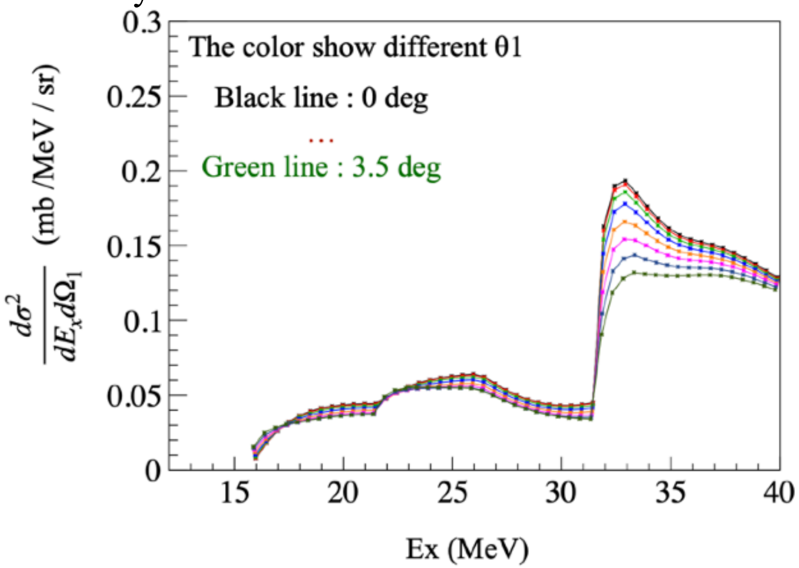
Quasi-free Scattering at 0-deg



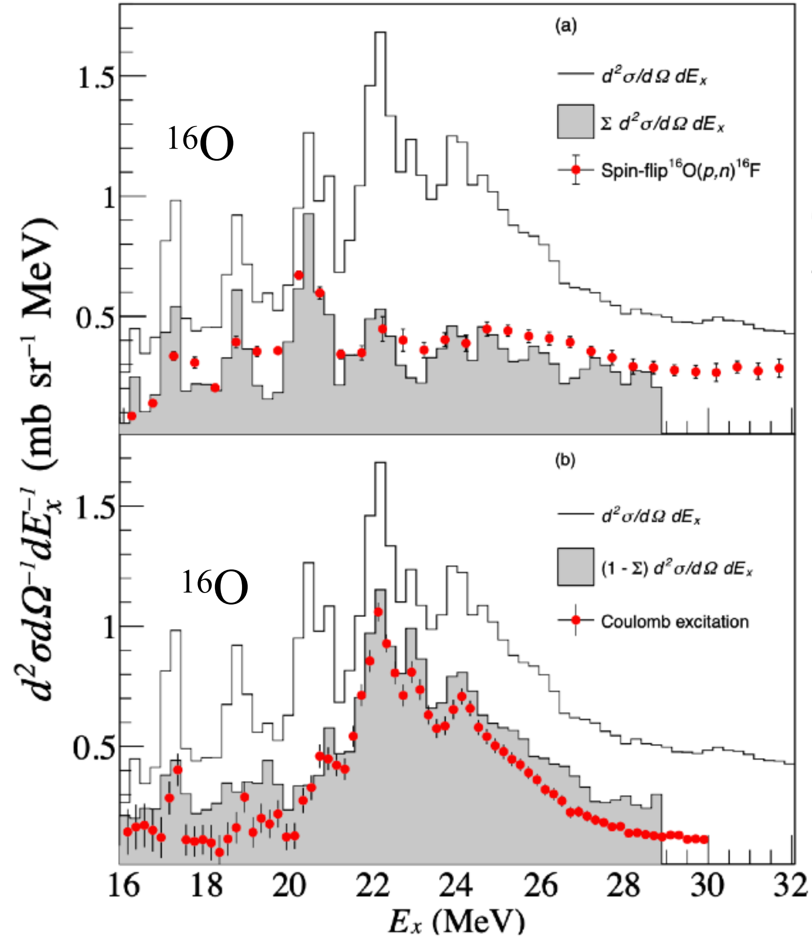
Quasi-free scattering c.s. at 0-deg



Preliminary



using q.-f. c.s. by Ogata



0度準弾性散乱の定量的記述

Sudo et al.,

spin-flip-probability taken from Kawabata et al.,

description of d-like correlation in nuclei would be important for describing quasi-free scattering c.s. at 0-deg?

Summary

RCNP Grand Raidenでの陽子散乱を使ったこれまでの実験から、
理解したいことをピックアップしてお話しました。

- d-like 相関の定量的記述
- 軽核の光核反応の記述: 光吸収+崩壊計算
- quasi-deuteron excitationの理解
- (IS/IV spin-M1)クエンチング機構の理解
- 基底状態の*np*-spin相関の理解
- 核物質のスピン磁化率の理解
- 巨大共鳴の崩壊の記述
- GDRの微細構造の起源と理解
- 準位密度の定量的・現象論的でない記述
- PDR機構の実験的証拠は何か?
- 0度準弾性散乱の定量的記述

Thank you for your attention!