Nuclear Excited Studied by proton scattering With a High-Resolution Magnetic Spectrometer

Atsushi Tamii (RCNP)

TU Darmstadt Topical Lecture Week

April 15 - 19, 2024

Nuclear Excited Studied by proton scattering With a High-Resolution Magnetic Spectrometer

Lecture I

Nuclear Excited States,
Giant Resonances
(overview)

Self Introduction

Atsushi Tamii

Research Center for Nuclear Physics (RCNP), Osaka University

Concurrent positions at
- Institute for Radiation Sciences (IRS), Osaka University
- Department of Physics, School of Science, Osaka University

Research Topics:

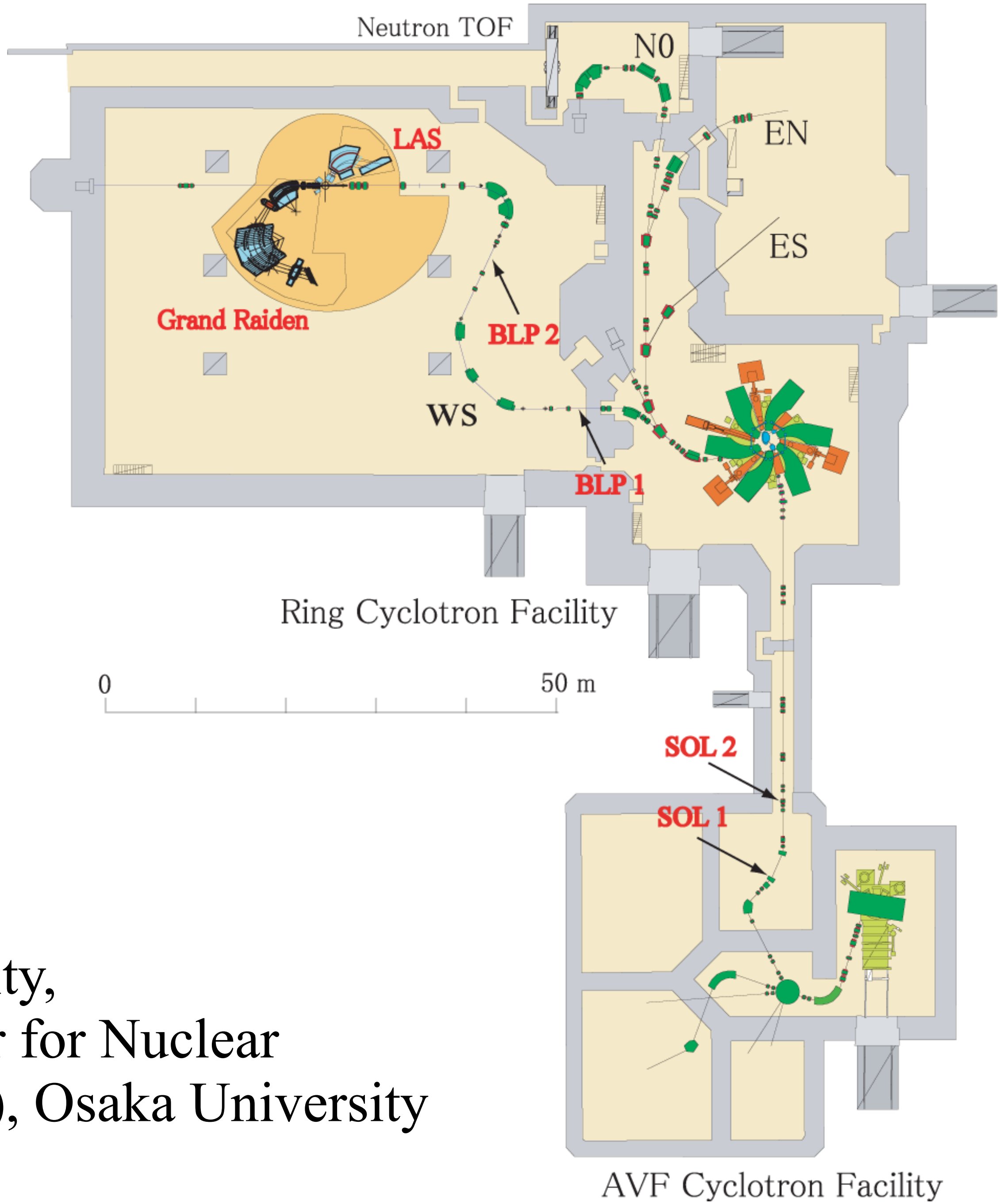
- Study of nuclear excited states and giant resonances by using spectrometer Grand Raiden (GR) at RCNP
- Electric dipole (E1) response of nuclei by proton scattering
- PANDORA project: photo-nuclear reaction of light nuclei
- Nuclear astrophysics
- Detection of gamma-radiation from laser plasma

high-resolution

zero-degree

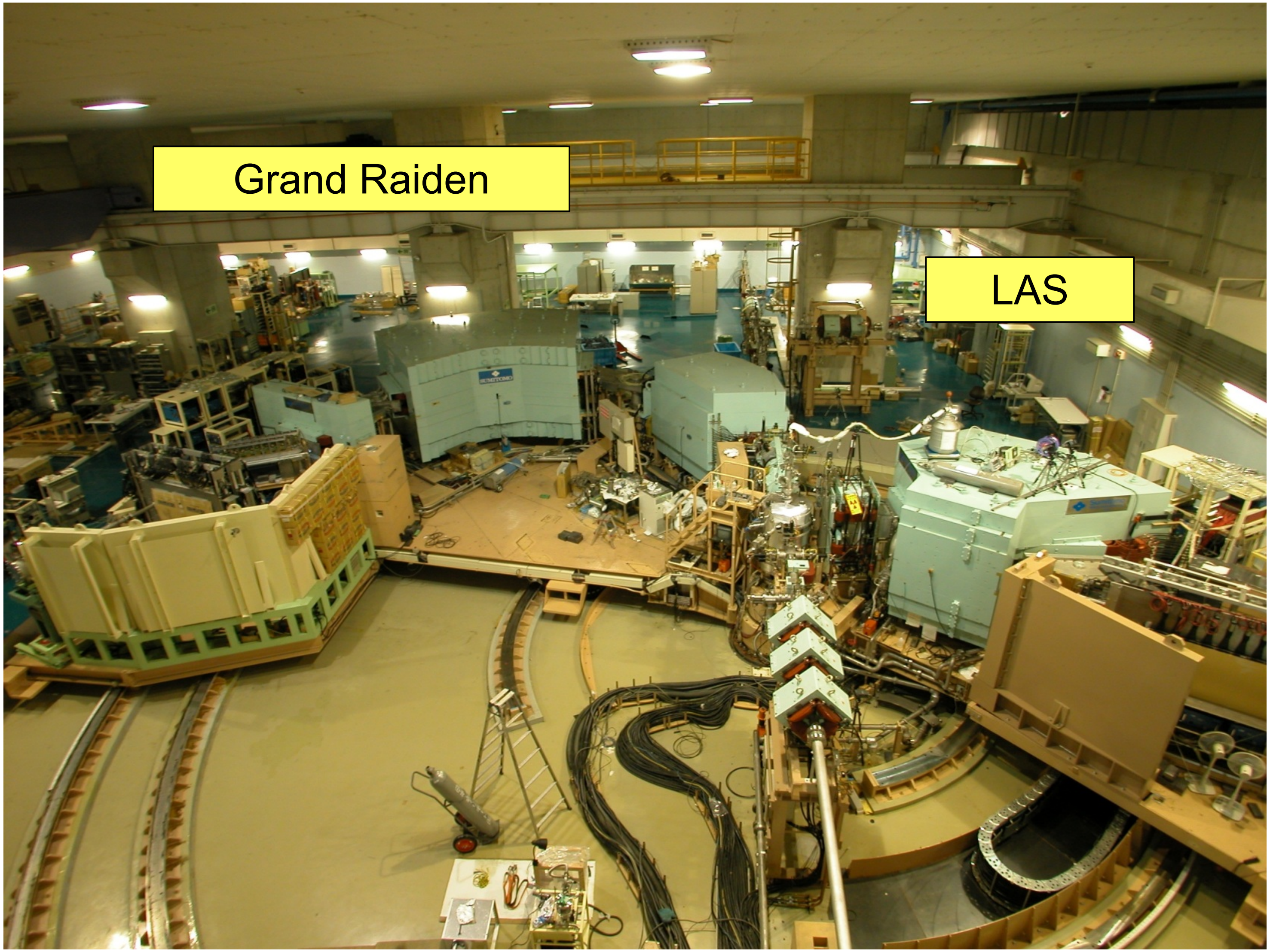
$E1$

Giant Resonances



Cyclotron Facility,
Research Center for Nuclear
Physics (RCNP), Osaka University

High-Resolution Spectrometer Grand Raiden and Large Acceptance Spectrometer



Outline of the Lectures

Monday, April 15
09:00 - 09:30 Introduction
09:30 - 10:30 Lecture 1: *Nuclear Excited States, Giant Resonances (overview)*
10:30 - 11:00 Coffee break
11:00 - 12:30 Lecture 2: *Experiments Using High-Resolution Spectrometer Grand Raiden*
12:30 - 12:45 Group picture
12:45 - 14:00 Lunch

Tuesday, April 16
09:00 - 10:30 Lecture 3: *Electric Response of Nuclei, Sum Rules*
10:30 - 11:00 Coffee break
11:00 - 12:30 Exercise 1: *Spectrometer Data Analysis, Startup, 1D/2D Histograms, Gate*
12:30 - 14:00 Lunch

18:30 Social Dinner

Wednesday, April 17
09:00 - 10:30 Lecture 4: *Nuclear Equation of State, Neutron Stars*
10:30 - 11:00 Coffee break
11:00 - 12:30 Exercise 2: *Calibrations, Excitation Energy, Cross Section*
12:30 - 14:00 Lunch

Thursday, April 18
09:00 - 10:30 Lecture 5: *Photo Reaction of Ultra-High-Energy Cosmic Rays*
10:30 - 11:00 Coffee break
11:00 - 12:30 Exercise 3: *Coincidence Analysis, Efficiency, Branching Ratio*
12:30 - 14:00 Lunch

Friday, April 19
09:00 - 10:30 Lecture 6: *Spin-Magnetic Response of Nuclei, n-p Correlation*
10:30 - 11:00 Coffee break
11:00 - 12:30 Lecture 7: *Fine Structure, Supplements, Summary*
12:30 - 14:00 Lunch

Shared Documents

Google shared drive

https://drive.google.com/drive/u/0/folders/12z-yvWinvoShI8A7Ql6j1KiLoZoYrEc4

google search: rcnp tamii

—> https://www.rcnp.osaka-u.ac.jp/~tamii/

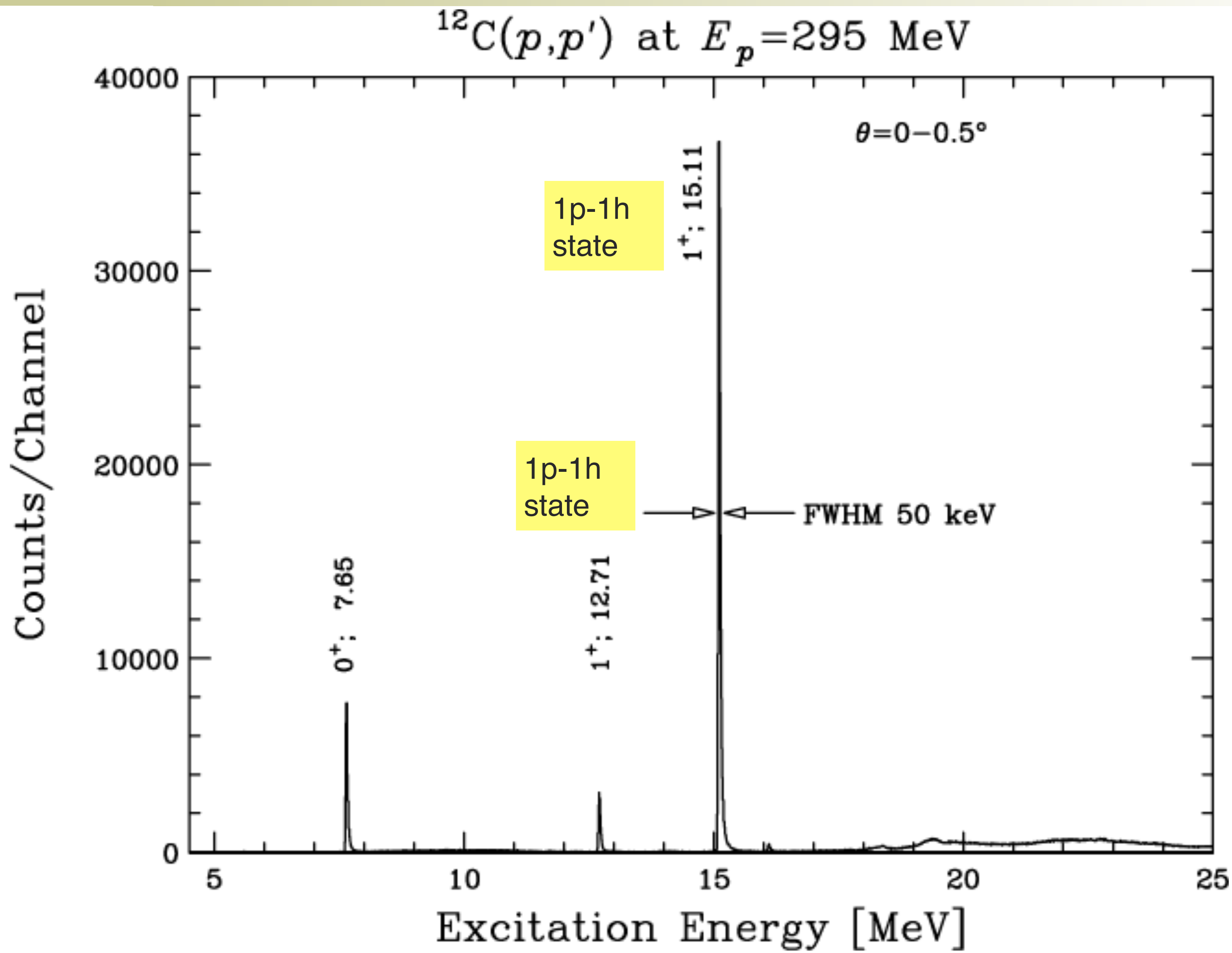
The link to the above google share drive is placed at the top of the page.

menti
free questions to Lecture I

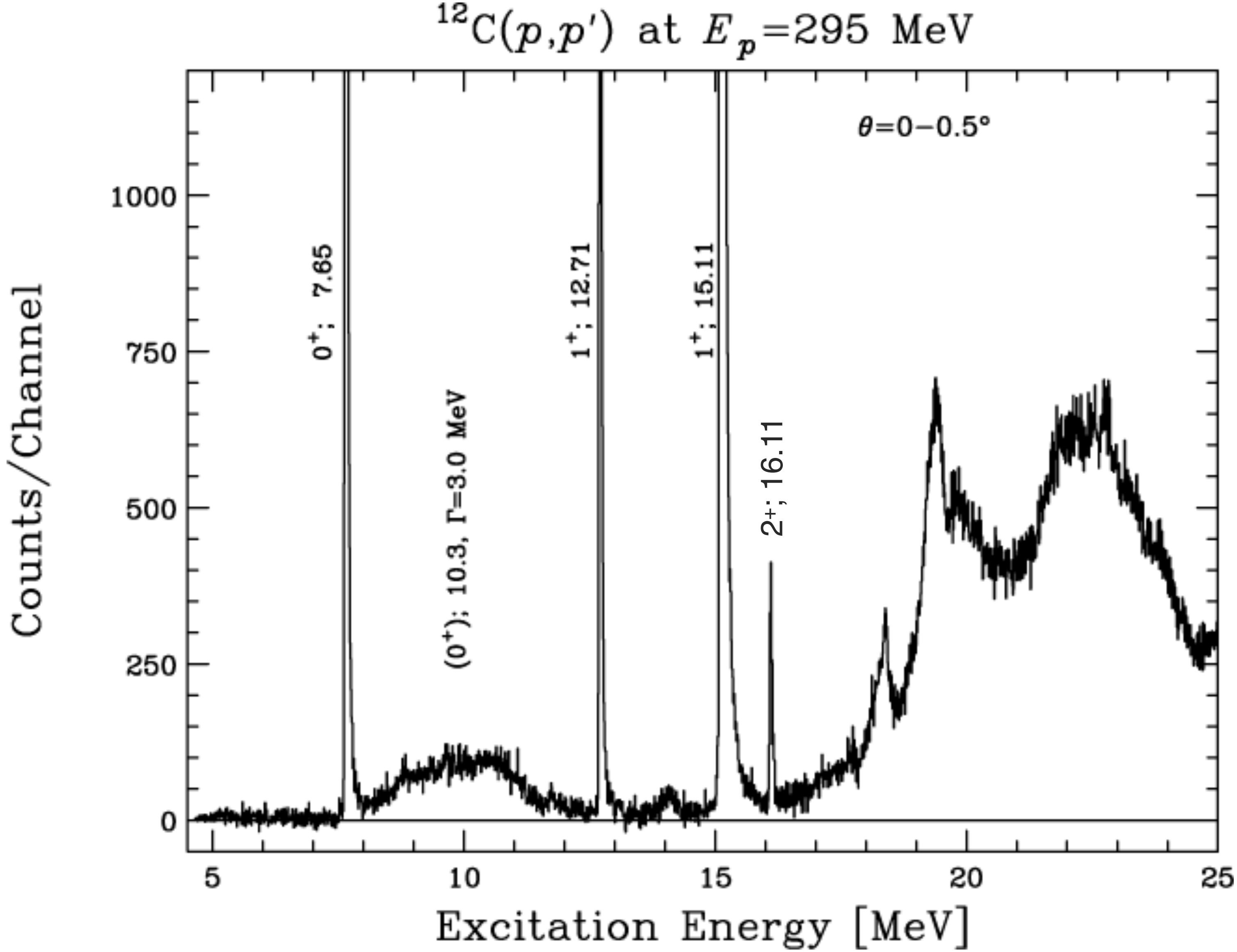
2606 1227 at https://menti.com

https://www.menti.com/altmxythmajj

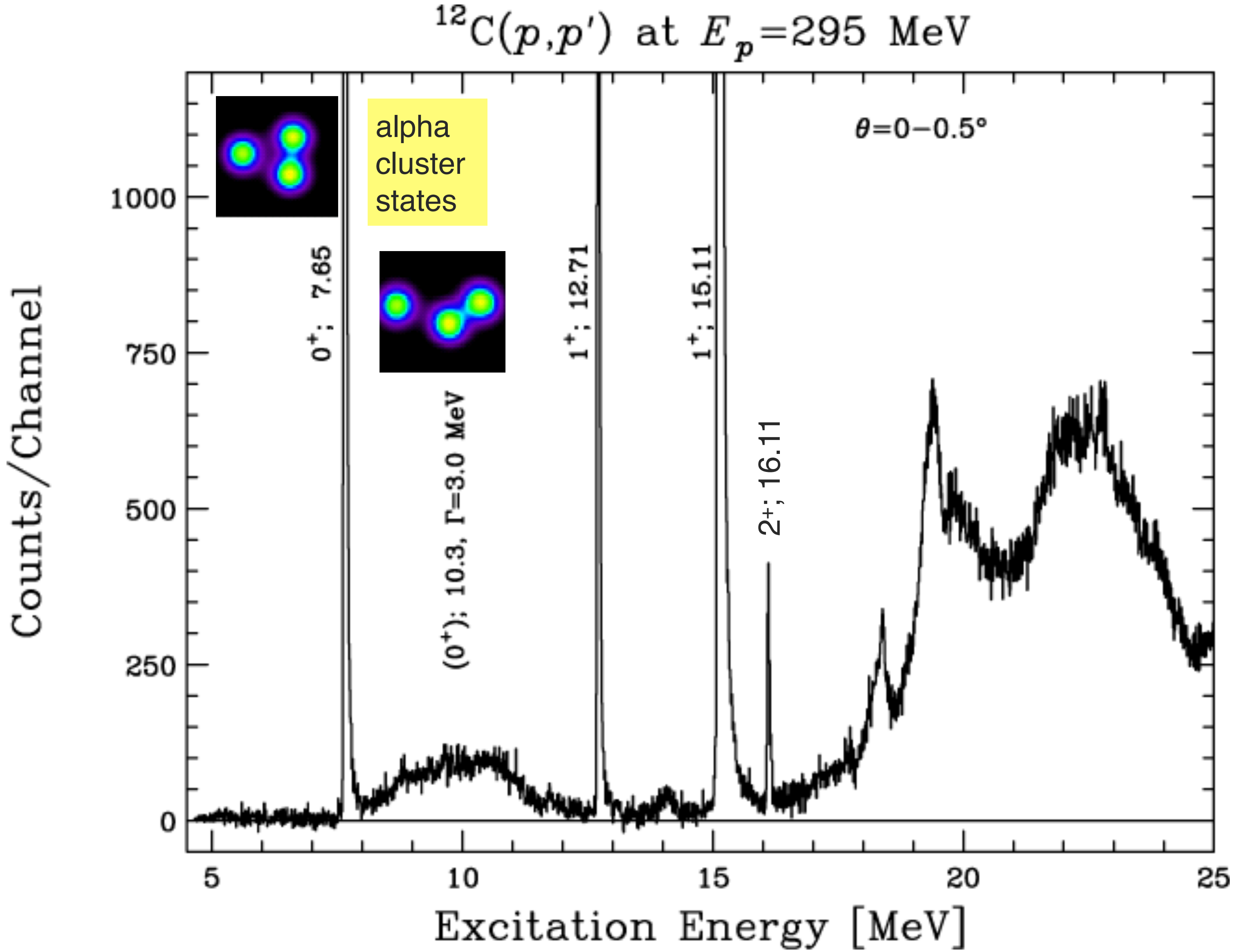
^{12}C Excitation Energy Spectrum



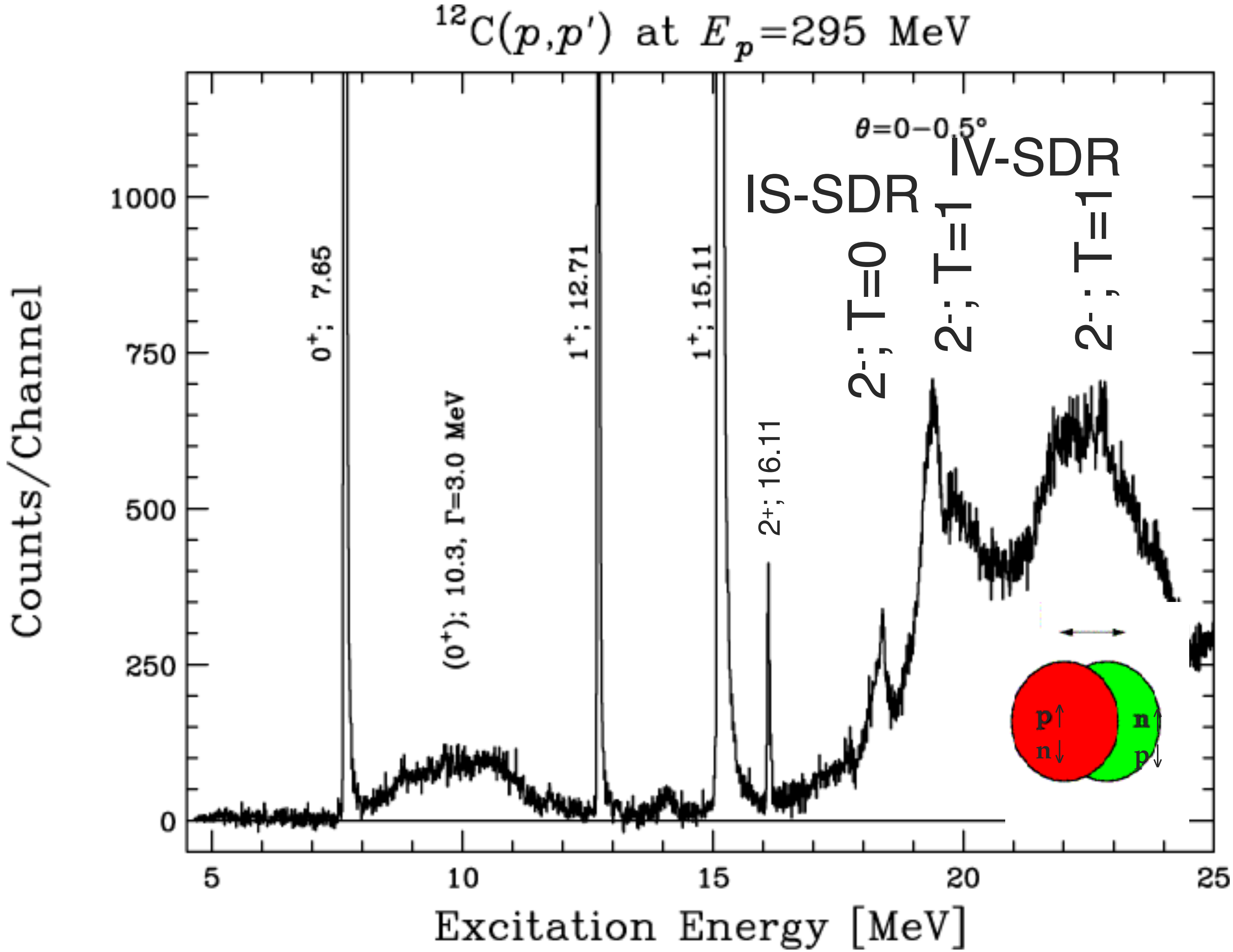
^{12}C Excitation Energy Spectrum



^{12}C Excitation Energy Spectrum



^{12}C Excitation Energy Spectrum



Theoretical Models of Nuclei

Few-Body ab initial calculations

Faddeev, Gaussian Expansion Ab-initio Green Function Monte-Carlo, …

Mean-Field Models

Shell Model

Self-Consistent Mean Field Models

Hartree-Fock, Hartree-Fock-Bogoliubov, Random Phase Approximation
2nd RPA, Quasi-particle RPM

Anti-symmetryized Molecular Dynamics (AMD)

Alpha-Cluster Model

Liquid Drop Model, Fluid Model

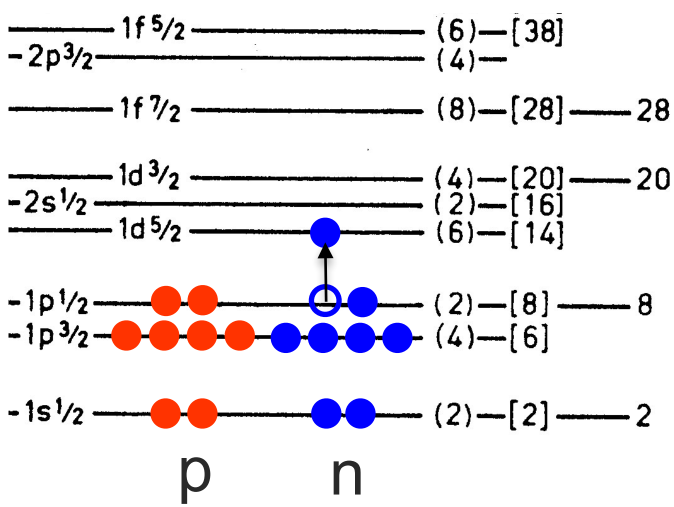
c.f. Lecture by Prof. K. Yoshida

Giant Resonances
(overview)

Nuclear Collective Excitations

Single Particle Excitations

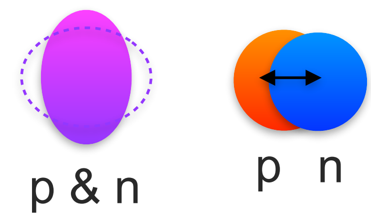
independent particle model



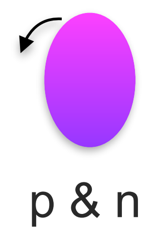
Collective Excitations

many nucleons contribute to an excited state

Vibrational Excitations
(giant resonances)



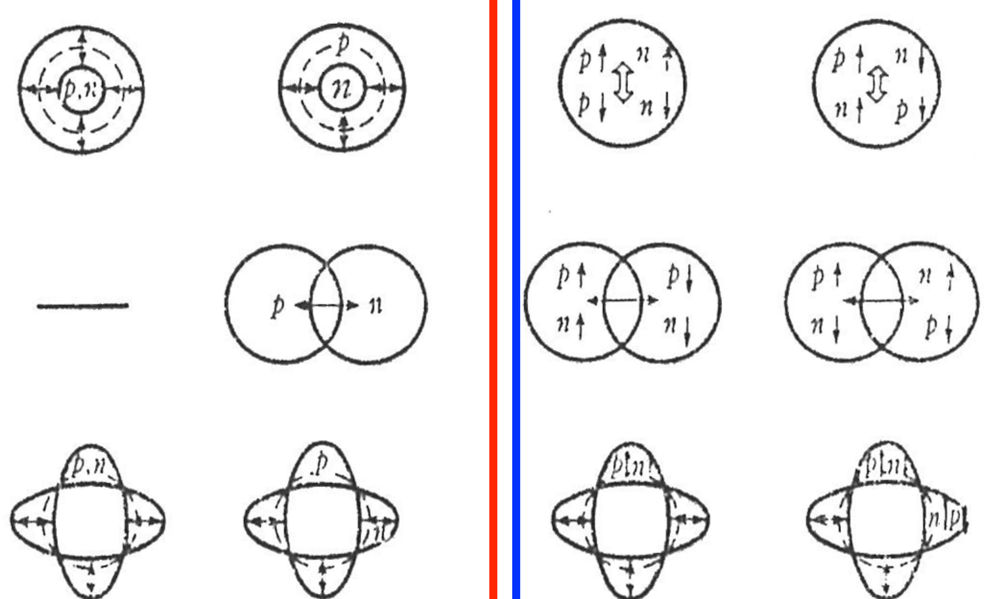
Rotational Excitations



Collective Vibrational Excitations

Electric $\Delta S = 0$ | Magnetic $\Delta S = 1$

		Isoscalar Electric	Isovector Electric	Isoscalar Magnetic	Isovector Magnetic
	$(\Delta T, \Delta S)$	(0, 0)	(1, 0)	(0, 1)	(1, 1)
Monopole	$\Delta L = 0$				
Dipole	$\Delta L = 1$				
Quadrupole	$\Delta L = 2$				
	$\cdots$				
Multipole					



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Collective Vibrational Excitations

Isoscalar $\Delta T = 0$ Isovector $\Delta T = 1$

		Isoscalar Electric	Isovector Electric	Isoscalar Magnetic	Isovector Magnetic
	$(\Delta T, \Delta S)$	(0, 0)	(1, 0)	(0, 1)	(1, 1)
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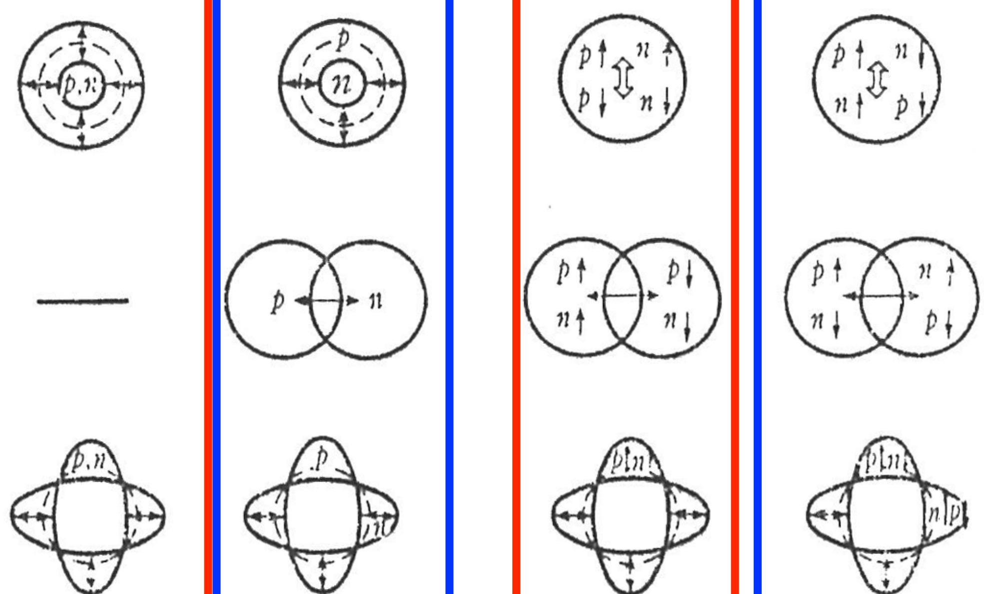
	$\cdots$				
Multipole					



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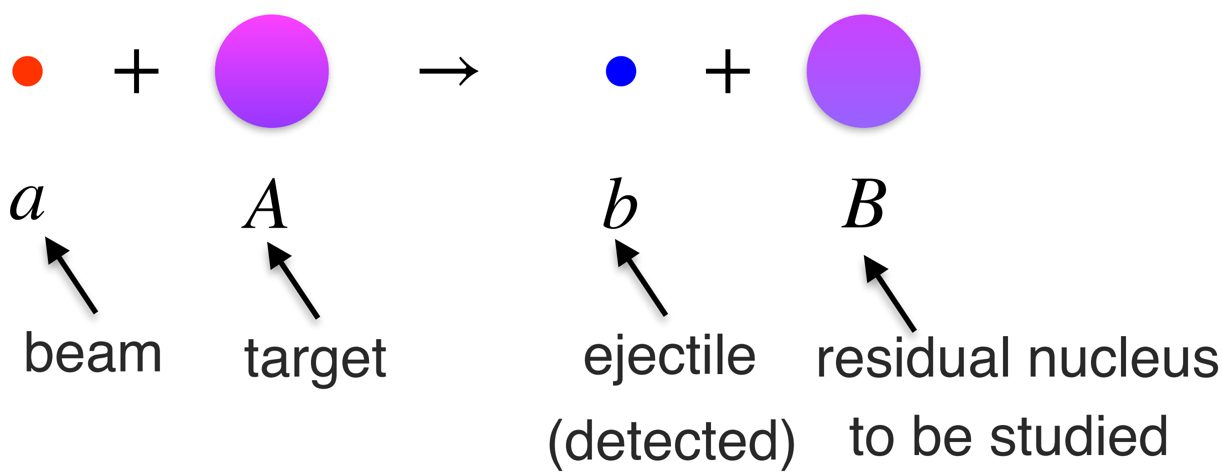
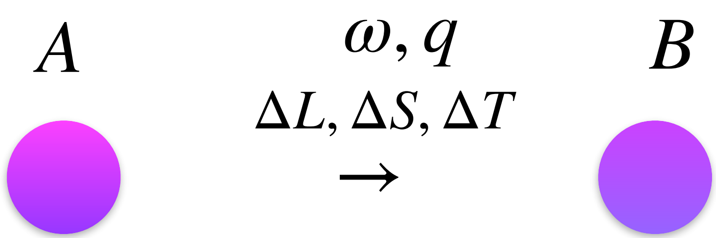
Light Ion Reactions and $\Delta S, \Delta T, \Delta L$

$A(a,b)B$





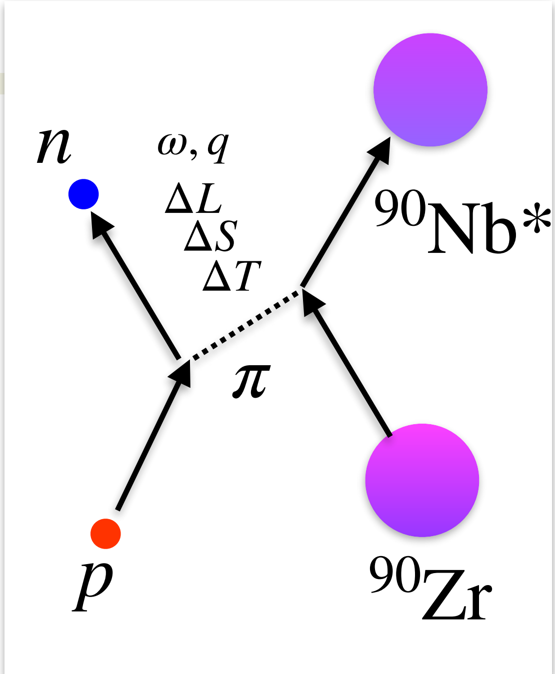
$\vec{T}_i$

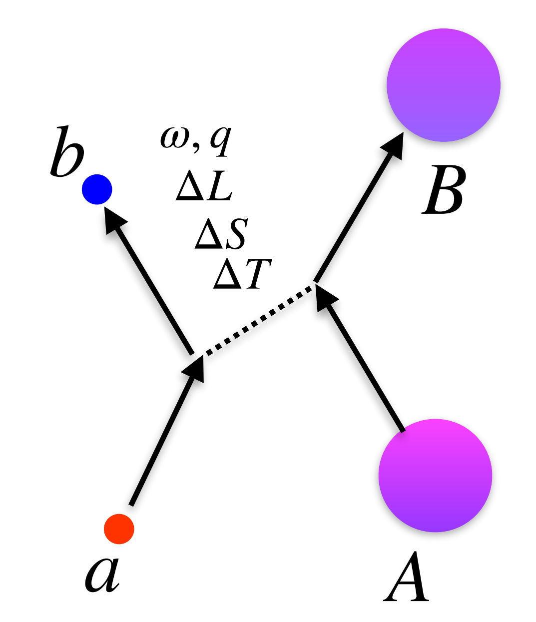
$\vec{J}_i$

$\vec{T}_f = \vec{T}_i + \Delta\vec{T}$

$\vec{J}_f = \vec{J}_i + \Delta\vec{J}$

$\Delta\vec{J} = \Delta\vec{L} + \Delta\vec{S}$





Spin and Isospin

spin

・A nucleon（proton and neutron）has a spin 1/2

Nucleon spin operator: $\mathbf{s} = \frac{\boldsymbol{\sigma}}{2}$ **σ**: Pauli matrices

s,**σ** are vectors having the x,y,z components.

$$\mathbf{s}^2|\uparrow\rangle = \frac{1}{2}\left(\frac{1}{2}+1\right)|\uparrow\rangle \qquad s_z|\uparrow\rangle = +\frac{1}{2}|\uparrow\rangle$$

↑: spin-up

$$\mathbf{s}^2|\downarrow\rangle = \frac{1}{2}\left(\frac{1}{2}+1\right)|\downarrow\rangle \qquad s_z|\downarrow\rangle = -\frac{1}{2}|\downarrow\rangle$$

↓: spin-down

isospin

・Nuclear interaction is the same for protons and neutrons（isospin independence）

The assumption is not completely correct but is very well full-filled.

A neutron and a proton are considered to be an identical particle but have a different 3rd component of isospin.

Nucleon isospin operator: $t = \frac{\boldsymbol{\tau}}{2}$ **τ**: Pauli matrices

t,**τ** are vectors having the x,y,z components.

τ has the same matrix expression as **σ** but operates in the isospin-space.

$$\mathbf{t}^2|n\rangle = \frac{1}{2}\left(\frac{1}{2}+1\right)|n\rangle \qquad t_z|n\rangle = +\frac{1}{2}|n\rangle$$

$$\mathbf{t}^2|p\rangle = \frac{1}{2}\left(\frac{1}{2}+1\right)|p\rangle \qquad t_z|p\rangle = -\frac{1}{2}|p\rangle$$

The sign definition is of the field of nuclear physics, that is opposite in the filed of particle physics (I and I_z)

The Collective Response of the Nucleus: Giant Resonances

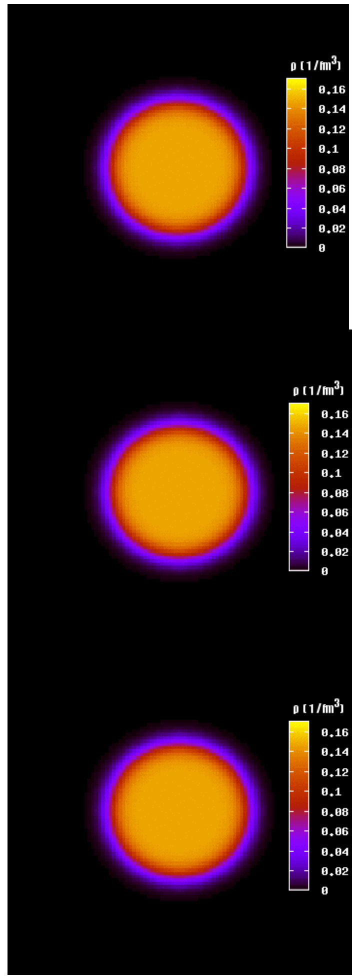
Isoscalar (In phase)
ΔT = 0

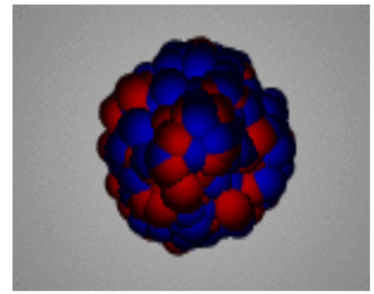
Isovector (Out of phase)
ΔT = 1

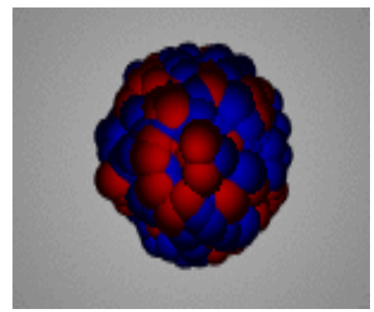
Monopole
ΔL = 0
(GMR)

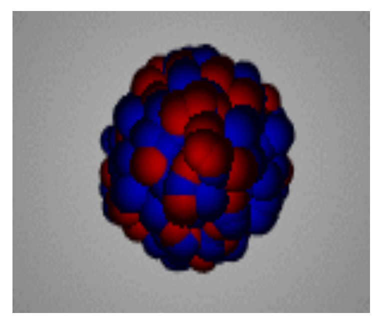
Dipole
ΔL = 1
(GDR)

Quadrupole
ΔL = 2
(GQR)







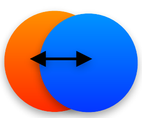


M. Itoh

Hitting a nucleus to oscillate: Operator

Wooden Hammers

Metalic Hammers



p n

a hammer = an operator

"probe"

A bell has its characteristic sounds depending on its structure.

The sound also depends on the used hammer.

A nucleus has its characteristic sound (collective vibrations).
The sound depends on the hammer (operator).

Courtesy of Y. Fujita

Operators

Operators to cause transitions for the ground state to a giant resonance

$$|\Psi_{\mathrm{GR}}^{\Delta L,\Delta S,\Delta T}> = O^{\Delta L,\Delta S,\Delta T}|\Psi_{\mathrm{g.s.}}>$$

Y: Spherical Harmonics

mathematical expansion of a “shape” into multi-poles

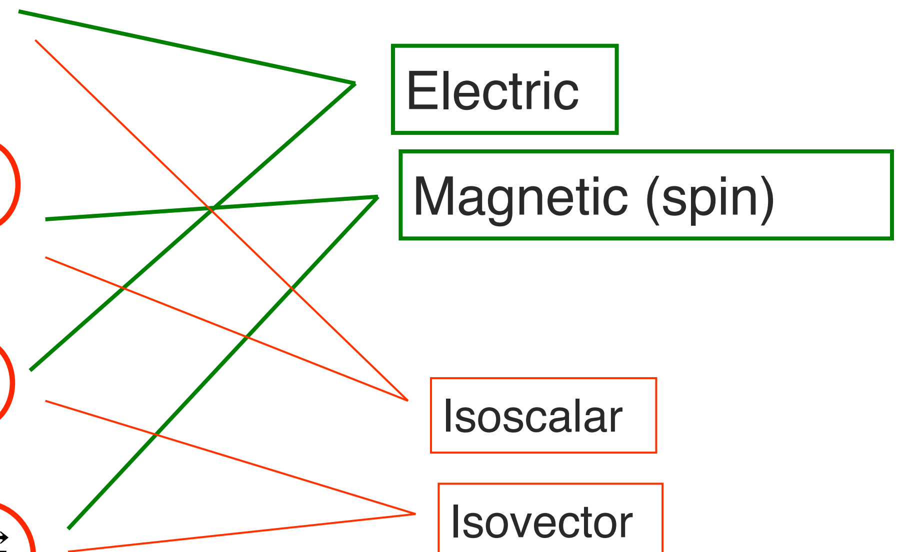
i spans nucleons

$$O^{\Delta L,\Delta S=0,\Delta T=0} = \sum_{i=1}^{A} r_i^{\Delta L} Y_{\Delta L}(\hat{r}_i)$$

$$O^{\Delta L,\Delta S=1,\Delta T=0} = \sum_{i=1}^{A} r_i^{\Delta L} Y_{\Delta L}(\hat{r}_i)\vec{\sigma}_i$$

$$O^{\Delta L,\Delta S=0,\Delta T=1} = \sum_{i=1}^{A} r_i^{\Delta L} Y_{\Delta L}(\hat{r}_i)\vec{\tau}_i$$

$$O^{\Delta L,\Delta S=1,\Delta T=1} = \sum_{i=1}^{A} r_i^{\Delta L} Y_{\Delta L}(\hat{r}_i)\vec{\sigma}_i\vec{\tau}_i$$



Operators

Operators to cause transitions for the ground state to a giant resonance

$$|\Psi_{\mathrm{GR}}^{\Delta L,\Delta S,\Delta T}> = O^{\Delta L,\Delta S,\Delta T}|\Psi_{\mathrm{g.s.}}>$$

Giant resonance is not a single state

door-way state

transition matrix element for the *i* th excited state: $\left\langle \Psi_{\mathrm{g.s.}} \middle| O^{\Delta L,\Delta S,\Delta T} \middle| \Psi_i \right\rangle$

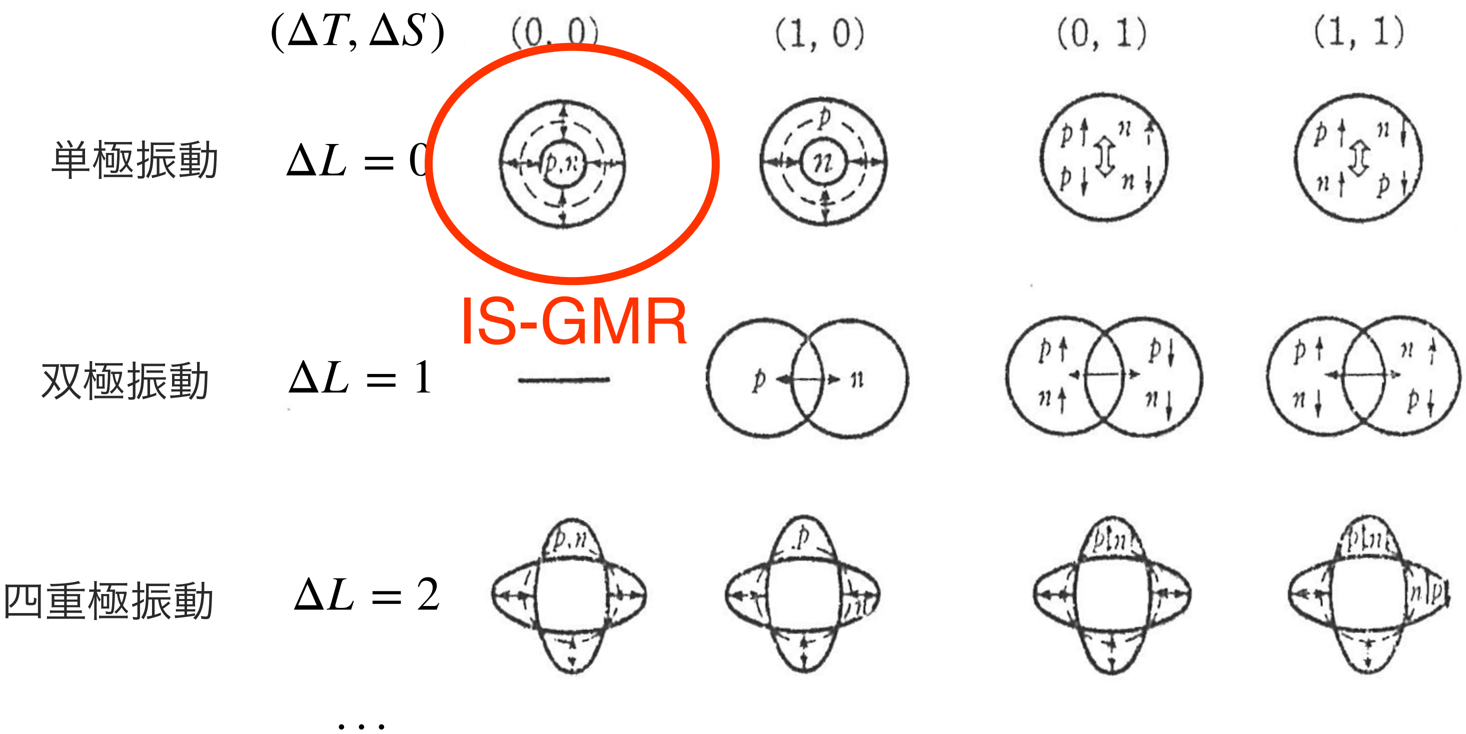
cross section of the *i* th excited state: $\propto \left| \left\langle \Psi_{\mathrm{g.s.}} \middle| O^{\Delta L,\Delta S,\Delta T} \middle| \Psi_i \right\rangle \right|^2$

Type of Giant Resonances

Giant Monopole Resonance (GMR)

$r^2 Y_0$

a higher harmonics



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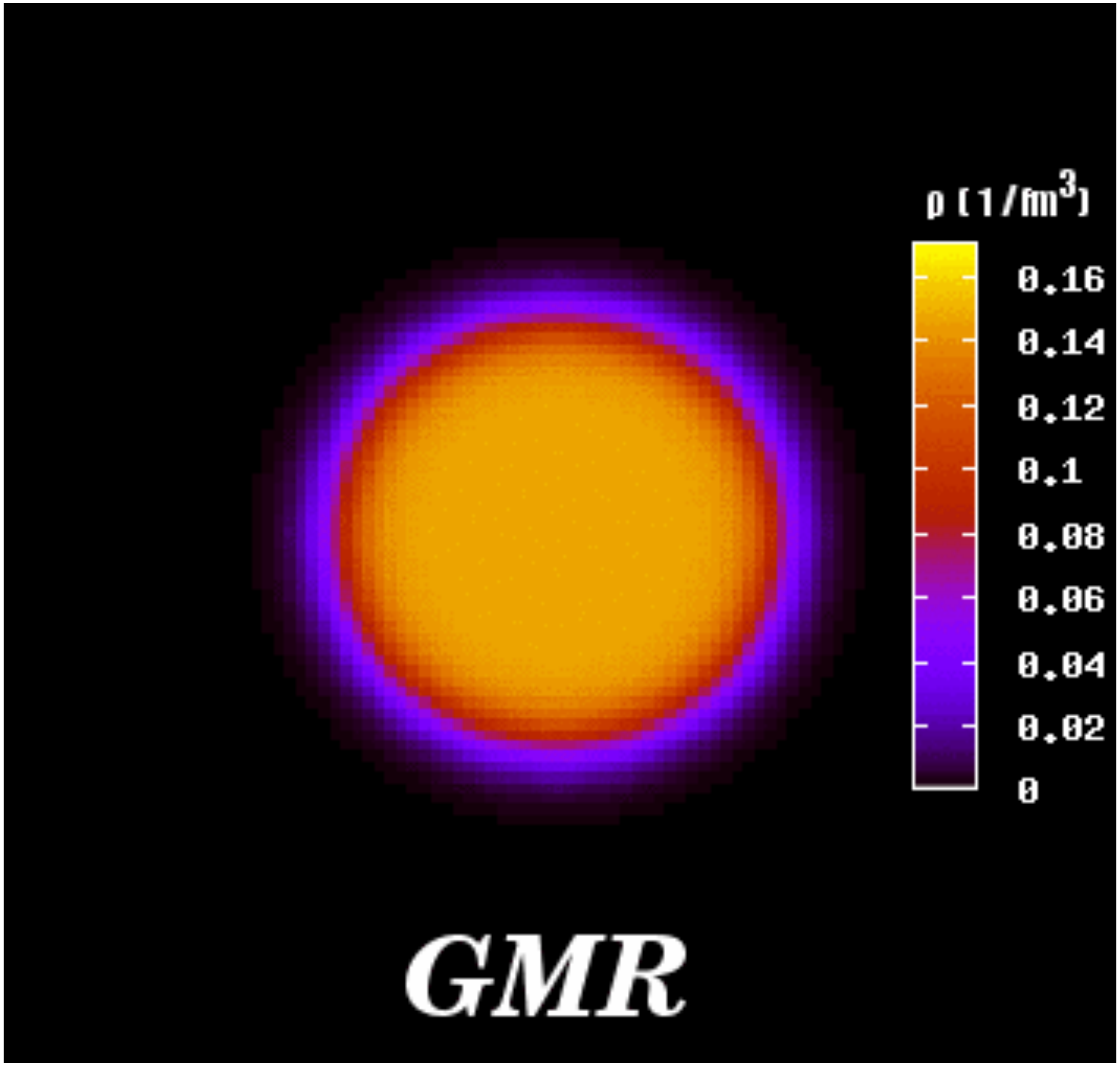
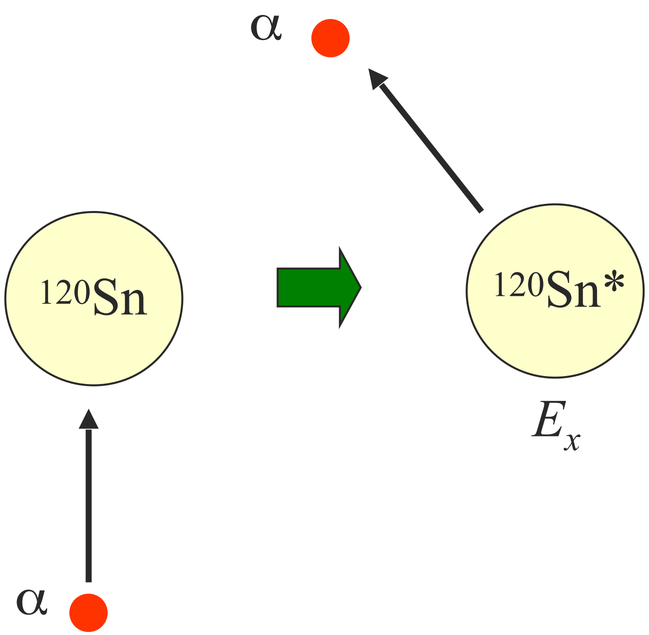
(Isoscalar) Giant Monopole Resonance (GMR)



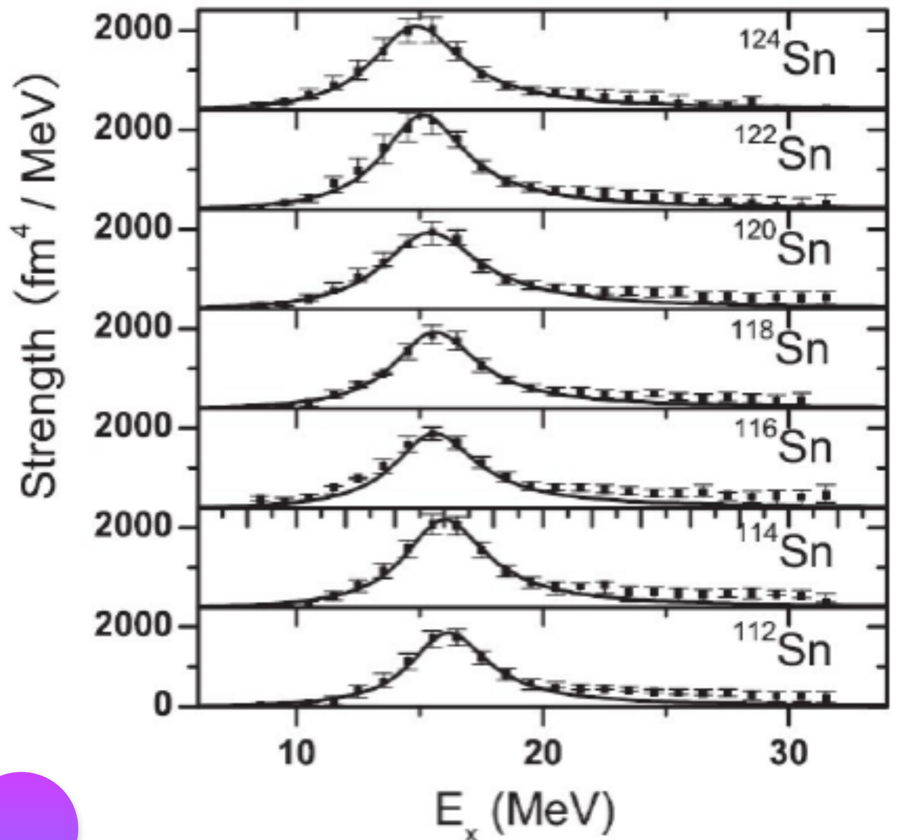
breathing mode

by M. Itoh

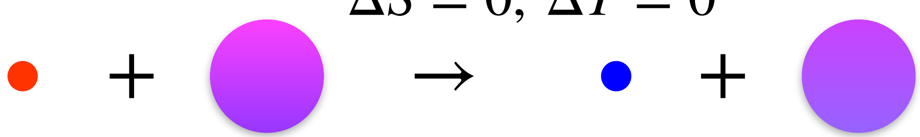
Type of Giant Resonances



T. Li et al., PRC99, 162503(2007)



$\Delta S = 0,\ \Delta T = 0$



$$\alpha + {}^{120}\mathrm{Sn} \rightarrow \alpha + {}^{120}\mathrm{Sn}^*$$

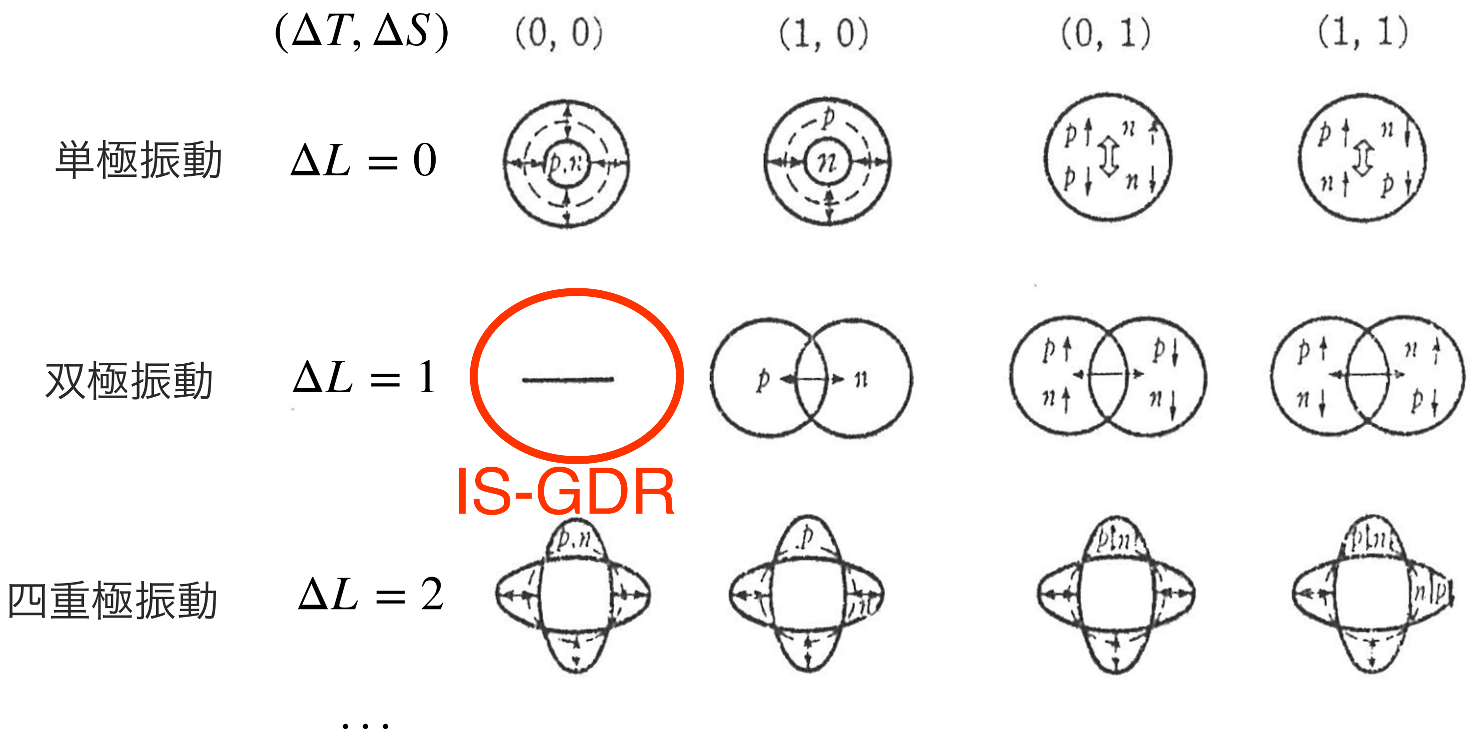
α	${}^{120}\mathrm{Sn}$	α	${}^{120}\mathrm{Sn}^*$
$T = 0$	$\vec{T}_i$	$T = 0$	$\vec{T}_f = \vec{T}_i$
spin 0	$\vec{J}_i$	spin 0	$\vec{J}_f = \vec{J}_i + \Delta \vec{L}$

Type of Giant Resonances

Isoscalar Giant Dipole Resonance (ISGDR)

$r^3 Y_1$

a higher harmonics



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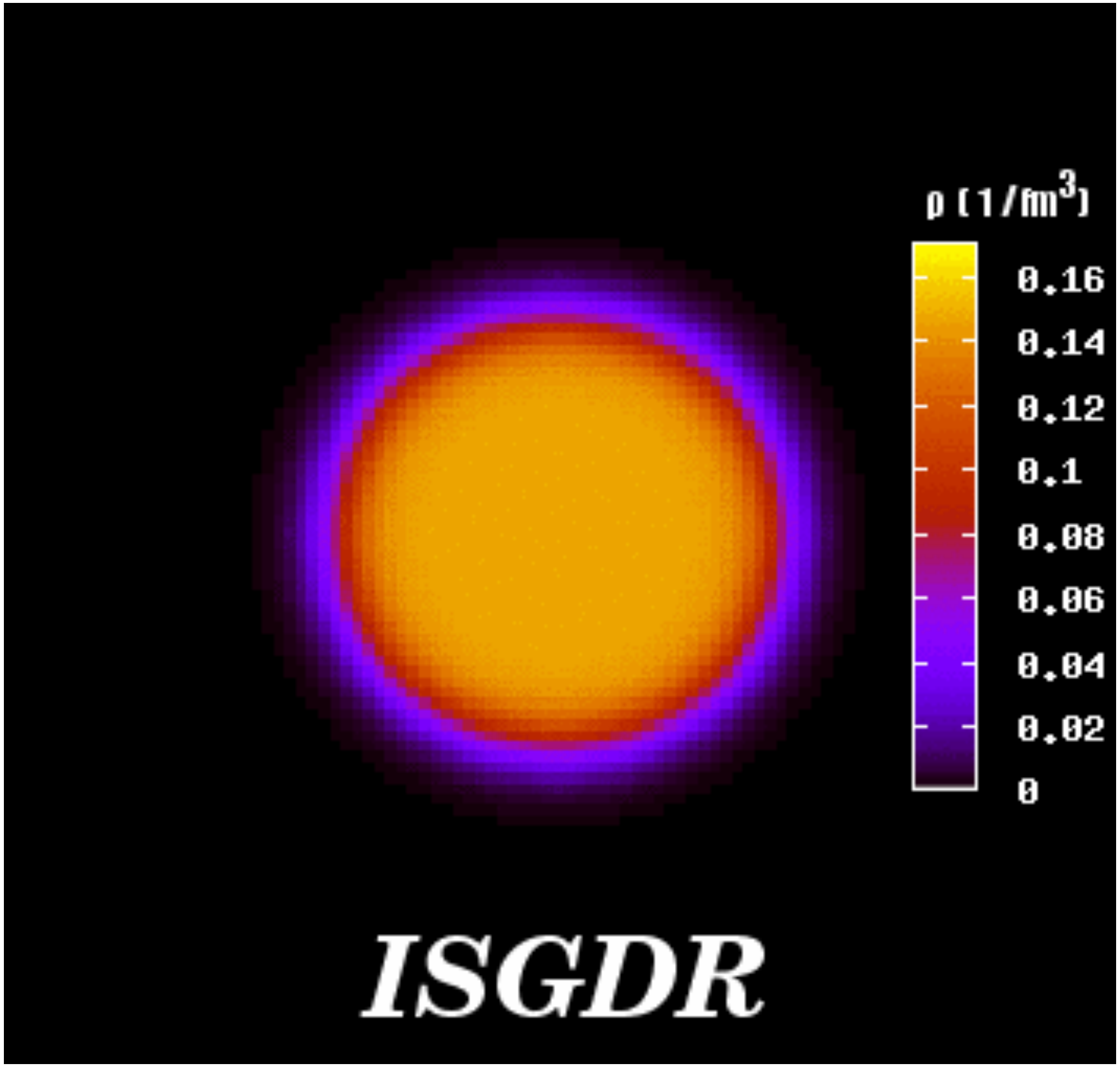
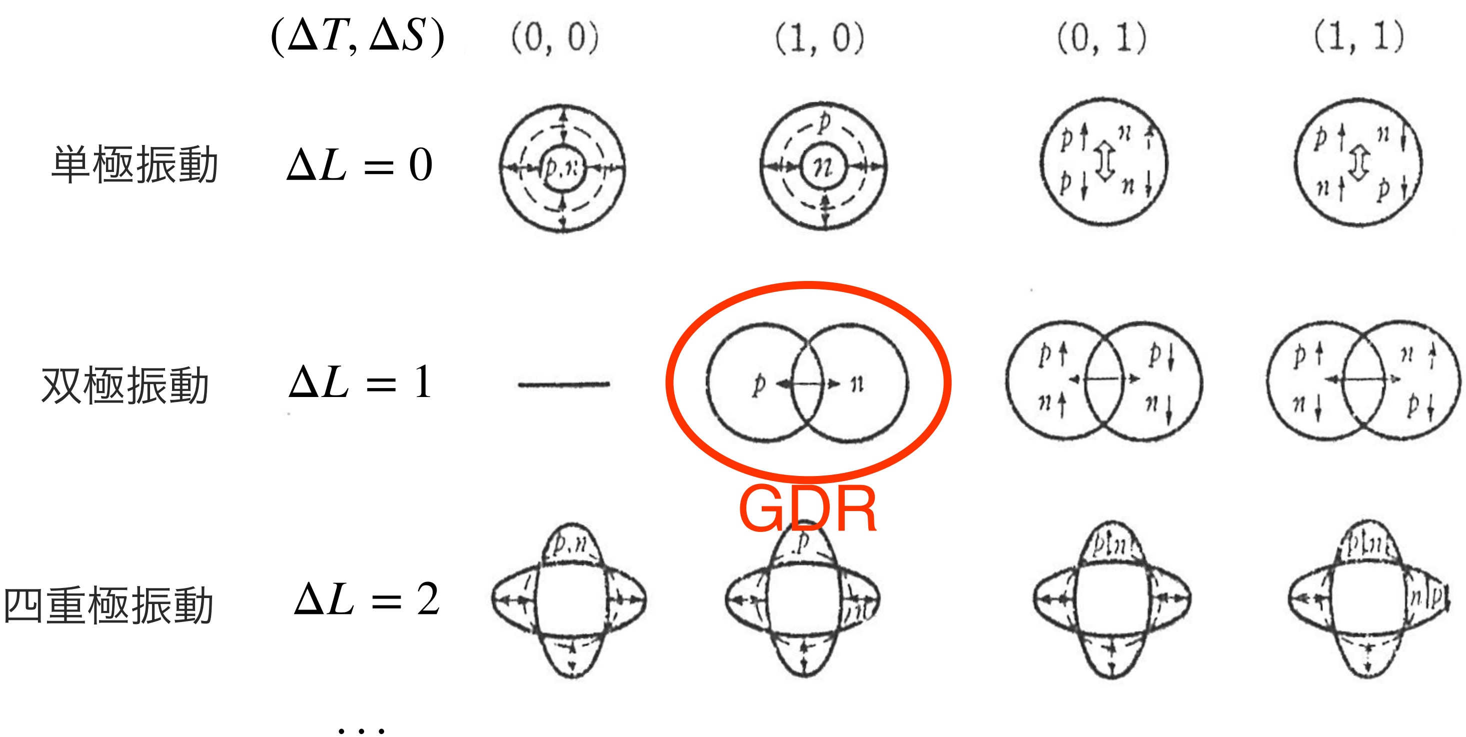
Isoscalar Giant Dipole Resonance (ISGDR)



by M. Itoh

Type of Giant Resonances

(Isovector) Giant Dipole Resonance (GDR) $rY_1\tau$



1944 prediction of GDR by A. Migdal
1947 experimental discovery of GDR

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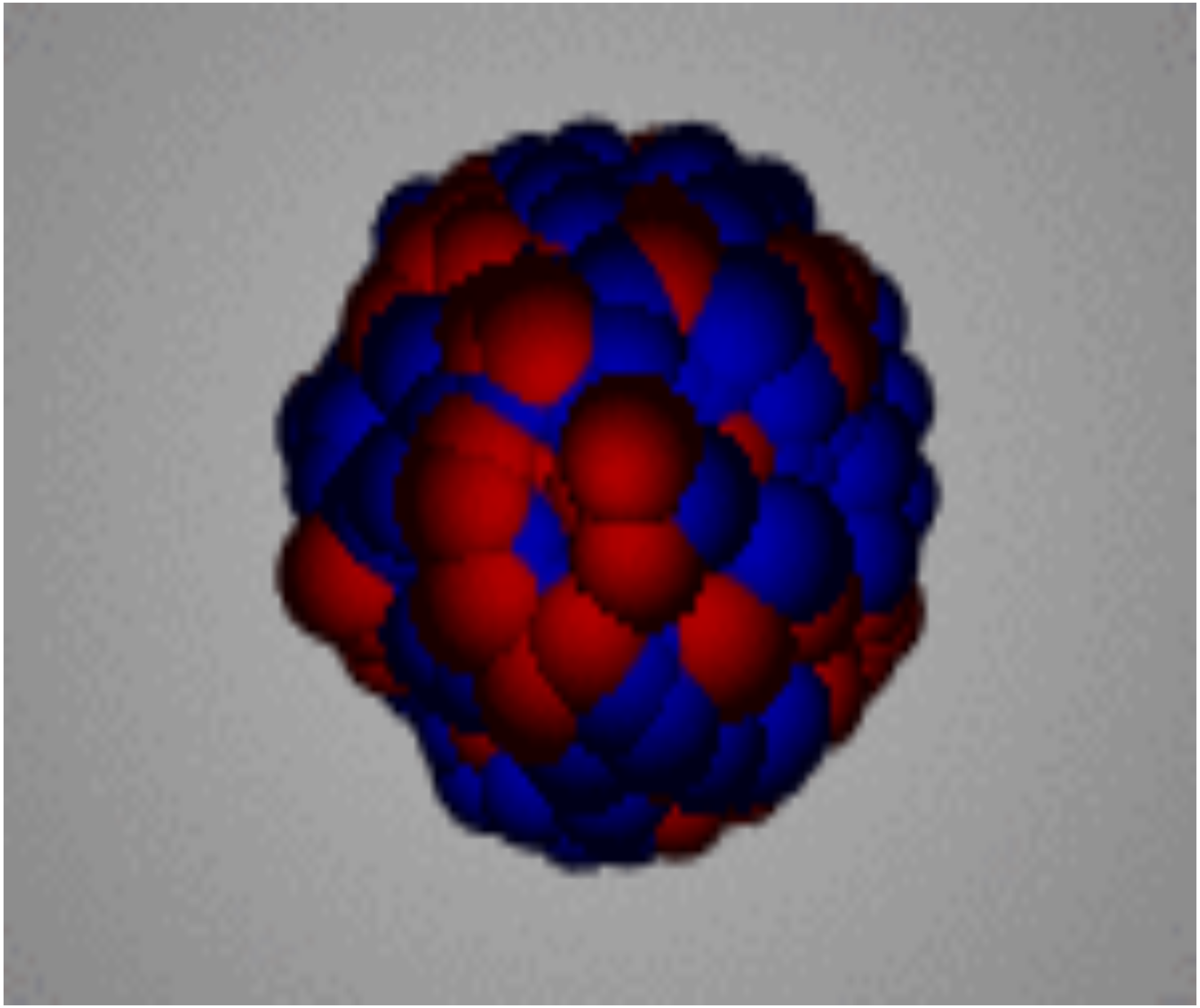
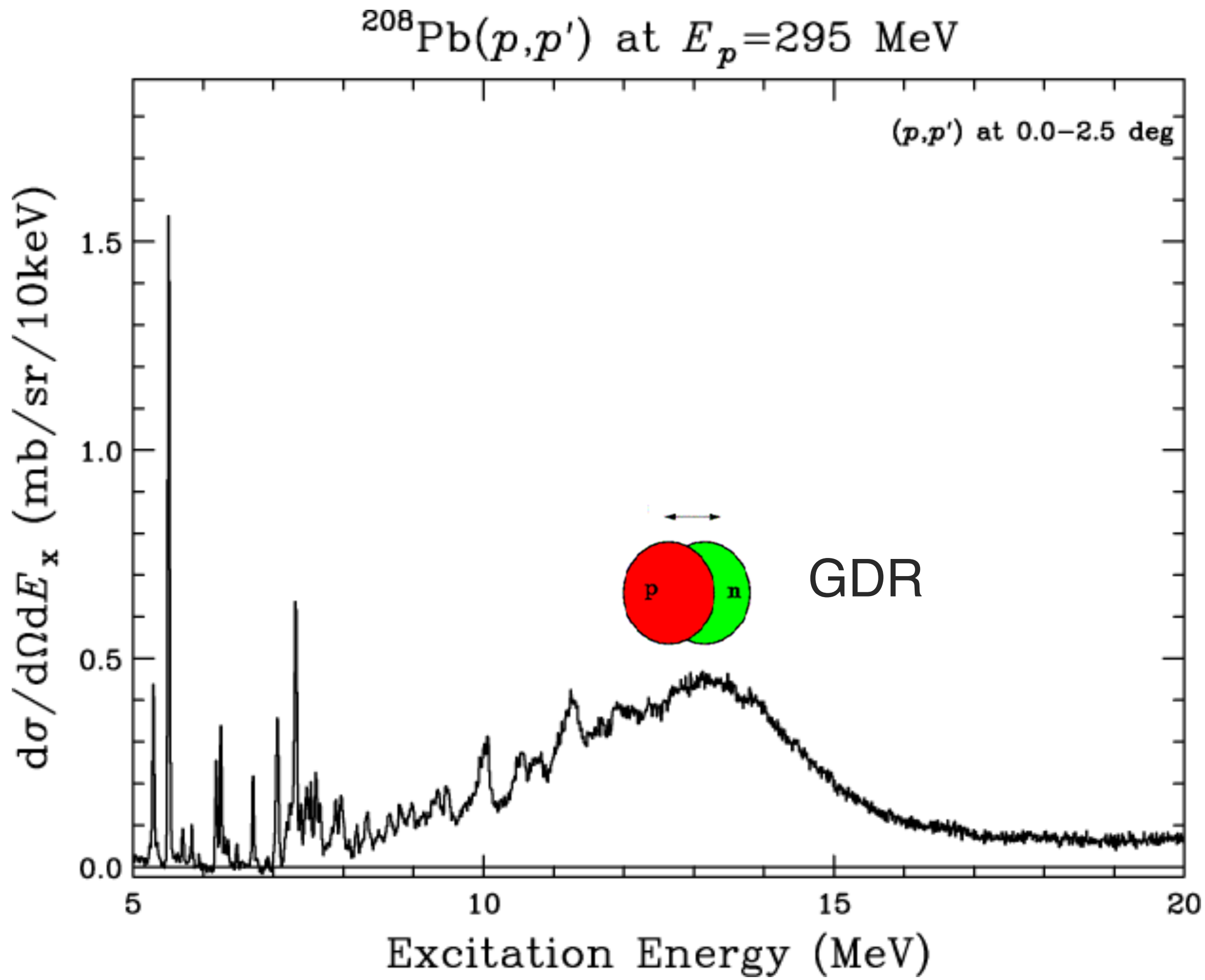
(Isovector) Giant Dipole Resonance (GDR)



by P. Adrich

(Isovector) Giant Dipole Resonance (GDR)

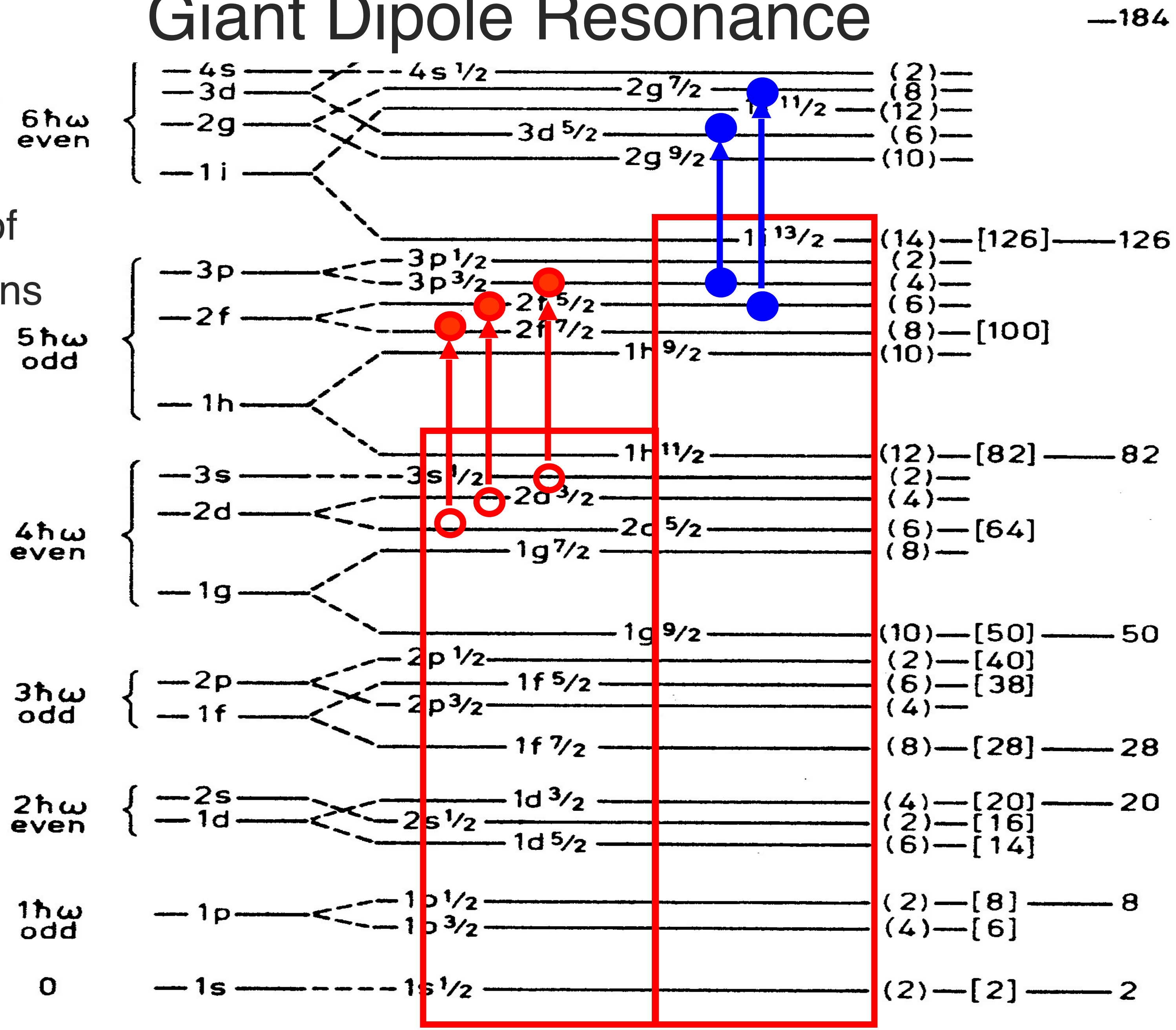


AT et al., PRL107, 062502 (2011)

Giant Dipole Resonance

superposition of

1p-1h excitations

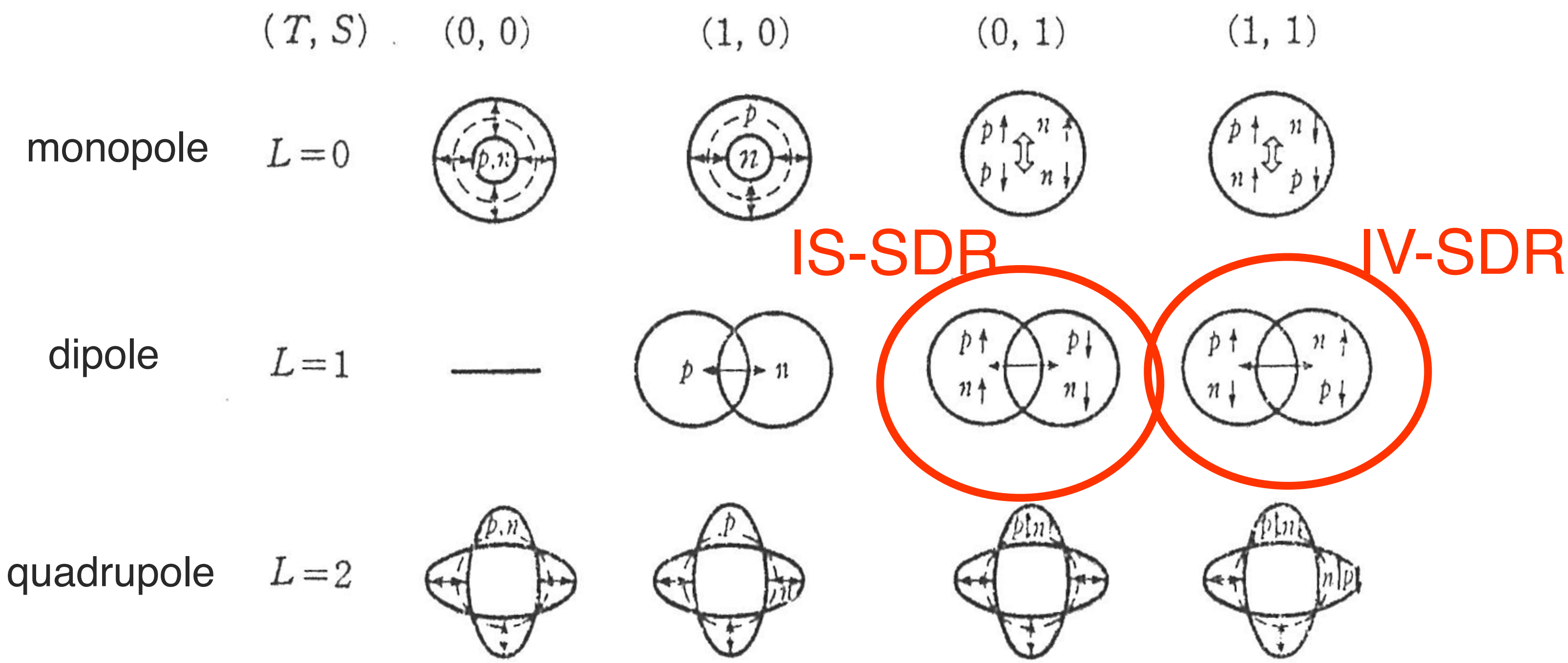


Type of Giant Resonances

Spin Dipole Resonance (SDR)

$rY_1\sigma$

$rY_1\sigma\tau$



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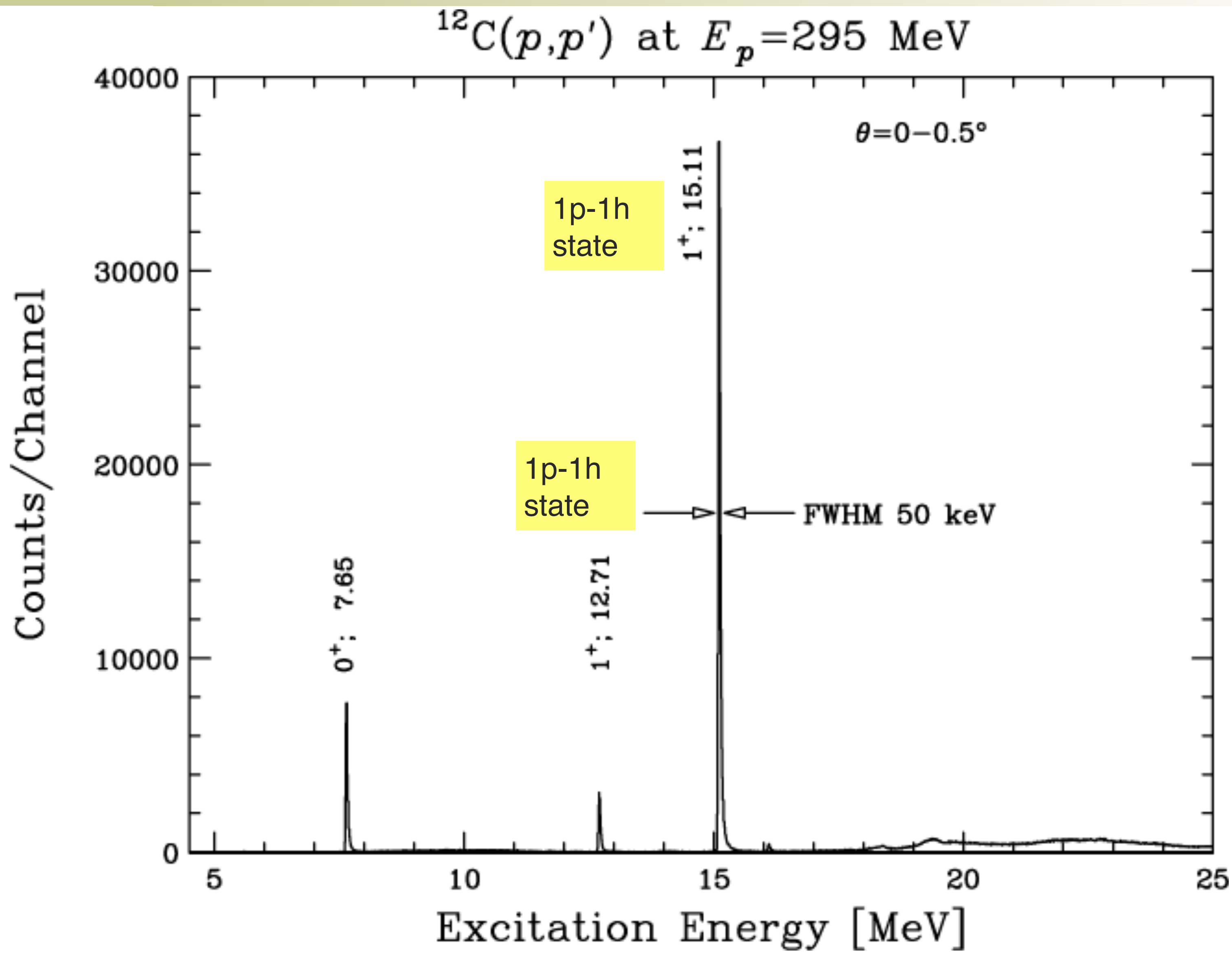
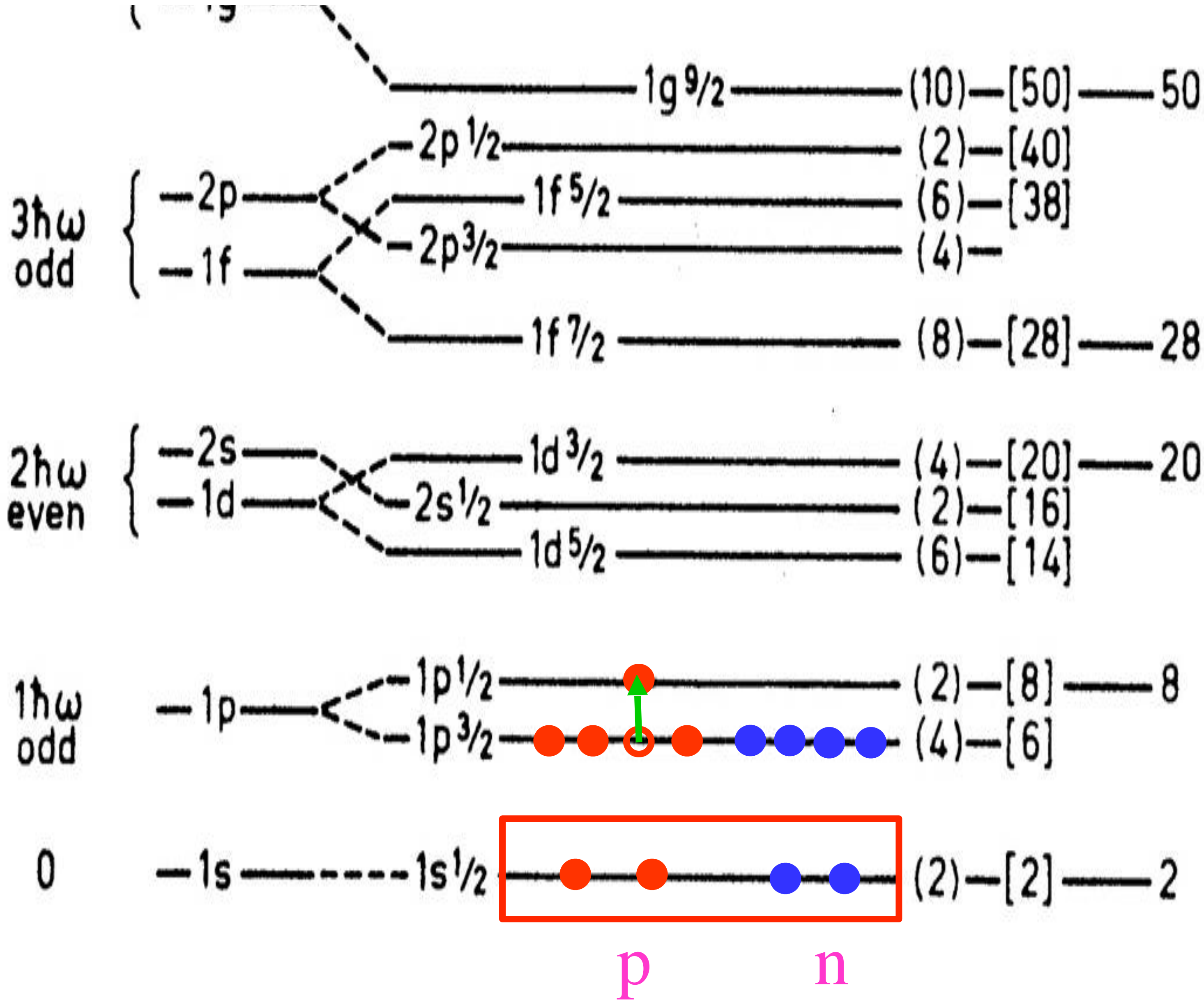
^{12}C Excitation Energy Spectrum



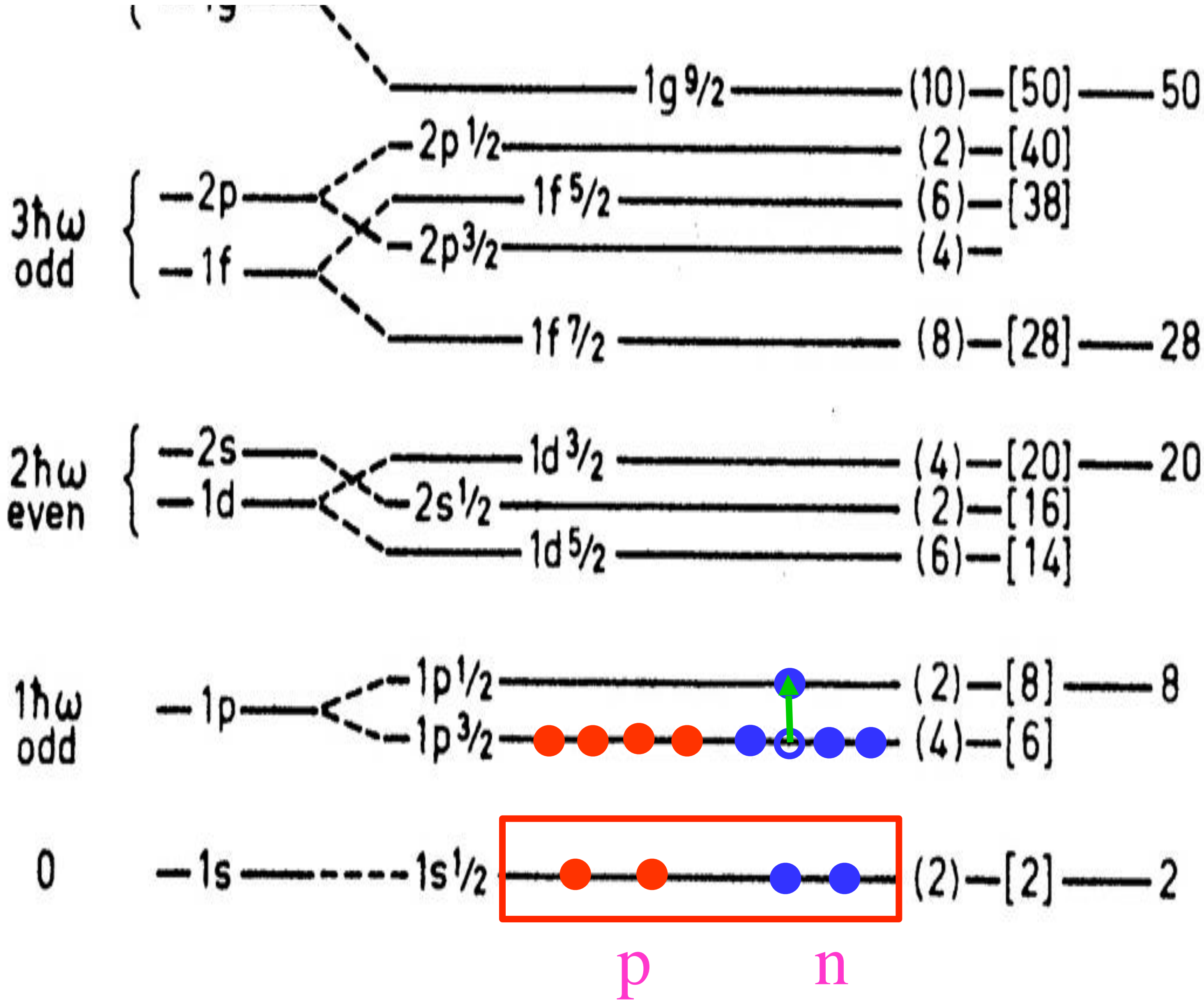
1-particle 1-hole state

1+ state

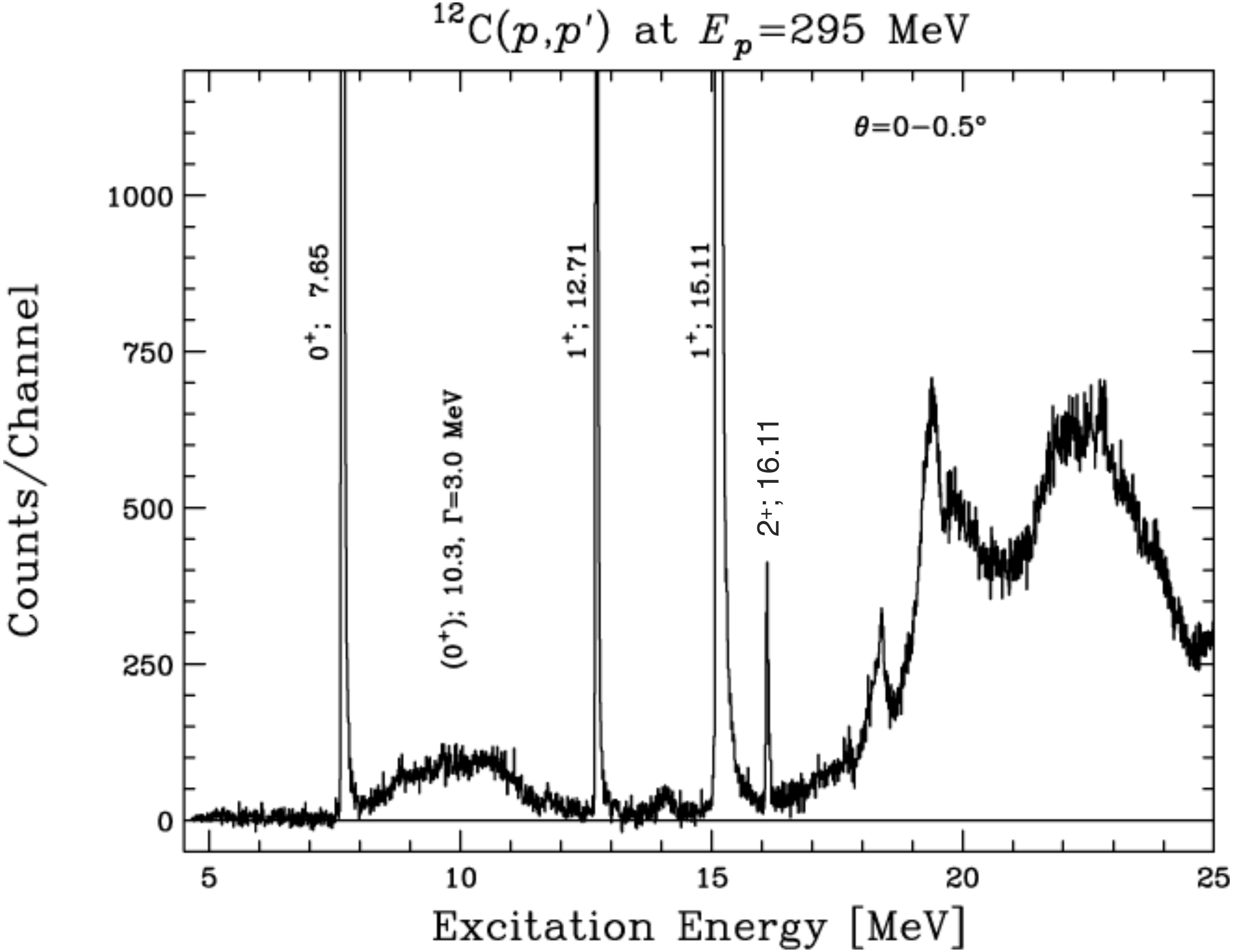


1-particle 1-hole state

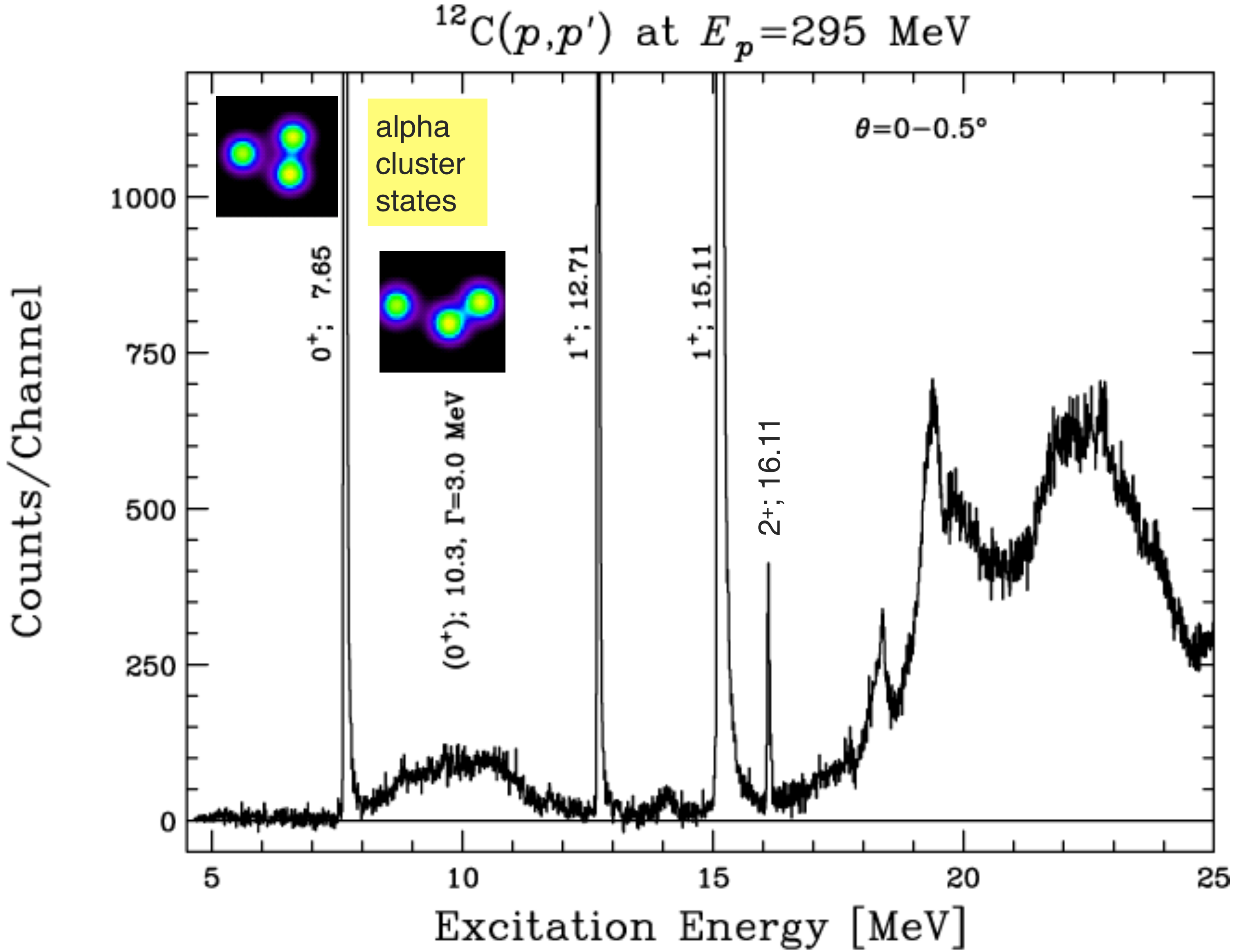
1+ state



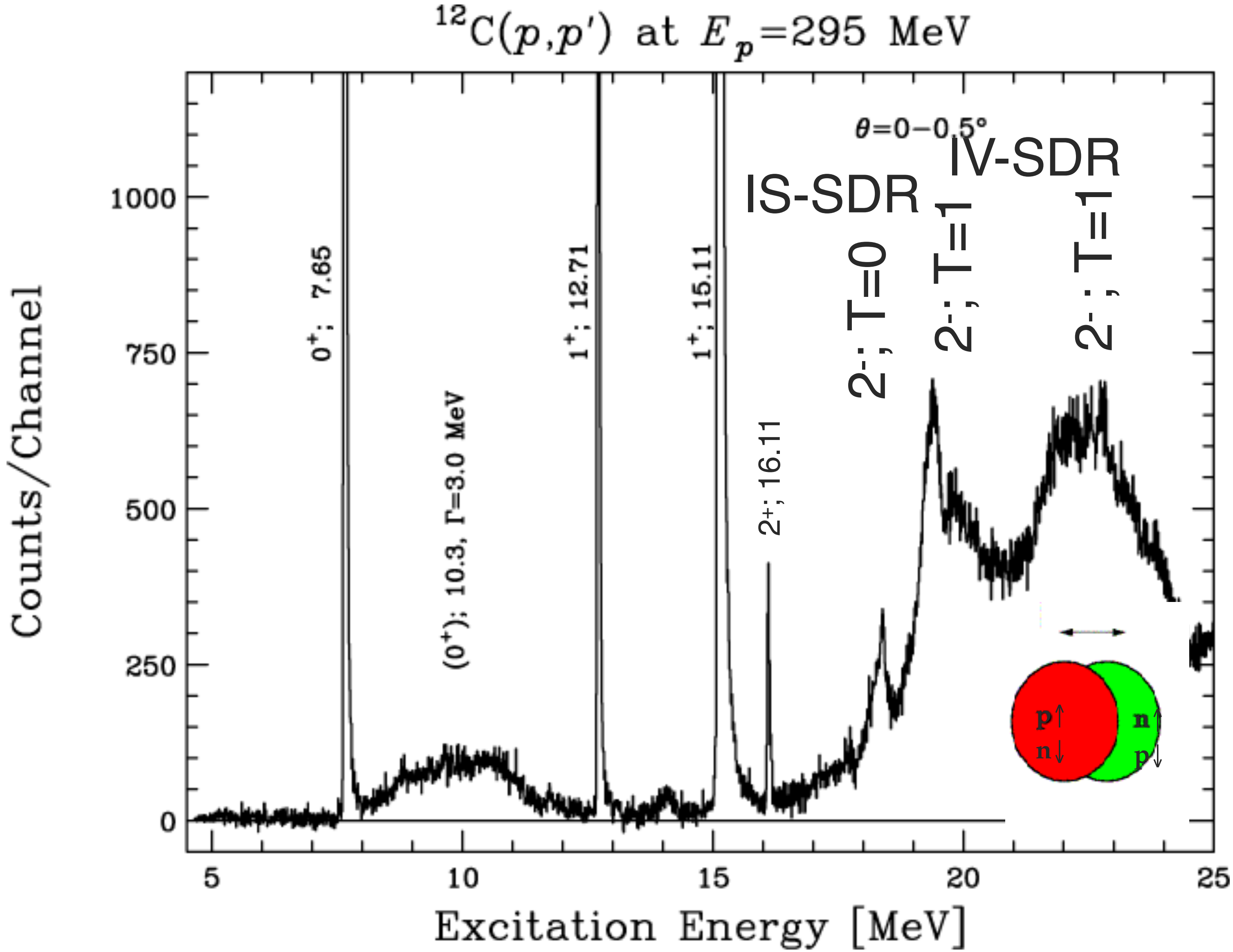
^{12}C Excitation Energy Spectrum



^{12}C Excitation Energy Spectrum



^{12}C Excitation Energy Spectrum



Type of Giant Resonances

Gamow-Teller Giant Resonance (GTGR)

monopole

dipole

quadrupole

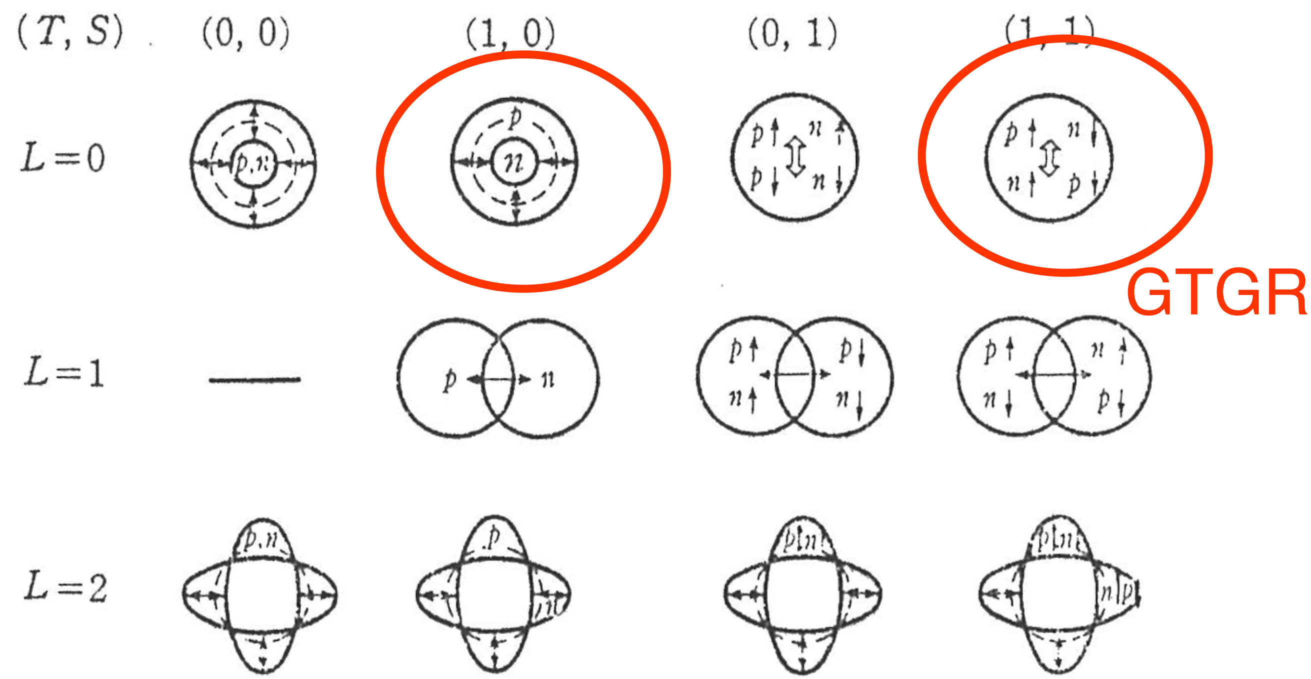


図 5·40　各種の振動モード

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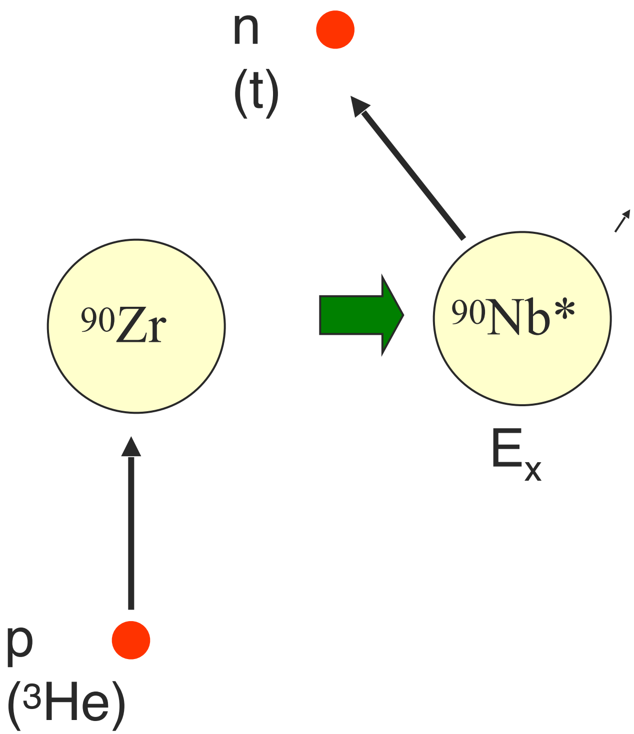
Gamow-Teller Giant Resonance (GTGR)



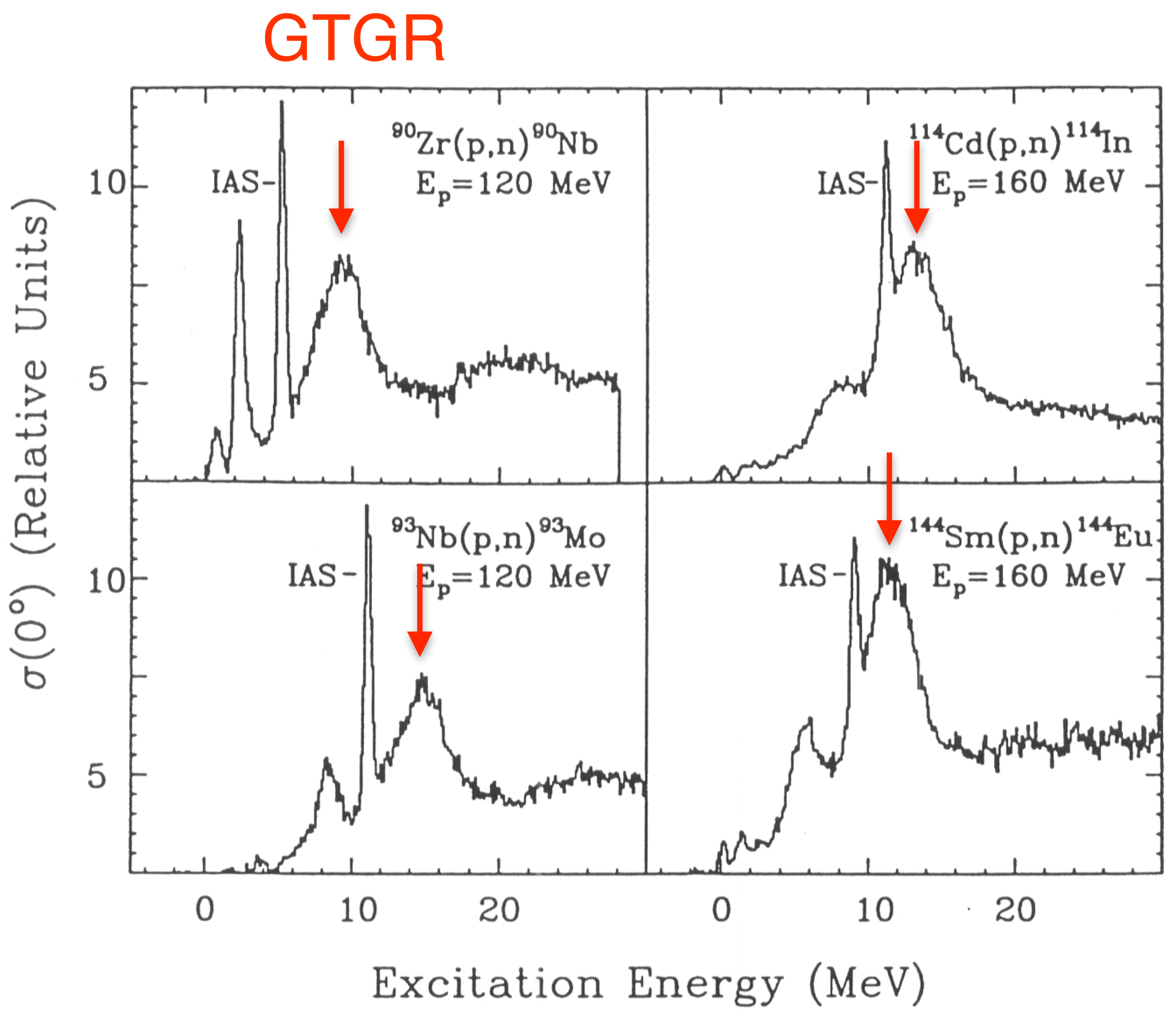


Figure 10 Zero-degree (*p,n*) spectra for medium *A*-mass nuclei at the indicated incident energies.

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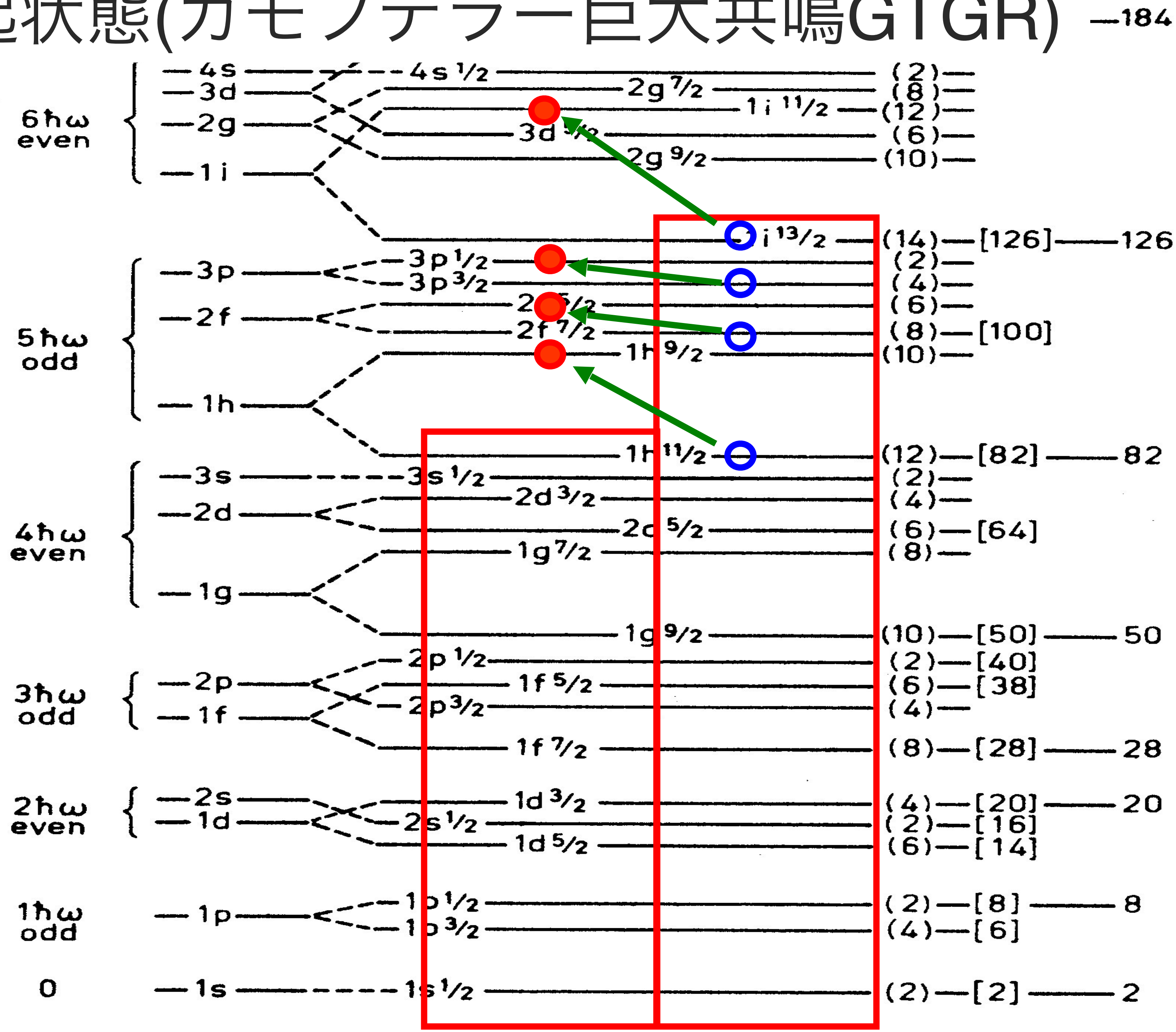
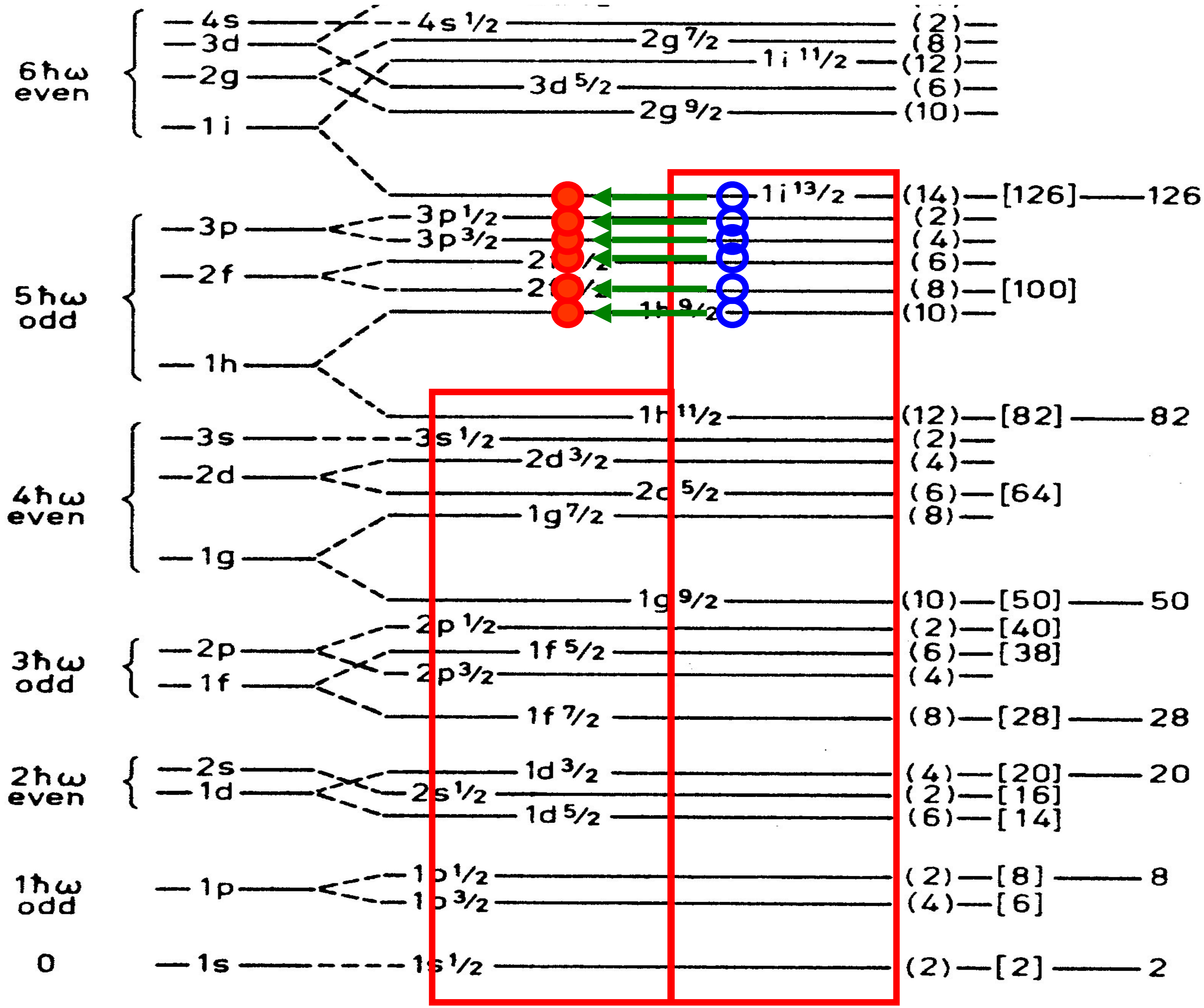
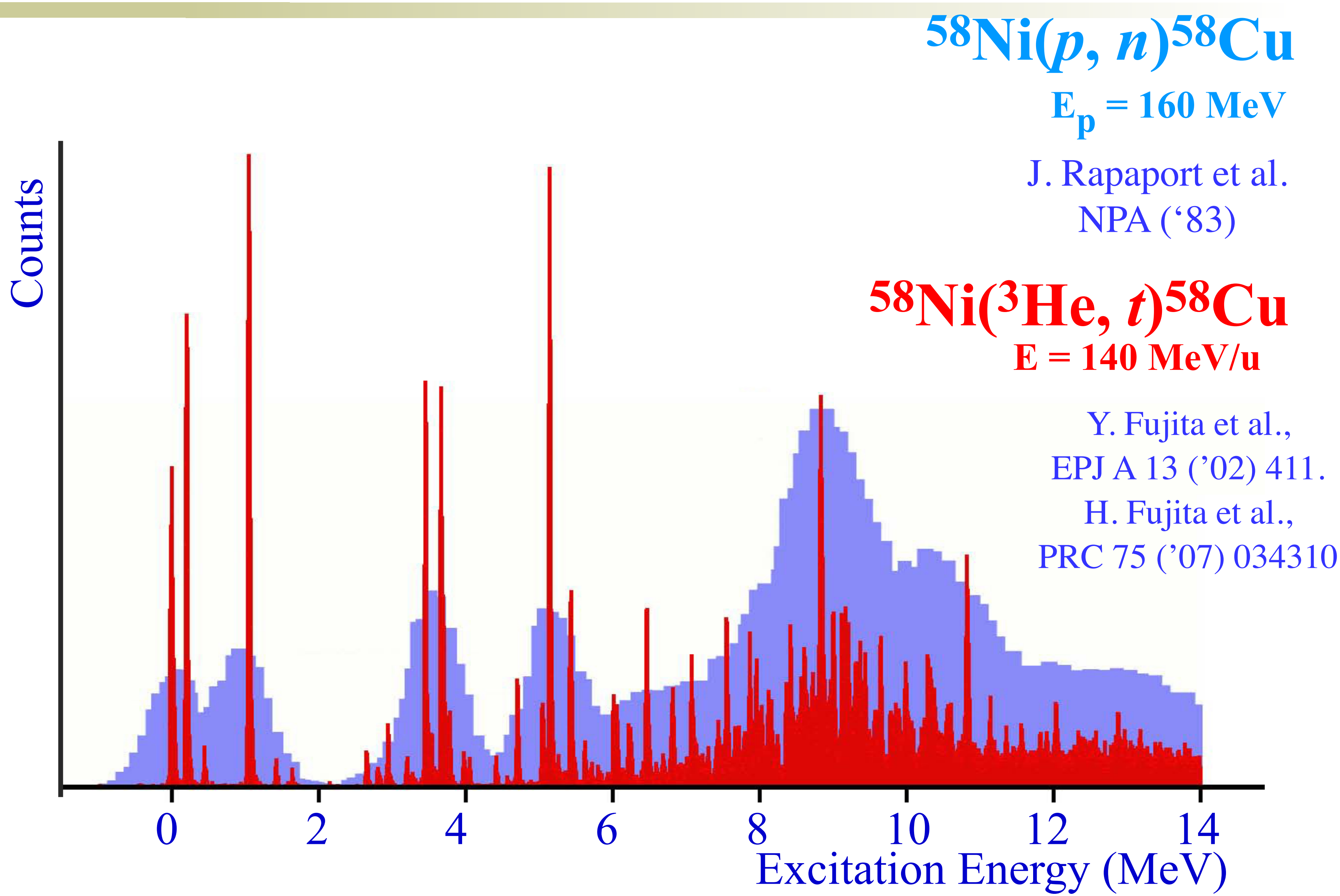
集団励起状態(ガモフテラー巨大共鳴GTGR)



集団励起状態(アイソバリックアナログ状態IAS)



集団励起状態(ガモフテラー巨大共鳴GTGR)



原子核の多様な振動モード：巨大共鳴

Isoscalar Giant Quadrupole Resonance (ISGQR)

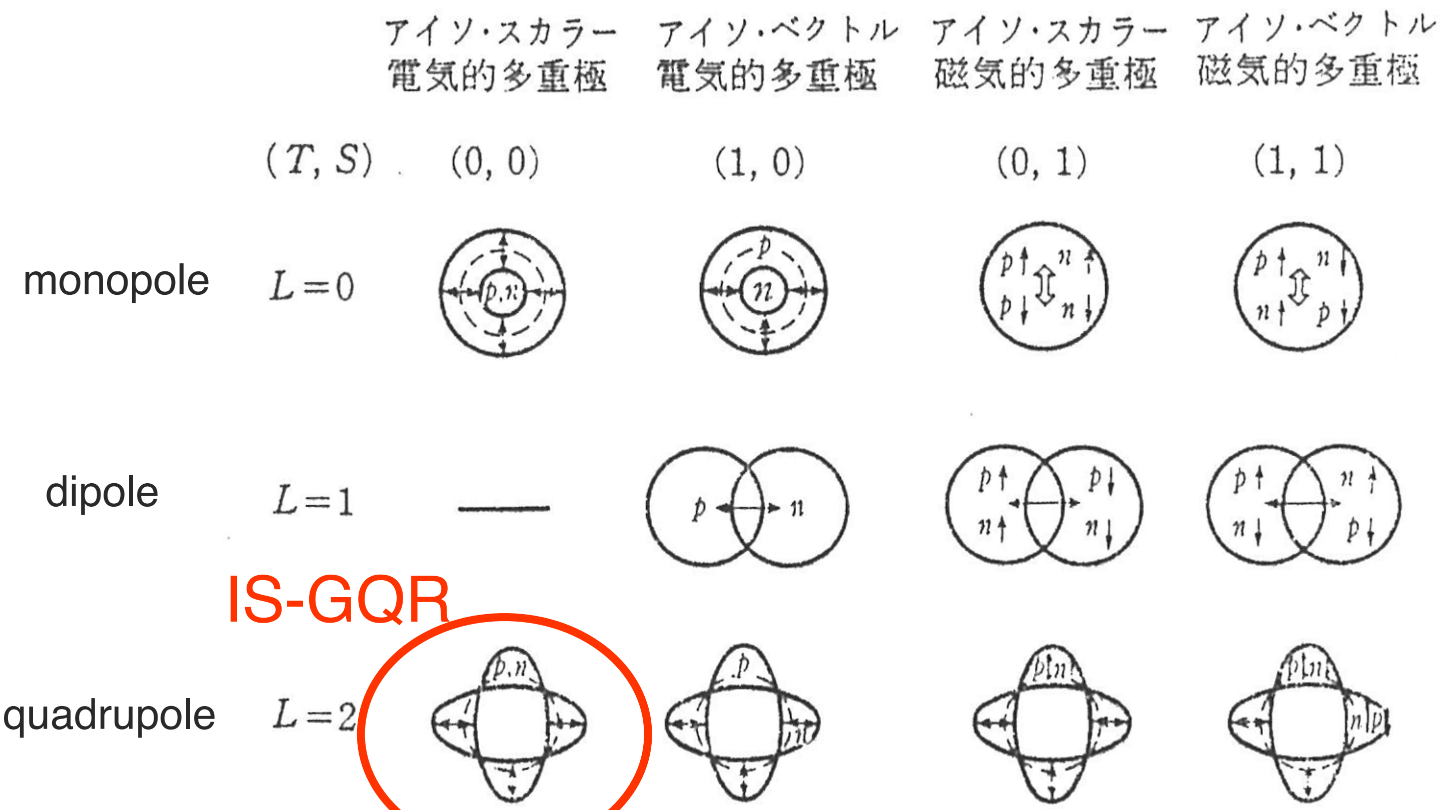


図 5·40 各種の振動モード

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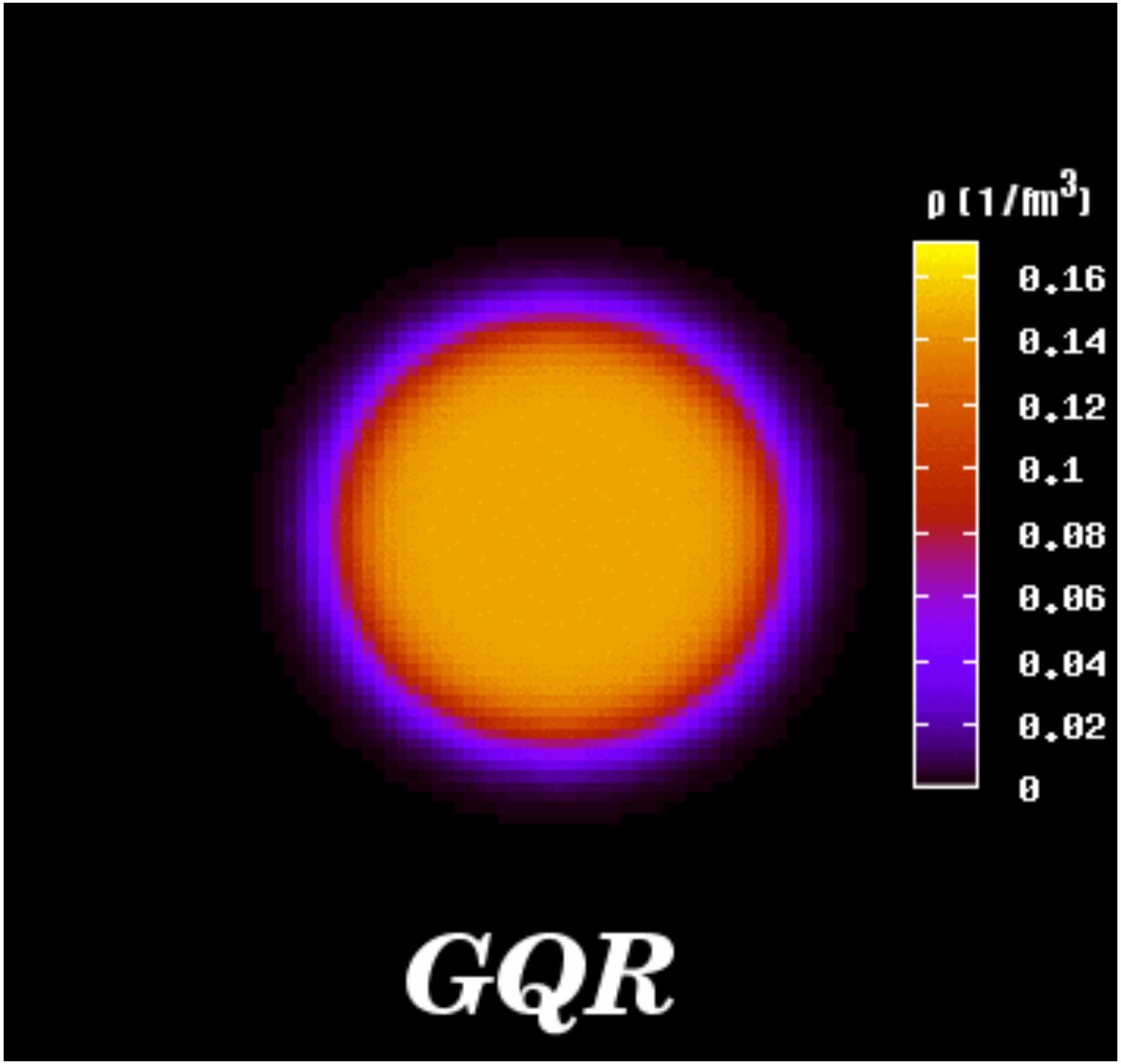
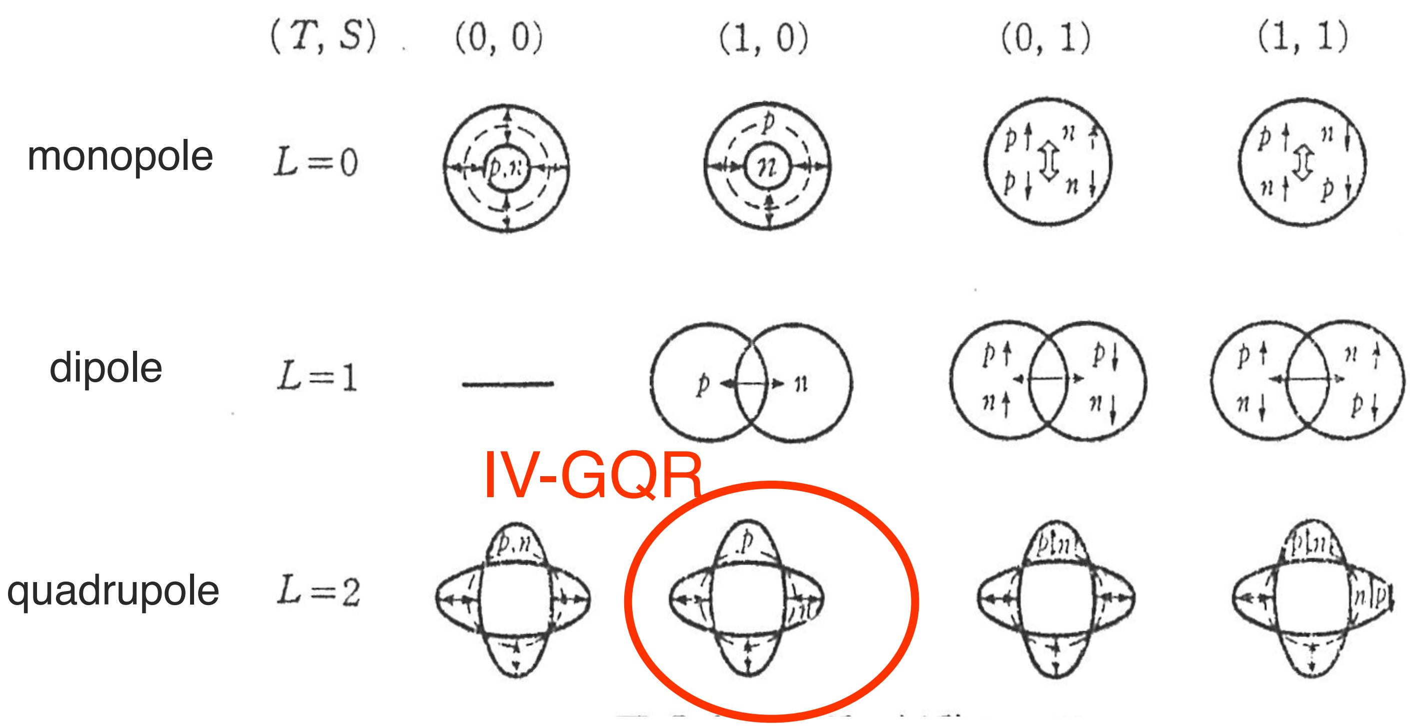
Isoscalar Giant Quadrupole Resonance (ISGQR)



by M. Itoh

原子核の多様な振動モード：巨大共鳴

Isovector Giant Quadrupole Resonance (IV-GQR)



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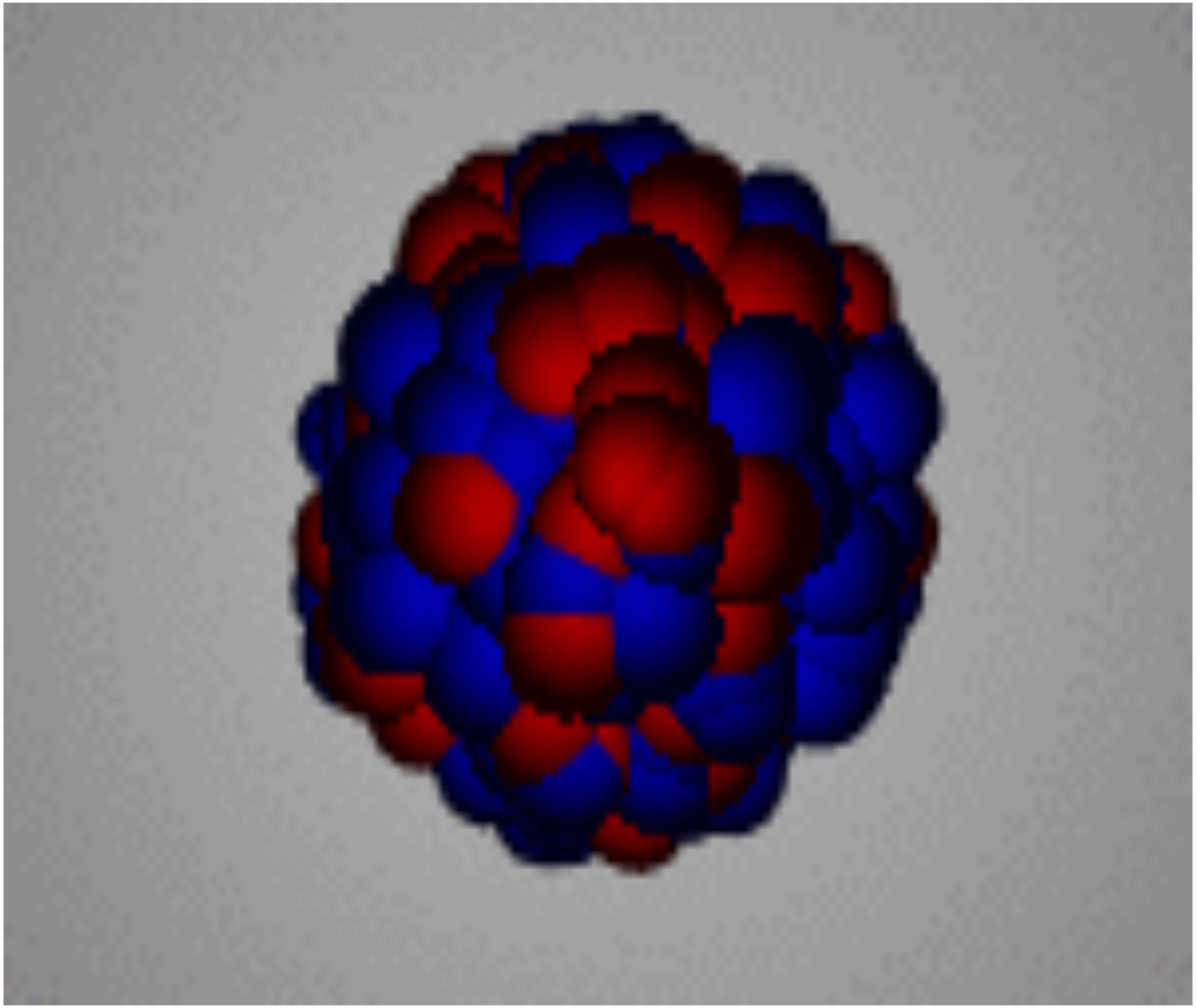
IV Giant Quadrupole Resonance (IVGQR)



by P. Adrich

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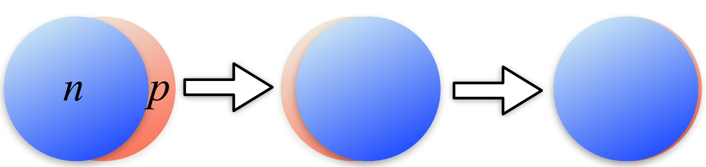
An exercise

Below, photo-absorption cross section data of ^{90}Zr are plotted.

The structure is recognized as isovector GDR, i.e. the dipole oscillation between neutrons and protons.

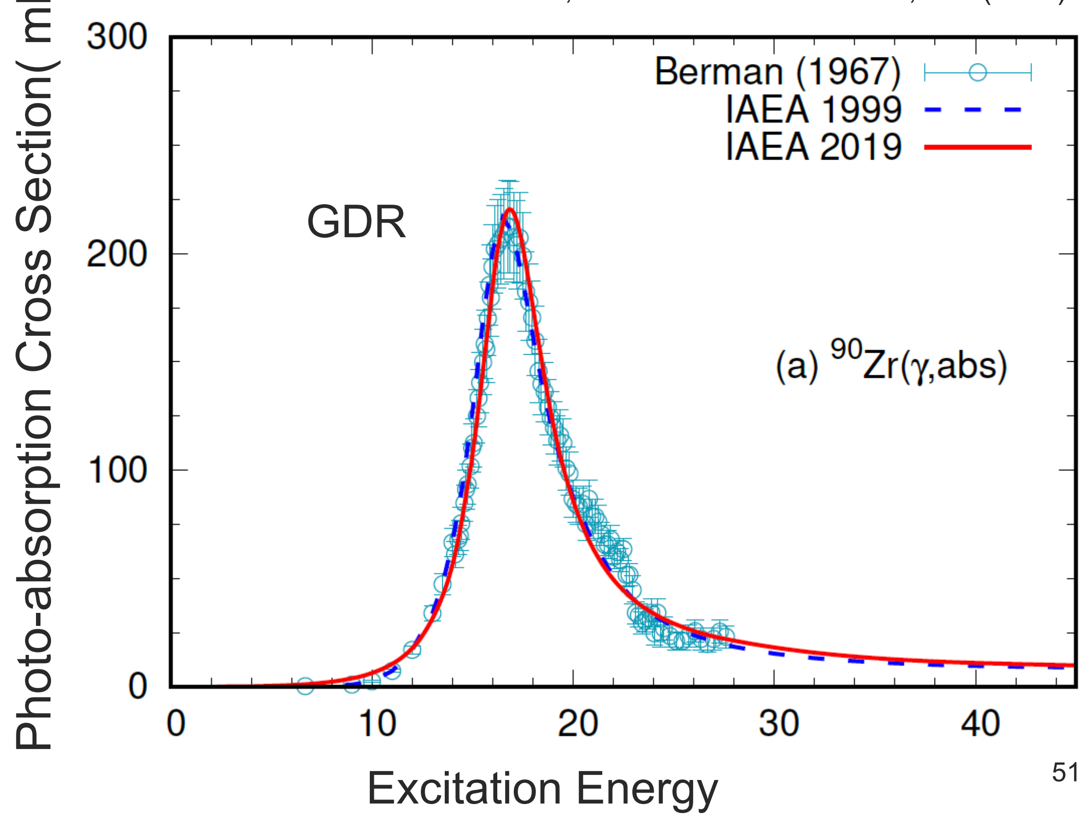
Estimate the following quantities of the GDR oscillation

- angular frequency (ω)
- damping constant (τ)



Damping of IVGDR

T. Kawano et al., Nuclear Data Sheets 163, 109 (2020)



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- angular frequency (ω)
- damping constant (τ)

centroid (~peak) energy E

$$E = \hbar\omega$$

width Γ (~FWHM)

$$\Gamma\tau \sim \hbar$$

uncertainty principle

$$\hbar c = 197\ \text{MeV} \cdot \text{fm}$$
$$c = 3 \times 10^8\ \text{m/s}$$

T. Kawano et al., Nuclear Data Sheets 163, 109 (2020)