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

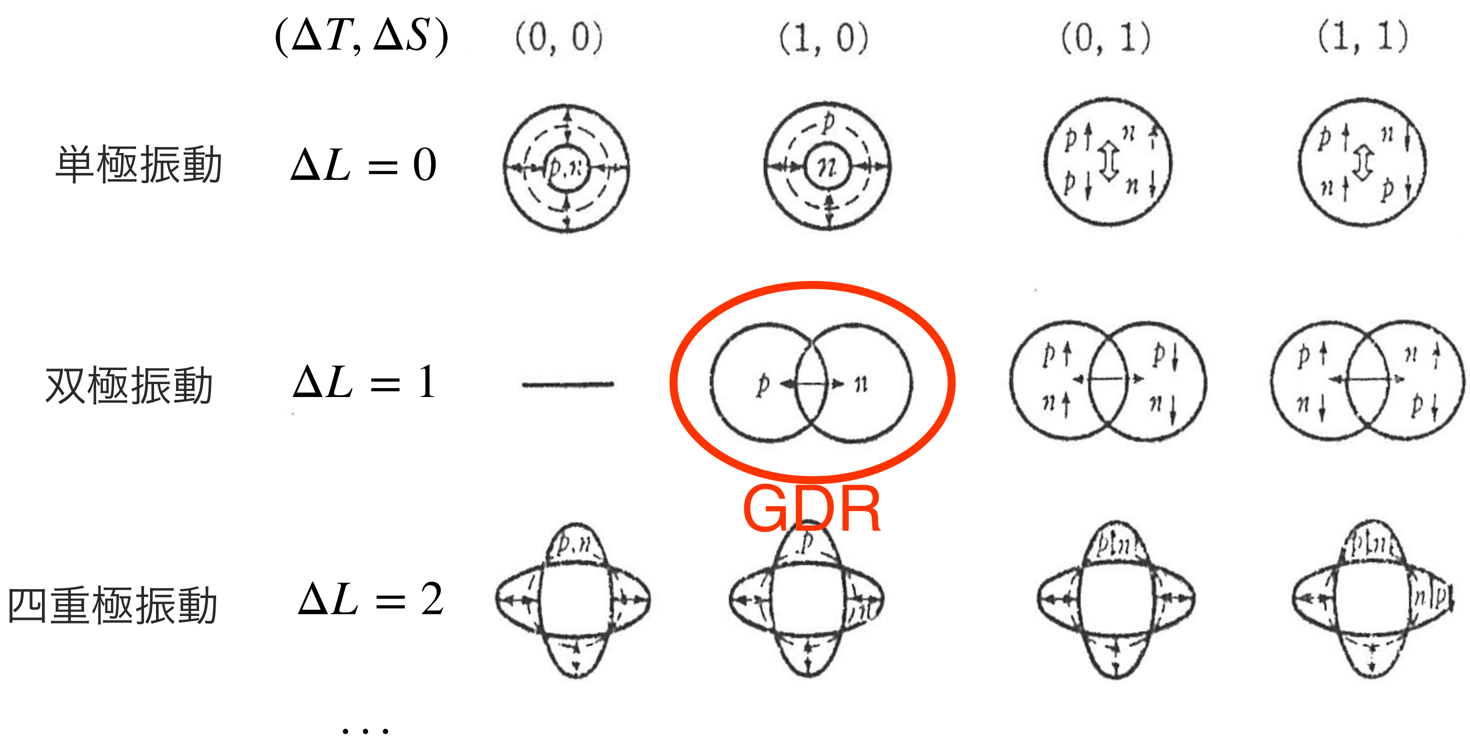
Lecture VII

Damping, Fine Structures, Gamma Decay of IVGDR

Damping, Width, Decay

Type of Giant Resonances

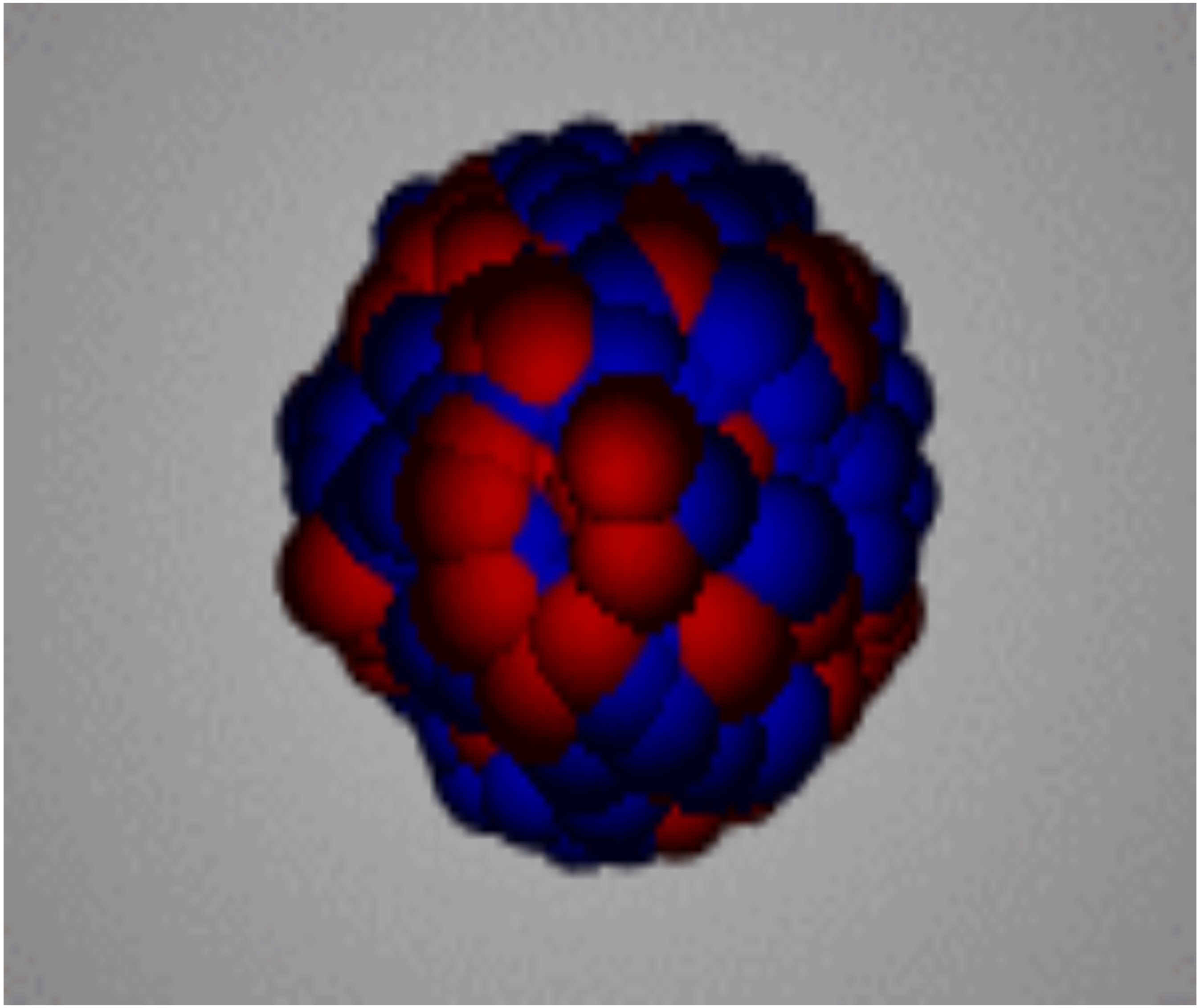
(Isovector) Giant Dipole Resonance (GDR) $rY_1\tau$



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

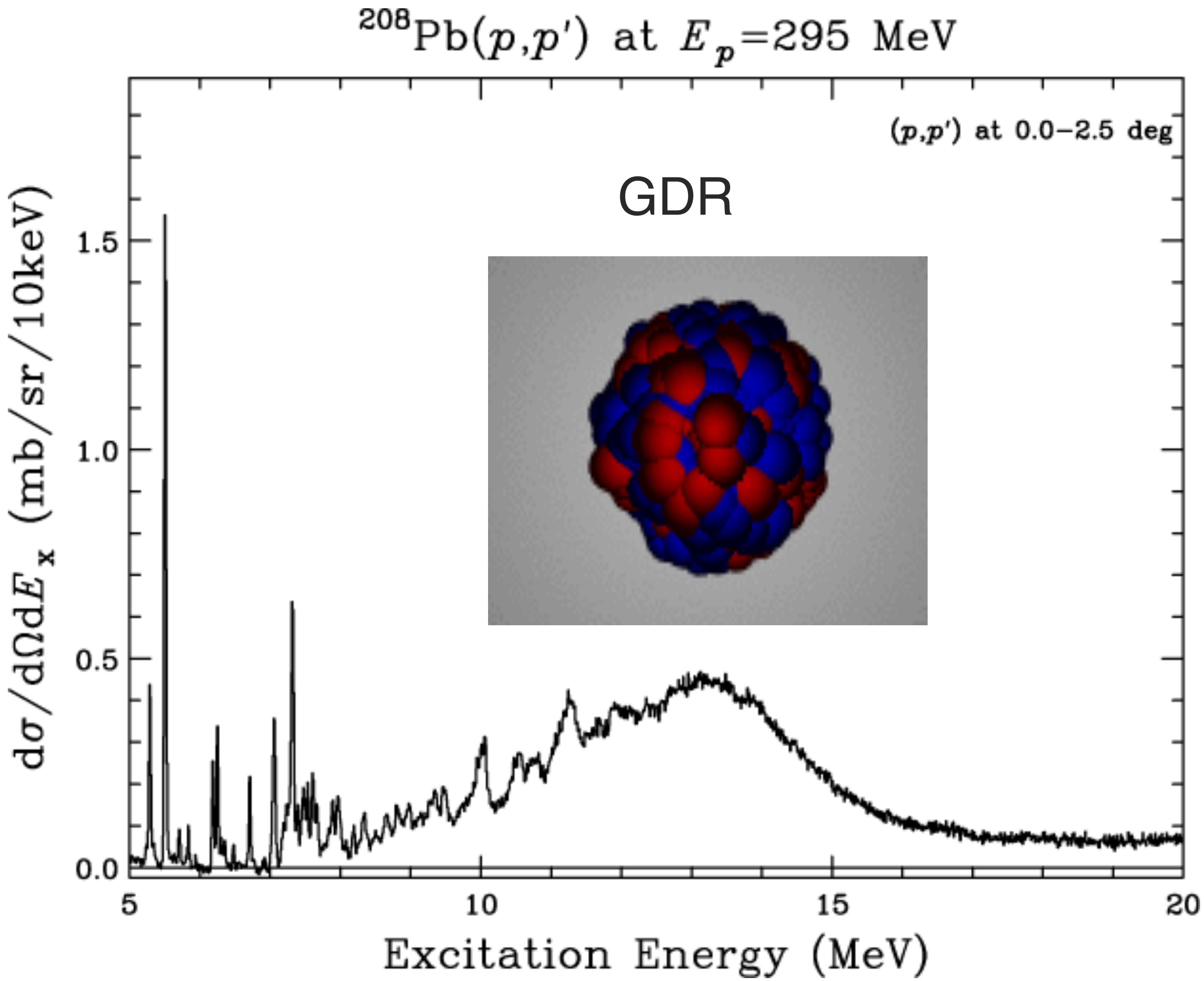
杉本・村岡「原子核構造学」

(Isovector) Giant Dipole Resonance (GDR)



by P. Adrich

(Isovector) Giant Dipole Resonance (GDR)



$\Delta S = 0, \Delta T = 1,$

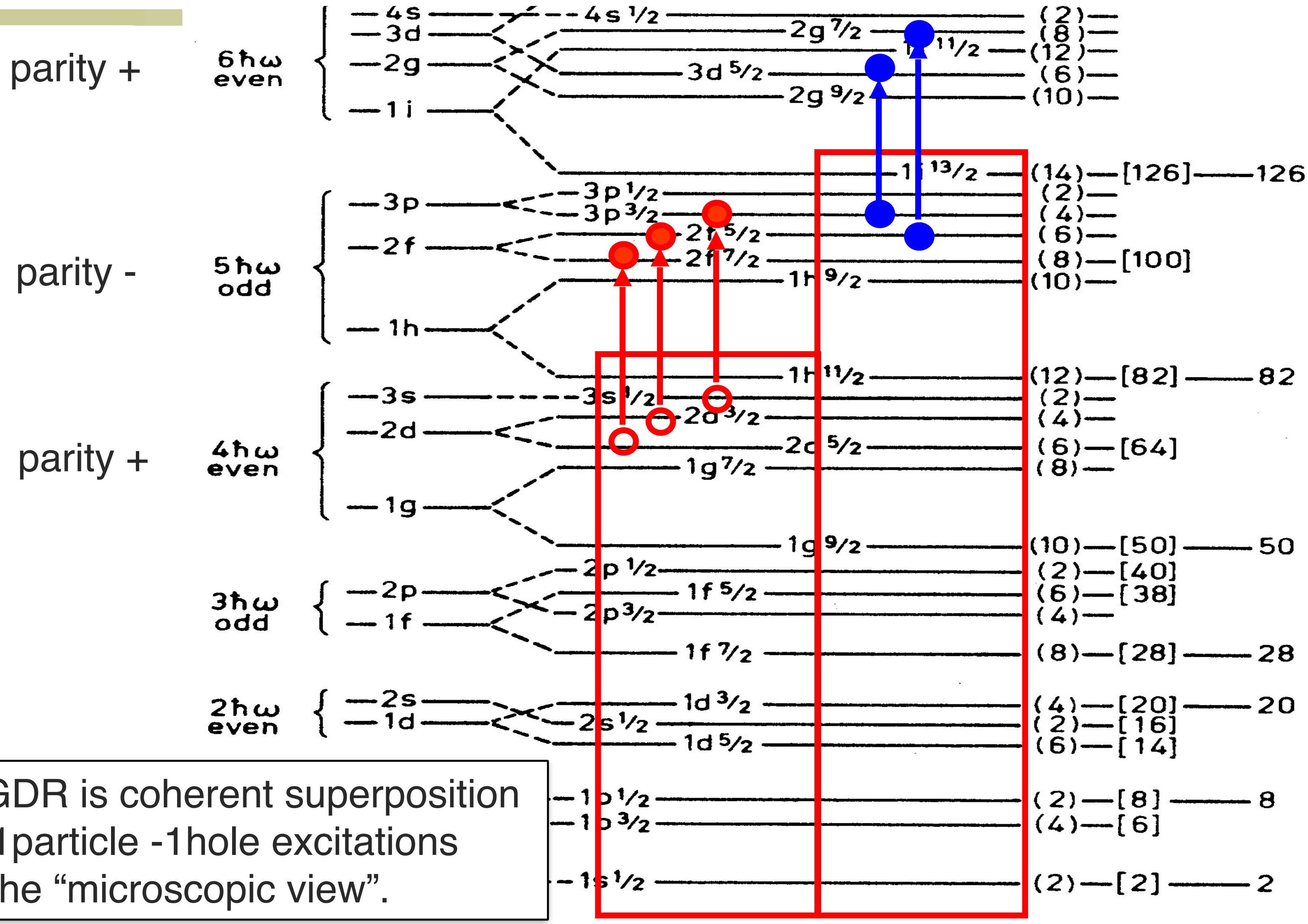
$\Delta L = 1$

$0^+ \rightarrow 1^-$

$\Delta\pi = (-1)^{\Delta L}$

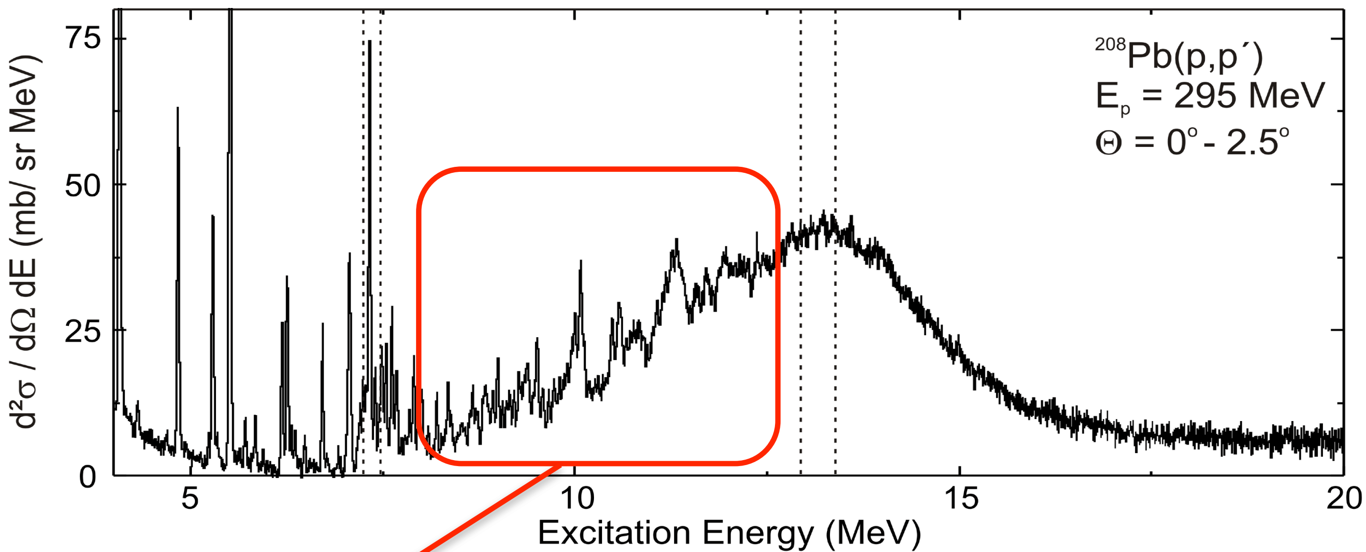
A GDR is a dipole oscillation mode between neutrons and protons in the “macroscopic view”.

Giant Dipole Resonance



A GDR is coherent superposition of 1particle -1hole excitations in the “microscopic view”.

Fine Structure of the GDR



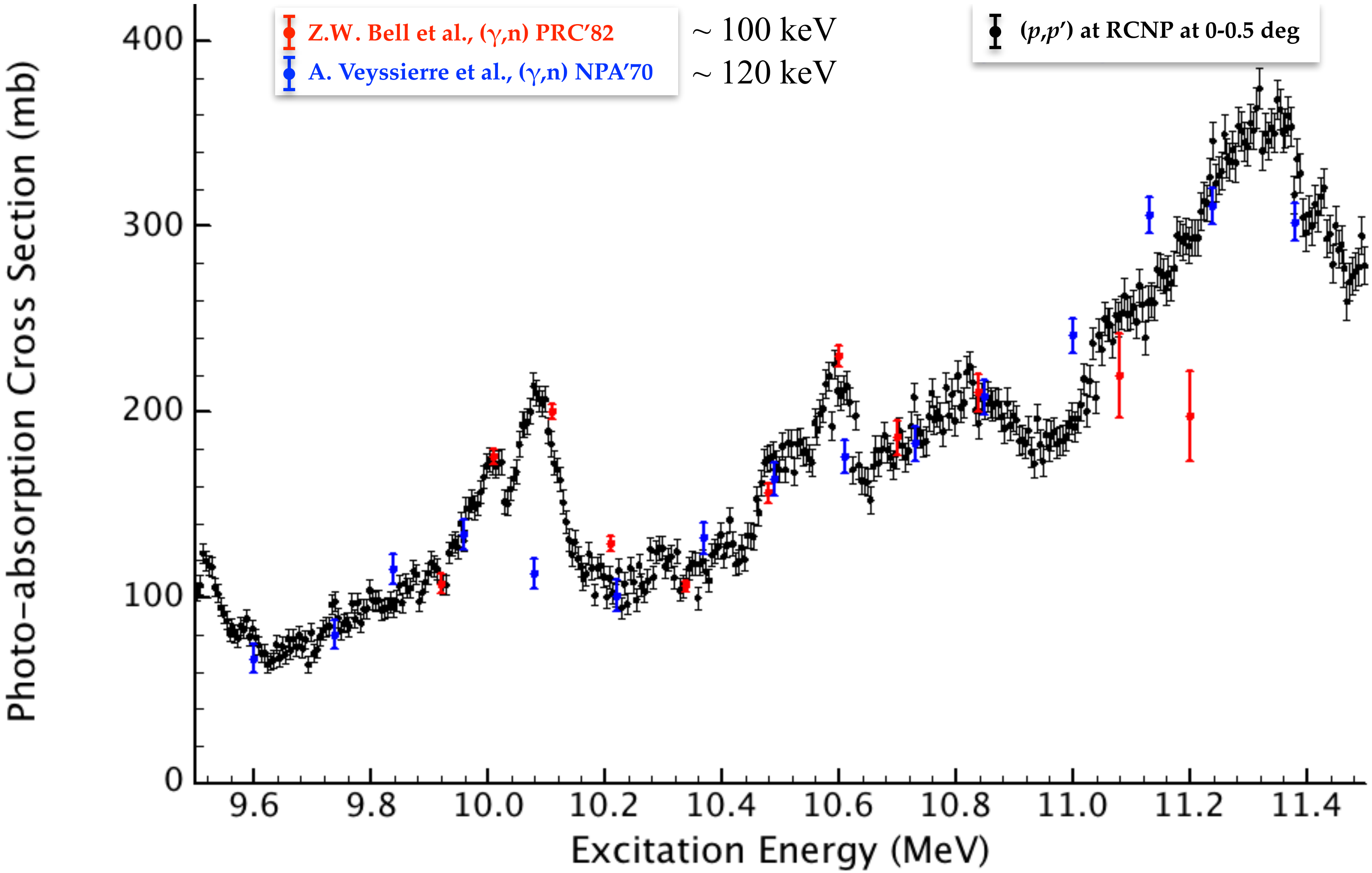
Fine structure of the GDR is clearly observed.

→ Energy dissipation and damping

Gamma decay measurement of the GDR will be one of interesting probes to study the damping mechanism of the GDR.

See e.g. J. Beene et al., PRC41, 920 (1990)

Fine Structure of the GDR

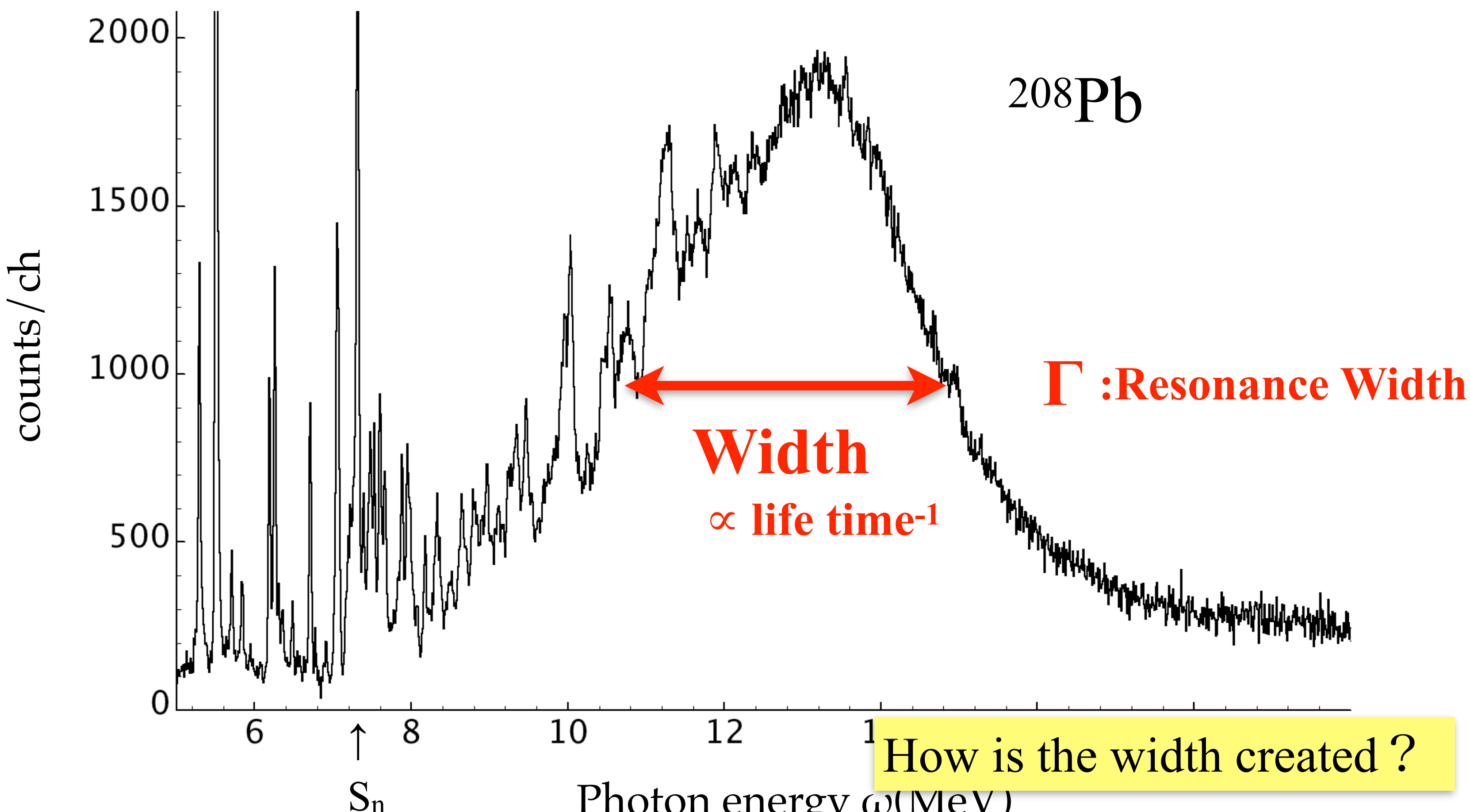


20-30 keV resolution is required.

Width of the IVGDR

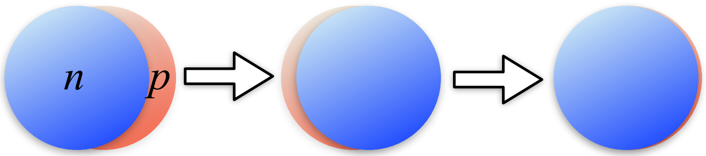
IVGDR

Low-energy dipole strength



How is the width created？

Damping Mechanism of Collective Excitations (IVGDR)



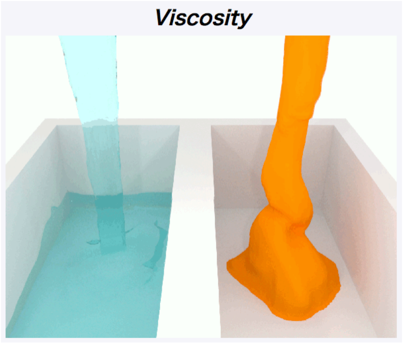
Damping of IVGDR

Macroscopically

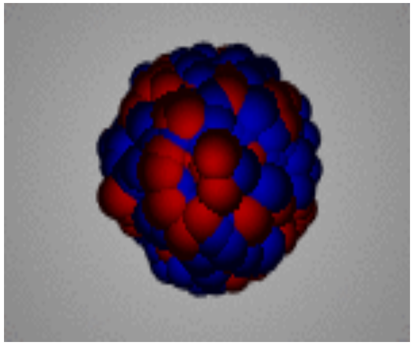
IVGDR: relative dipole oscillation between *p* and *n*

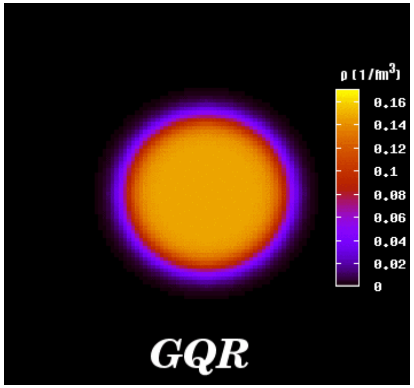
Damping: due to viscosity between the p and n fluids

see e.g. J. Wambach, Rep. Prog. Phys.'88



wikipedia

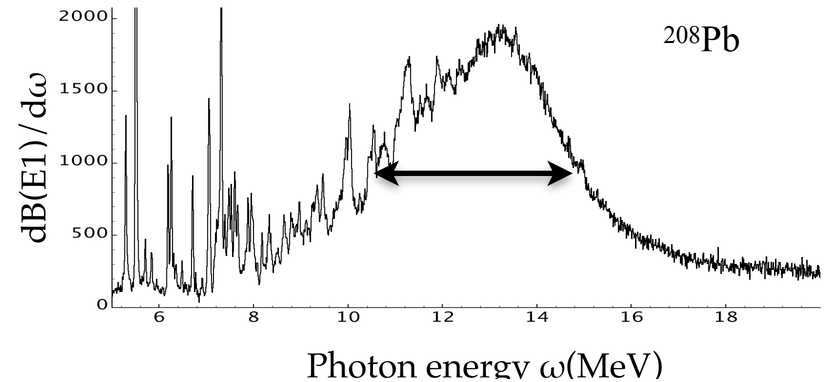




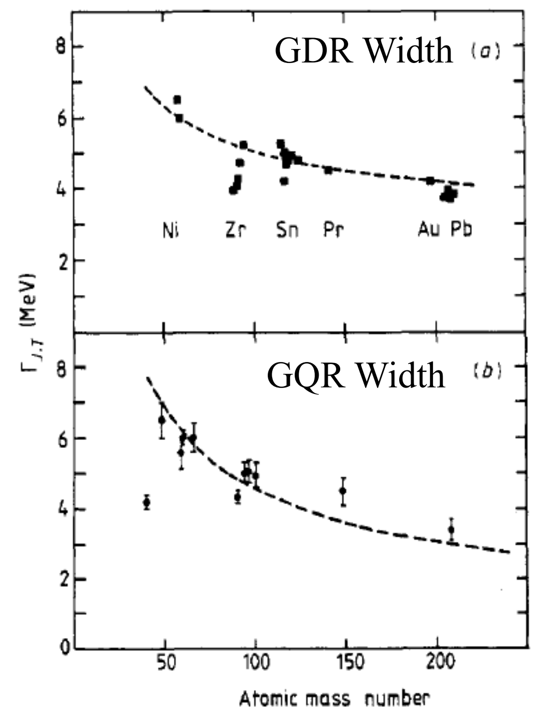
Damping: due to viscosity between identical fluids

Nuclear Viscosity: damping of the resonances (width)

The damping of a resonance is induced by the viscosity.
(friction between nucleons of different motions)



Systematic understanding of the width and the fine-structures of the resonances.
(also at higher temperatures)



Navier-Stokes equations of viscous two fluids

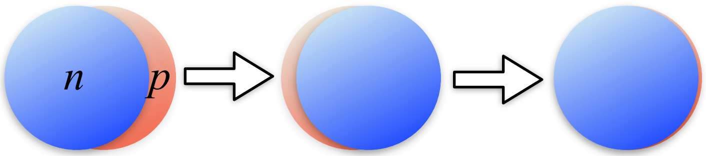
$$\frac{\partial \mathbf{v}_p}{\partial t} = -\frac{1}{\rho_{p,0}}\nabla P_p + \nu\nabla^2\mathbf{v}_p + \frac{1}{3}\nu\nabla\nabla\cdot\mathbf{v}_p - \gamma\frac{\rho_{n,0}}{\rho_{n,0}+\rho_{p,0}}(\mathbf{v}_p-\mathbf{v}_n)$$

$$\frac{\partial \mathbf{v}_n}{\partial t} = -\frac{1}{\rho_{n,0}}\nabla P_n + \nu\nabla^2\mathbf{v}_n + \frac{1}{3}\nu\nabla\nabla\cdot\mathbf{v}_n + \gamma\frac{\rho_{p,0}}{\rho_{n,0}+\rho_{p,0}}(\mathbf{v}_p-\mathbf{v}_n).$$

N. Auerbach and A. Yeverechyahu, Ann. Phys. 1975

J. Wambach, Rep. Prog. Phys. 1988

Damping Mechanism of Collective Excitations (IVGDR)



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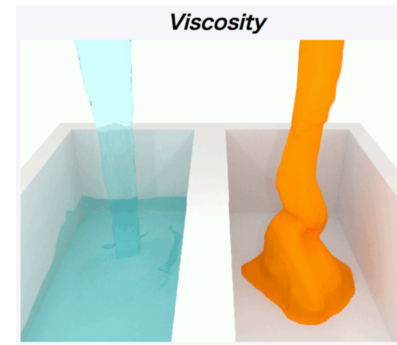


wikipedia

Microscopically

Origins of the damping

$$\Gamma = \Delta\Gamma + \Gamma^{\downarrow} + \Gamma^{\uparrow}$$

Γ total width

widths (MeV)

$$\Gamma = \frac{\hbar}{\tau}$$

large width = short life-time

= fast transition

$\Delta\Gamma$ **Landau damping:** distribution of the unperturbed 1p-1h components

$\Gamma^{\uparrow}$ **escape width**: particle and gamma decays from the doorway state

transition to another state with losing energy

T2 relaxation in NMR

T1 relaxation in NMR

$\Gamma^{\downarrow}$ **spreading width** : spreading from the doorway state into more complex configurations

damping due to the loss of coherence without losing energy

$$|\Psi_{\rm GDR}> = O({\rm GDR})|\Psi_{\rm g.s.}> \qquad O({\rm GDR}) \equiv \sum_i r_i Y_1(\hat{r}_i)$$

$$|\Psi_{\rm GDR}> = \sum_k |\Psi_k><\Psi_k|O({\rm GDR})|\Psi_{\rm g.s.}>$$

$$= \sum_k \alpha_k |\Psi_k>$$

$$\alpha_k = <\Psi_k|O({\rm GDR})|\Psi_{\rm g.s.}>$$

α_k is non-zero only for the $J_k^\pi = 1^-$ states if $J_0^\pi = 1^-$ for the g.s.

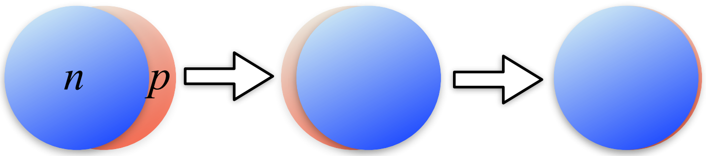
$$|\Psi_k> = |\Psi_k^{\rm GDR}> + |\Psi_k^{\rm non-GDR}>$$

$$<\Psi_k^{\rm GDR}|O({\rm GDR})|\Psi_{\rm g.s.}> = \alpha_k \neq 0$$

$$<\Psi_k^{\rm non-GDR}|O({\rm GDR})|\Psi_{\rm g.s.}> = 0$$

door-way state (component) $|DW_k>$

Damping of IVGDR: Spreading Width



Damping of IVGDR

in coherence

$$|\Psi_{\mathrm{GDR}}> = \sum_k \alpha_k |DW_k>$$

doorway collective state
excited by1p-1h from the g.s.

$$|\Psi_k> = c|\mathrm{DW_k}> + \sum c'|2p2h_k> + \ldots + c''\sum|CN_k>$$

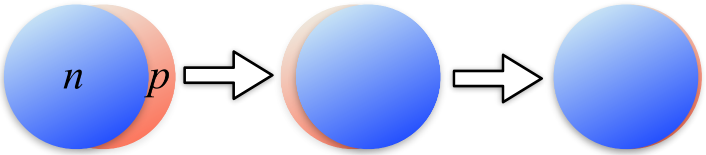
out of coherence

damping due to the loss of coherence

→**Spreading width**

collision among students (nucleons)

Damping of IVGDR: Spreading Width



Damping of IVGDR

out of coherence

Spreading width:

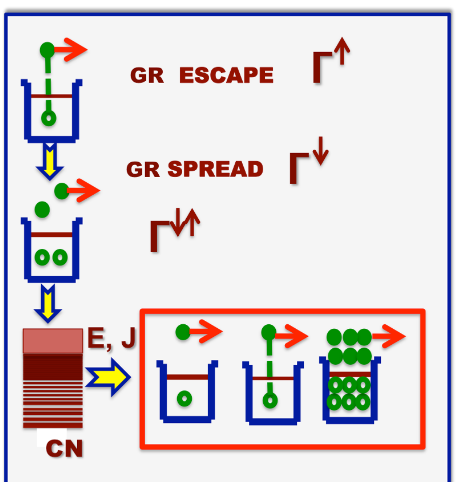
W.F. of an excited state

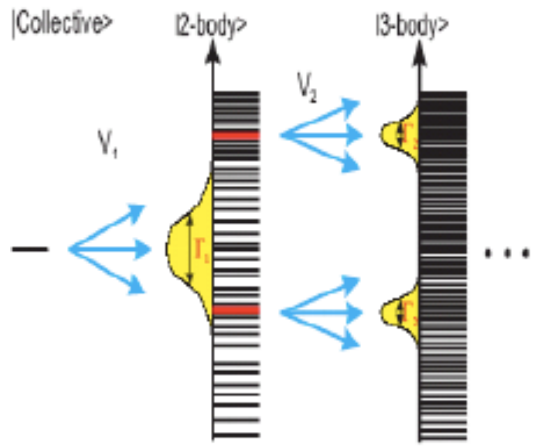
doorway collective state
excited from the g.s.

$$|\Psi_k> = c|\mathrm{DW}_\mathrm{k}> + \sum c'|2p2h_k> + \ldots + c''\sum |CN_k>$$

damping due to the loss of coherence

doorway collective state
excited from the g.s.





coupling to 2p-2h and
many-p many-h states

Fine structure of IVGDR

PDR

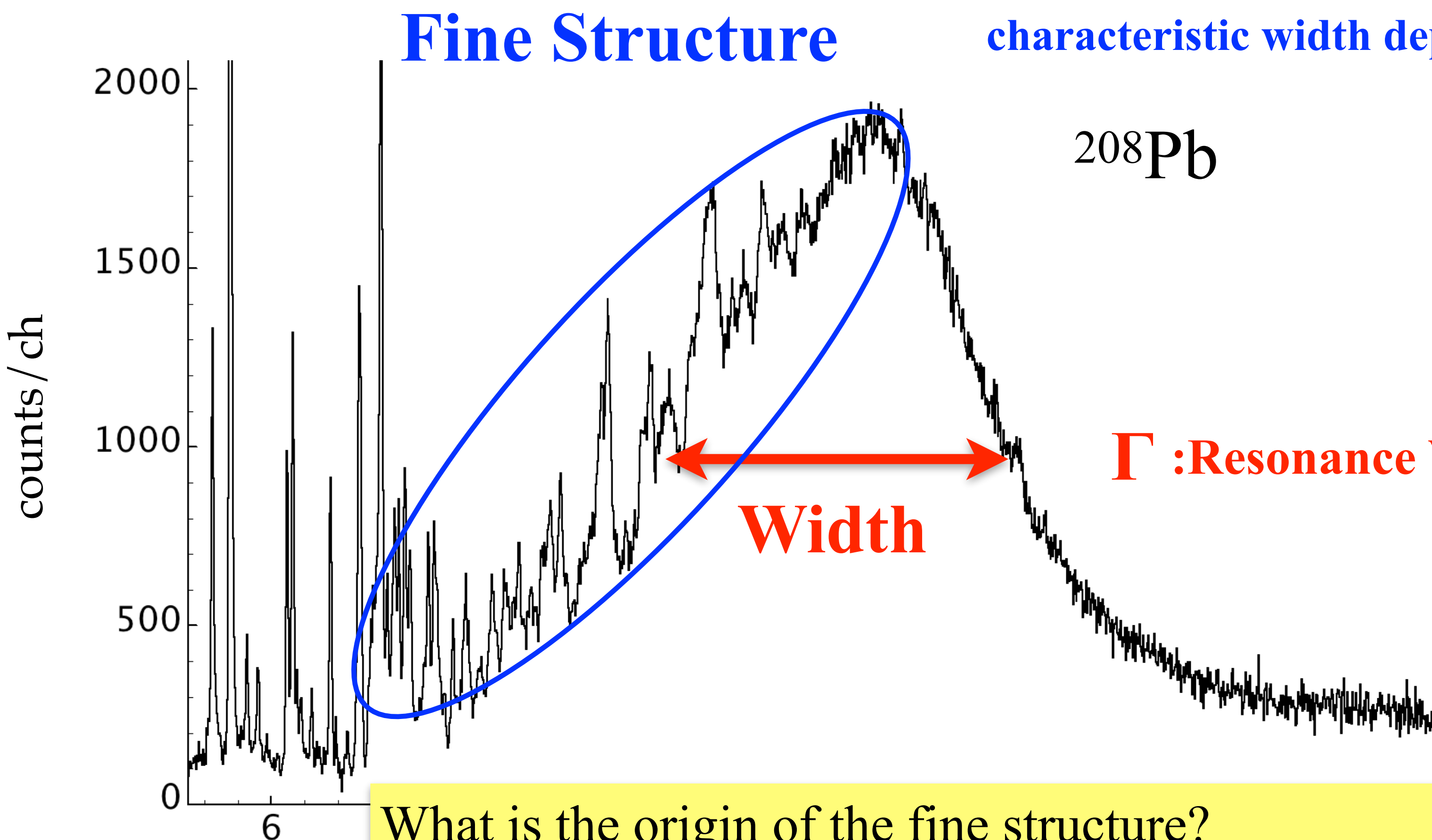
Low-energy dipole strength

IVGDR

The fine structure would have its characteristic width dep. on E_x

^{208}Pb

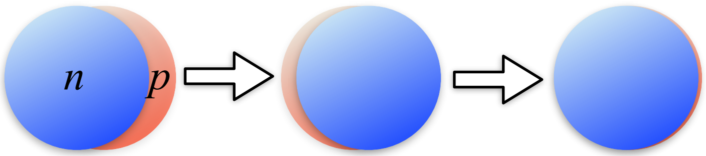
Γ :Resonance Width



What is the origin of the fine structure?

Does it have characteristic width depending on E_x?

Another Way to Study Γ: the Decay



Damping of IVGDR

IVGDR eventually transits to another state with losing its energy.

Each decay channel is categorized by the emitted particle (gamma) and the energy

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

Experimentally, branching ratio can be measured for each decay

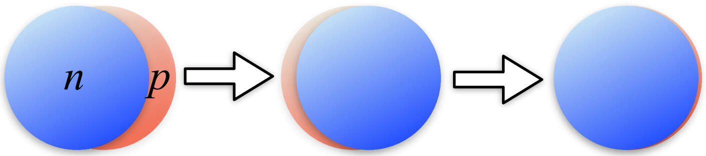
branching ratio: $b_i = \dfrac{\Gamma_i}{\Gamma}$ total width $\Gamma = \sum \Gamma_i$

We focus on the <u>gamma decay to the ground state.</u>

Γ_{γ_0} $b_{\gamma_0} \sim 1\,\%$

Why ?

Γ_{bin} as a function of E_x



Damping of IVGDR

The g.s. gamma-decay is the inverse process of the Coulomb excitation.

$\frac{d^2\sigma}{d\Omega dE_x}$ by Coulomb excitation

→ B(E1)↑

→ B(E1)↓ (detailed balance)

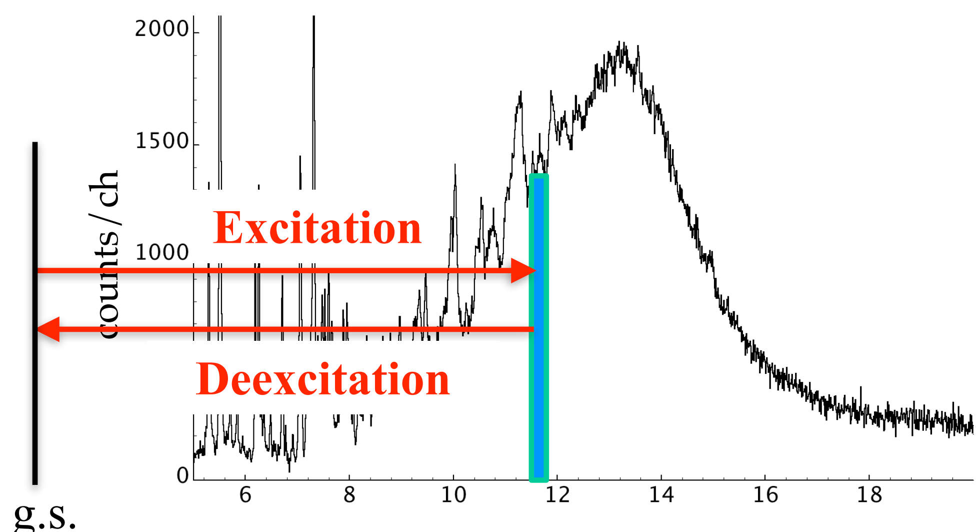
→ Γ_{γ_0}

Gamma coincidence measurement

→ branching ratio $b_{\gamma_0} = \frac{\Gamma_{\gamma_0}}{\Gamma_{bin}}$

→ $\Gamma_{bin}(Ex)$ can be determined.

Γ_{bin} can be determined for each E_x bin



What will be observed? How Γ_{bin} distributes in E_x?

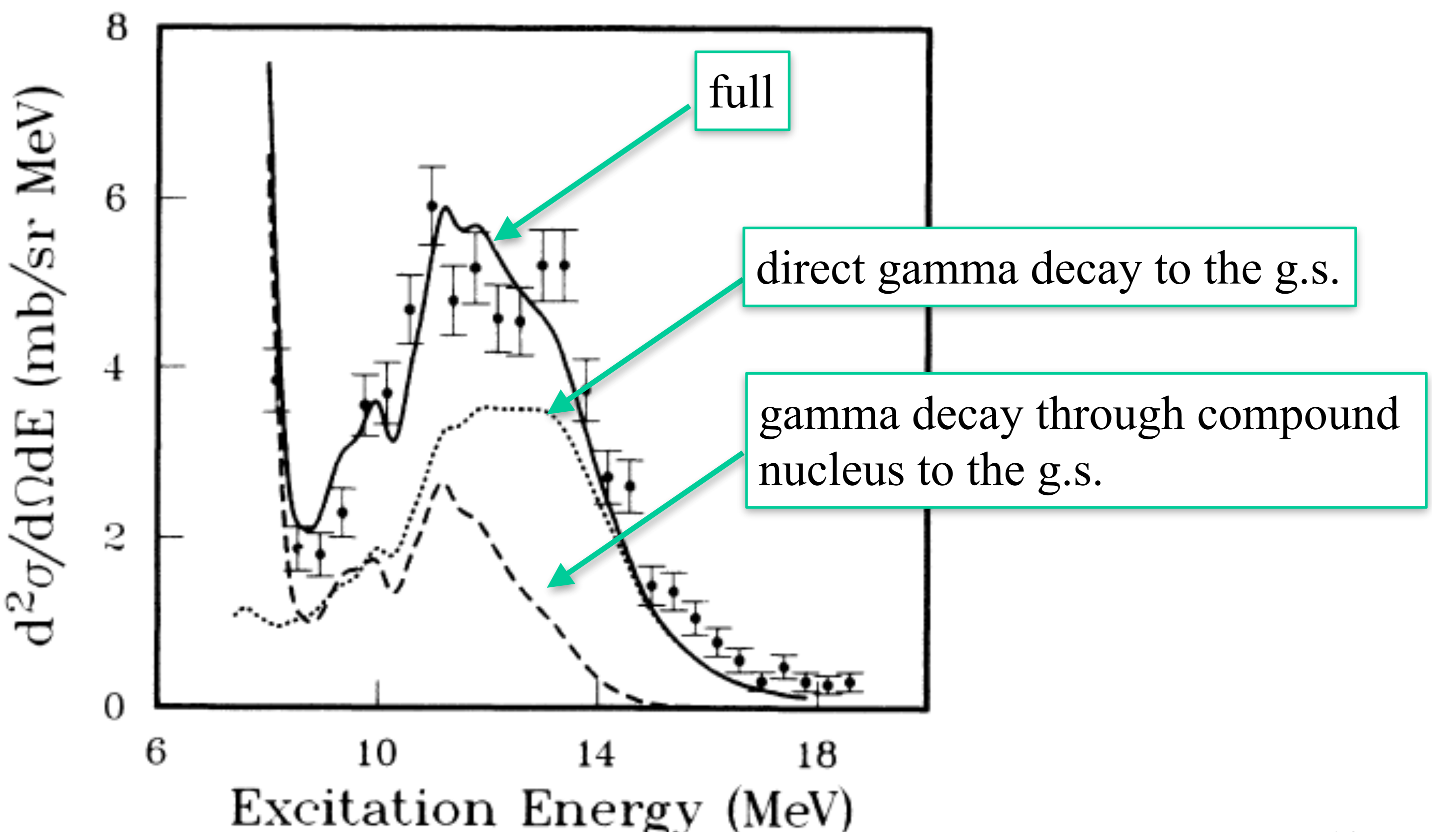
Gamma Decay of IVGDR

coincidence measurement of excitation and gamma-decay

Only one experiment exists!

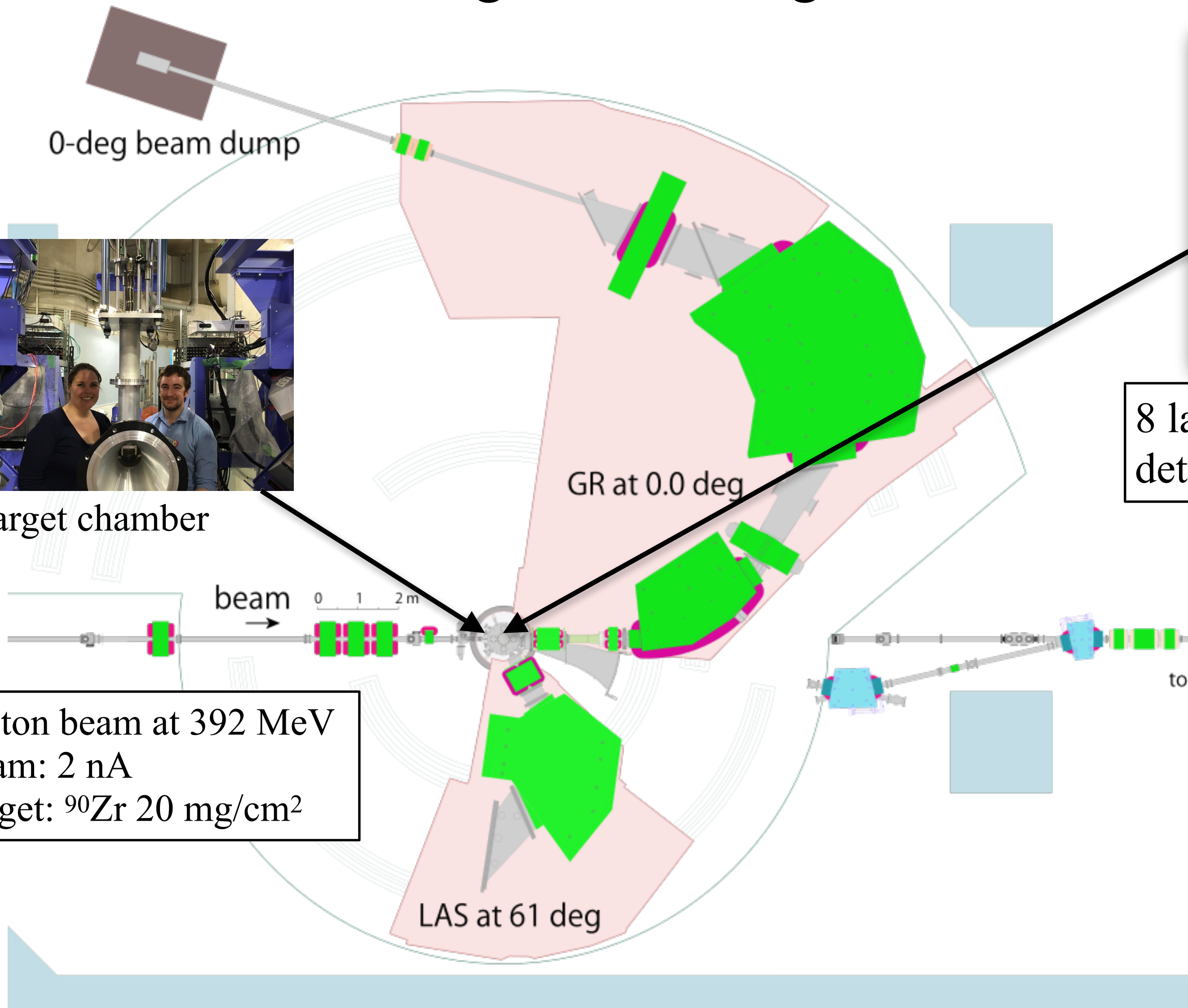
J.R. Beene et al., PRC41, 920 (1990)

$^{208}Pb(^{17}O, ^{17}O'\gamma)$ SSD+NaI

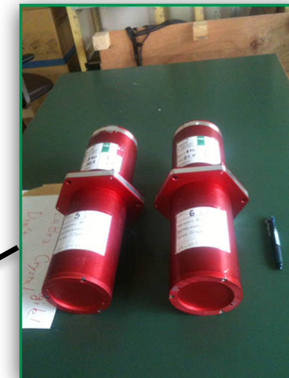


E498: Experimental Methods

GR 0-deg mode + large volume $LaBr_3$



target chamber



8 large volume $LaBr_3$ detectors from Milano

3.5″ϕ×8″L

Proton beam at 392 MeV
Beam: 2 nA
Target: ^{90}Zr 20 mg/cm^2

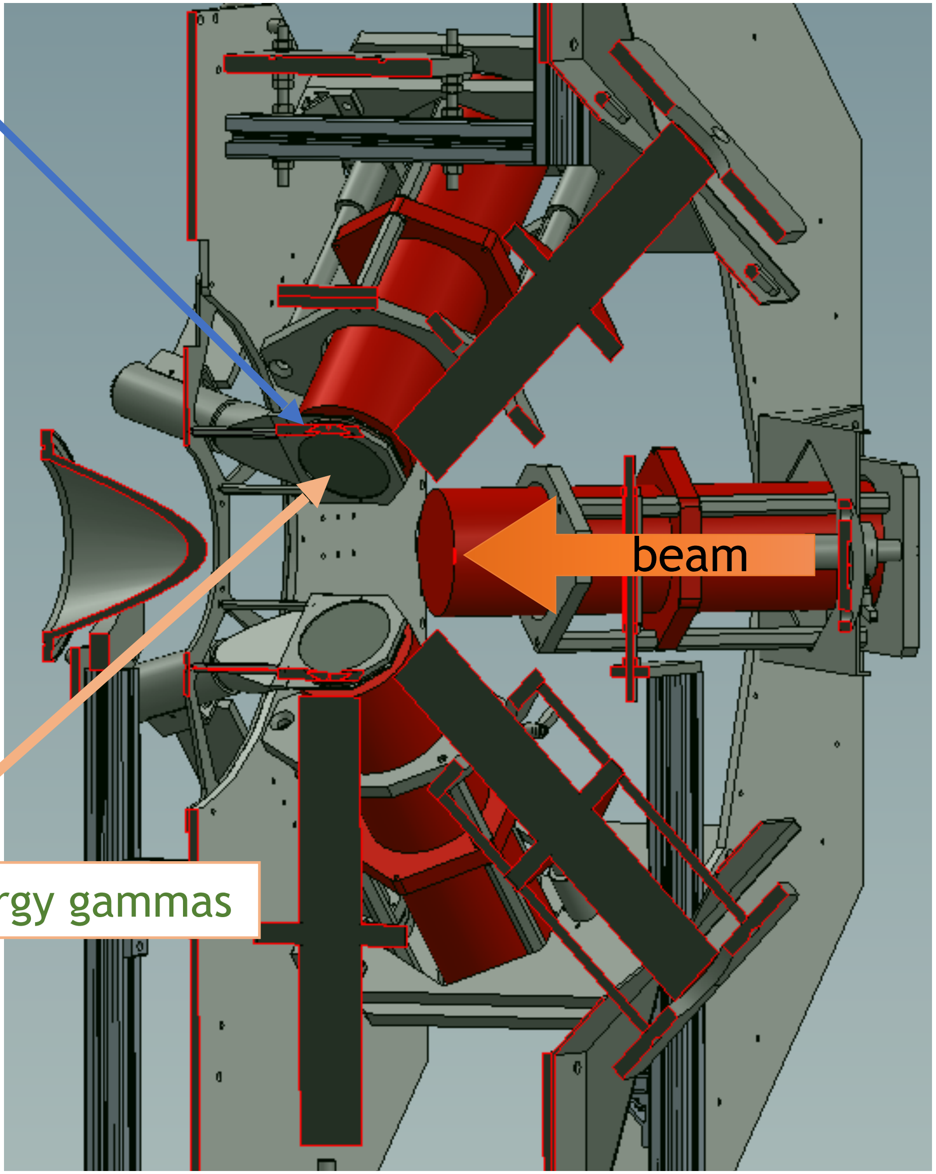
Achromatic mode: ΔE_x = ~100 keV

Gamma ray detector array

Plastic (2mm^t) for charged particle veto

Scylla

Total Number of detectors	8
Detectors at 90’	4
Detectors at 135’	4
Distance from target	135 mm
Solid angle	20% of 4pi
Efficiency @ 15MeV	

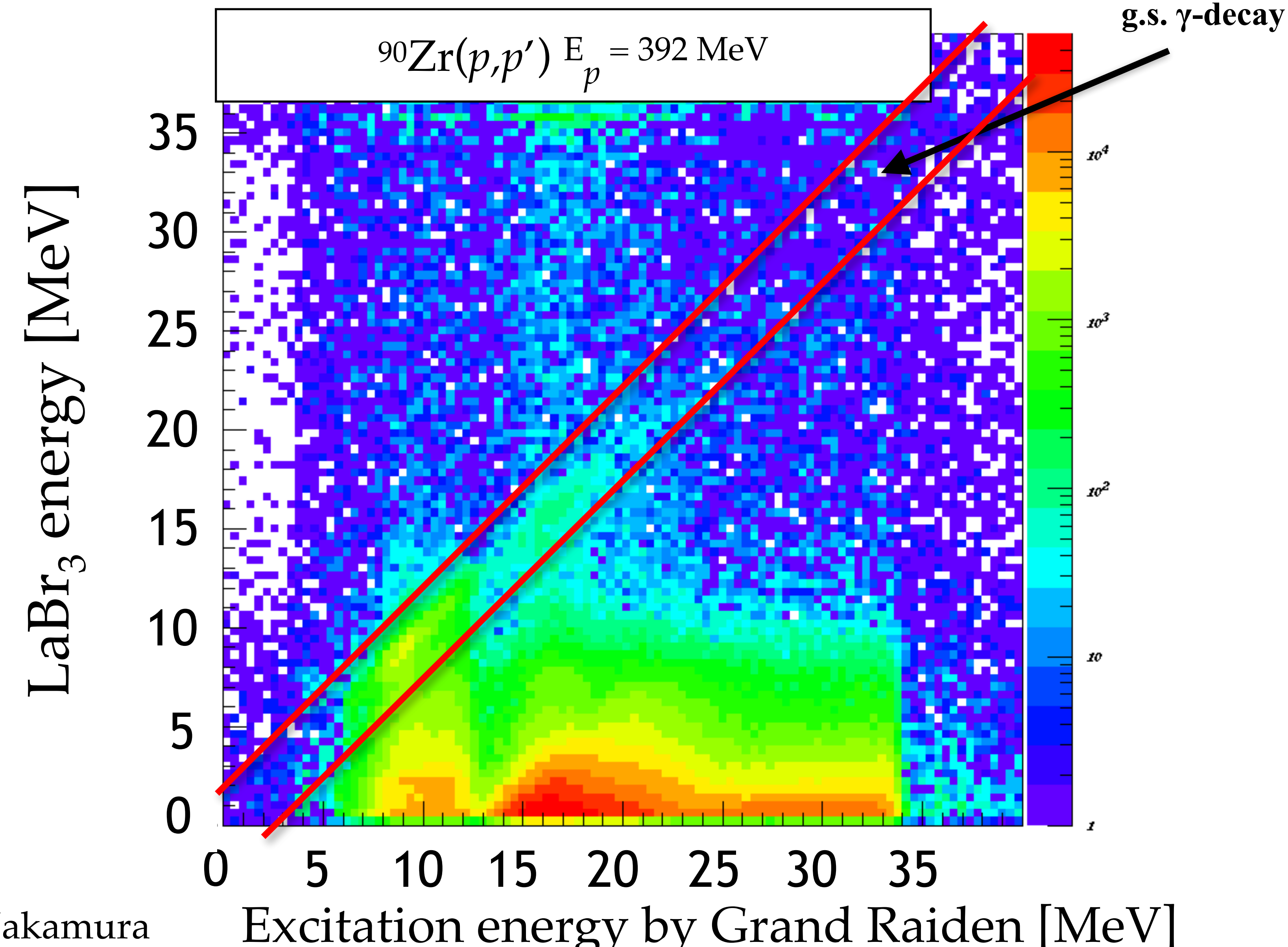


Pb(2mm^t) and Cu(4mm^t) absorber for low energy gammas

by S. Nakamura

Coincidence matrix of Grand Raiden and LaBr3

means the ground state gamma decay



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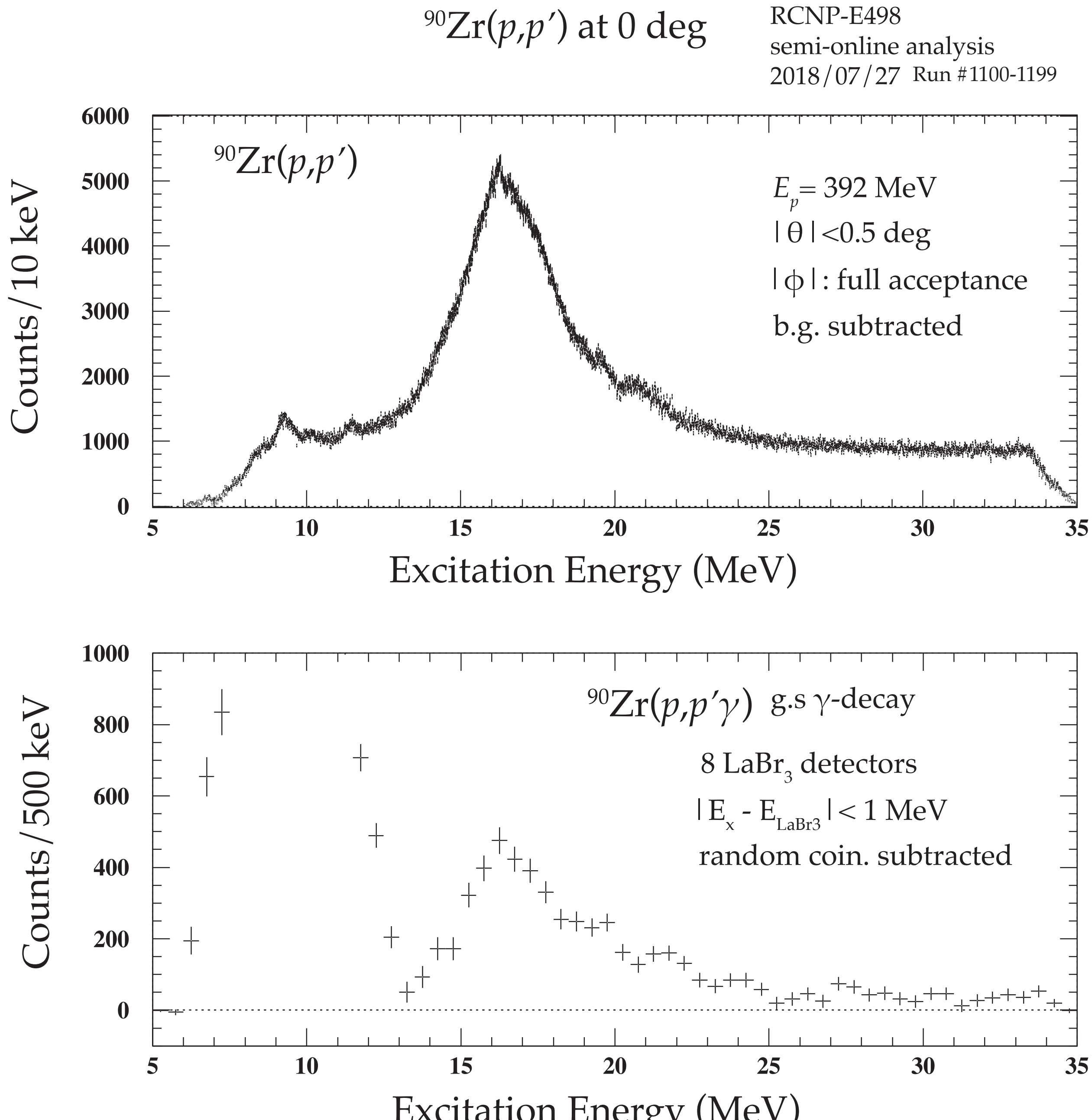
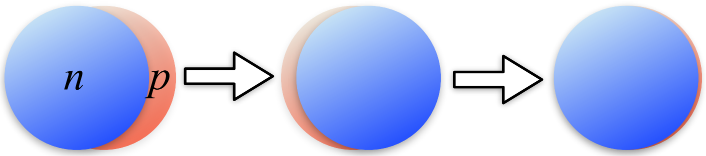


g.s. γ-decay was clearly measured covering fully the IVGDR

Γ_{bin} as a function of E_x



Damping of IVGDR

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$\rightarrow$ B(E1)↑

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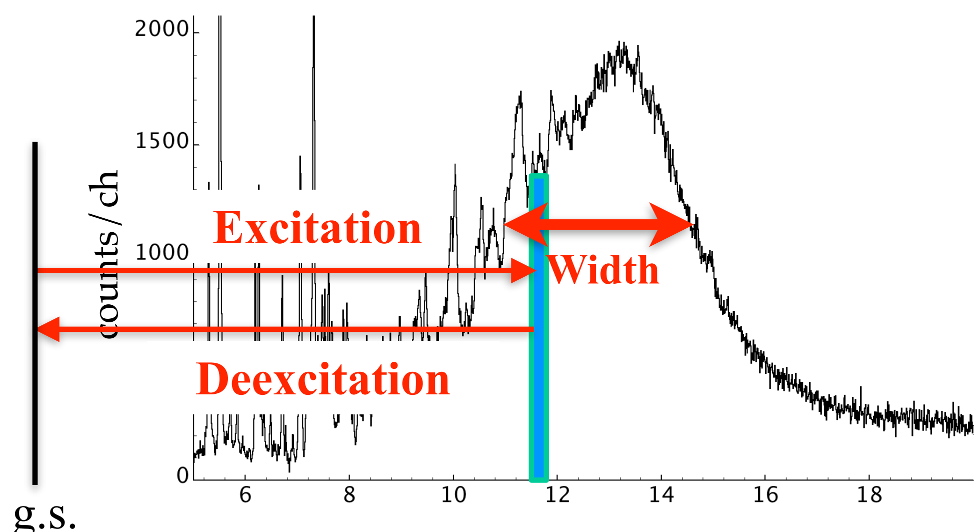
$\rightarrow$ Γ_{γ_0}

Gamma coincidence measurement

$\rightarrow$ branching ratio $b_{\gamma_0} = \frac{\Gamma_{\gamma_0}}{\Gamma_{bin}}$

$\rightarrow$ Γ_{bin}(Ex) can be determined.

Γ_{bin} can be determined for each E_x bin

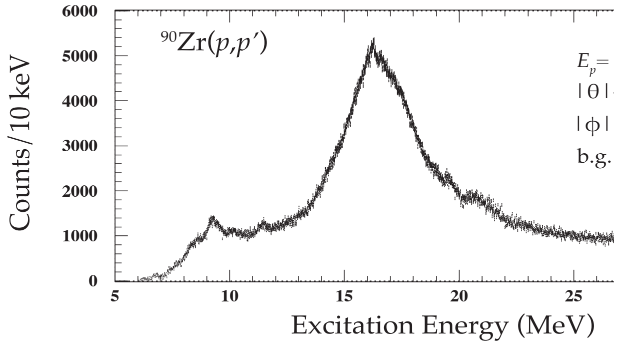


What will be observed? How is Γ_{bin} distributed in E_x?

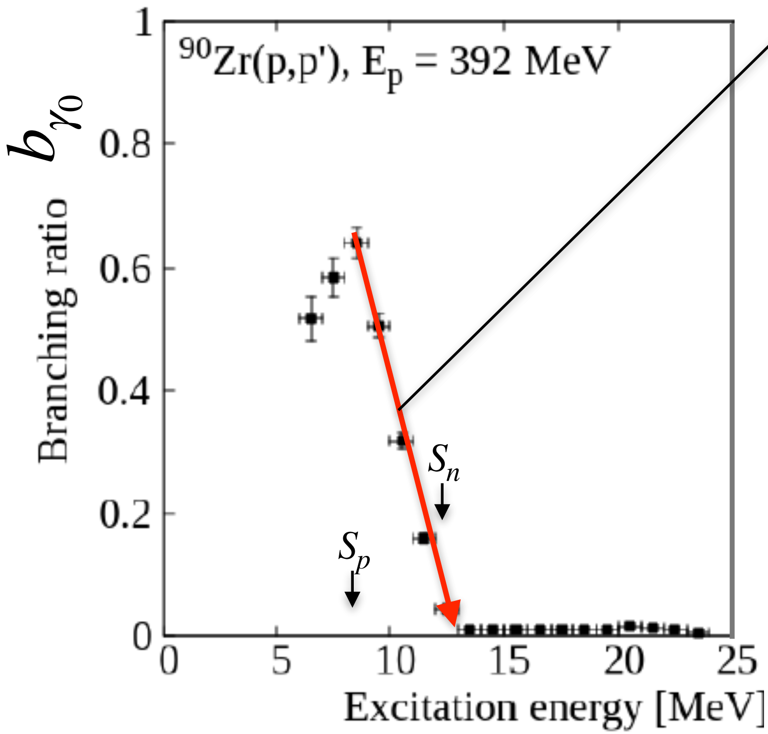
Experimental Results
(preliminary)

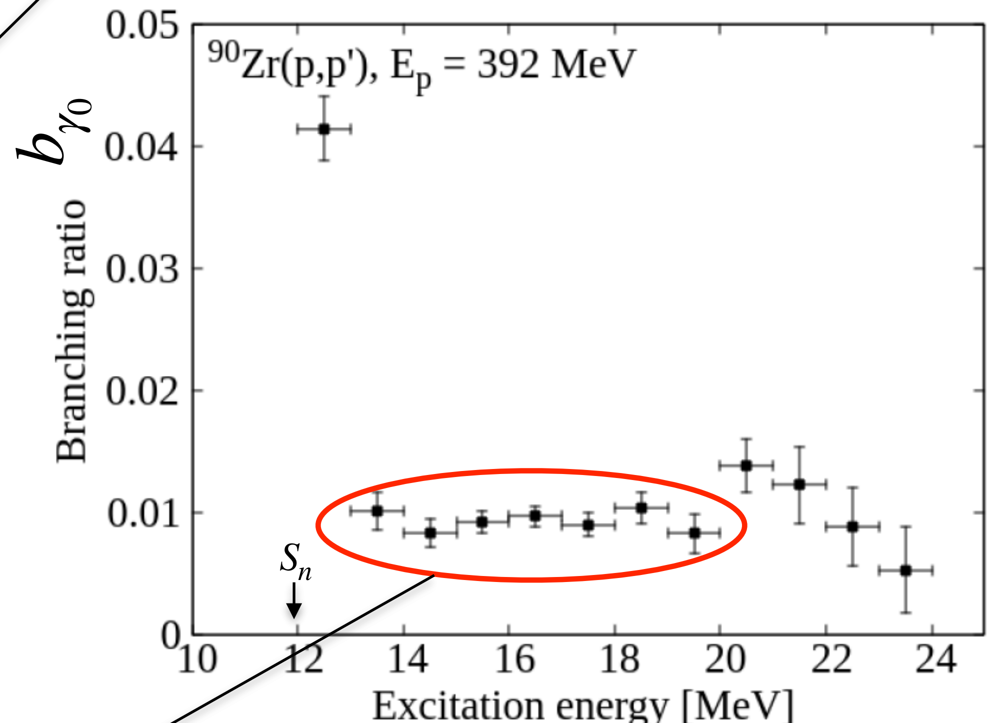
g.s. γ-Decay Branching Ratio

Preliminary



Drop due to increase of cascade γ-decays and the opening of proton decay





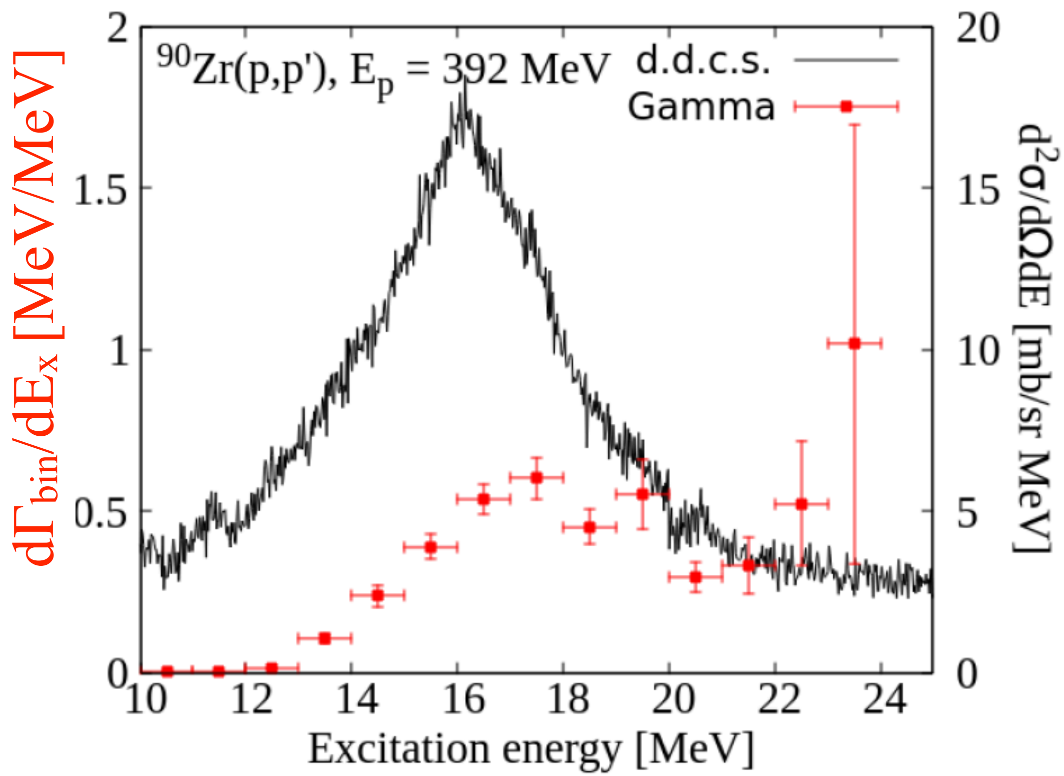
The observed g.s.γ-decay branching ratio is nearly constant in the IVGDR region.

S. Nakamura, master thesis

E_x dependence of Γ_{bin}

Preliminary

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



The observed $d\Gamma_{bin}/dE_x$ increases with E_x in the IVGDR region.

How can we interpret the data?

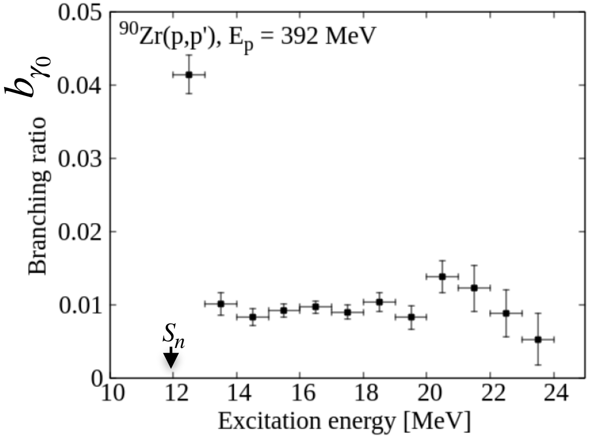
[N]akamura, master thesis

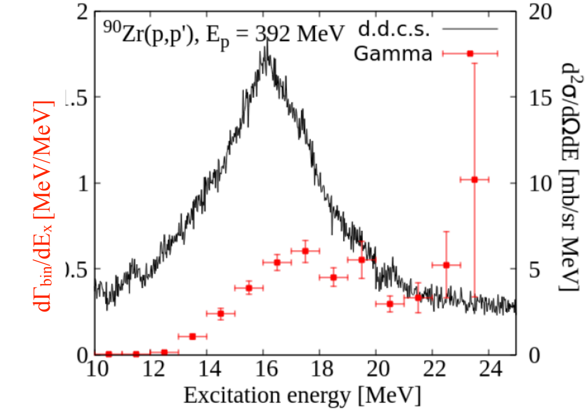
Physical Interpretation (open question)

Why $b_{\gamma 0}$ is nearly flat in the IVGDR region?

The underlying physical reason is unclear yet.

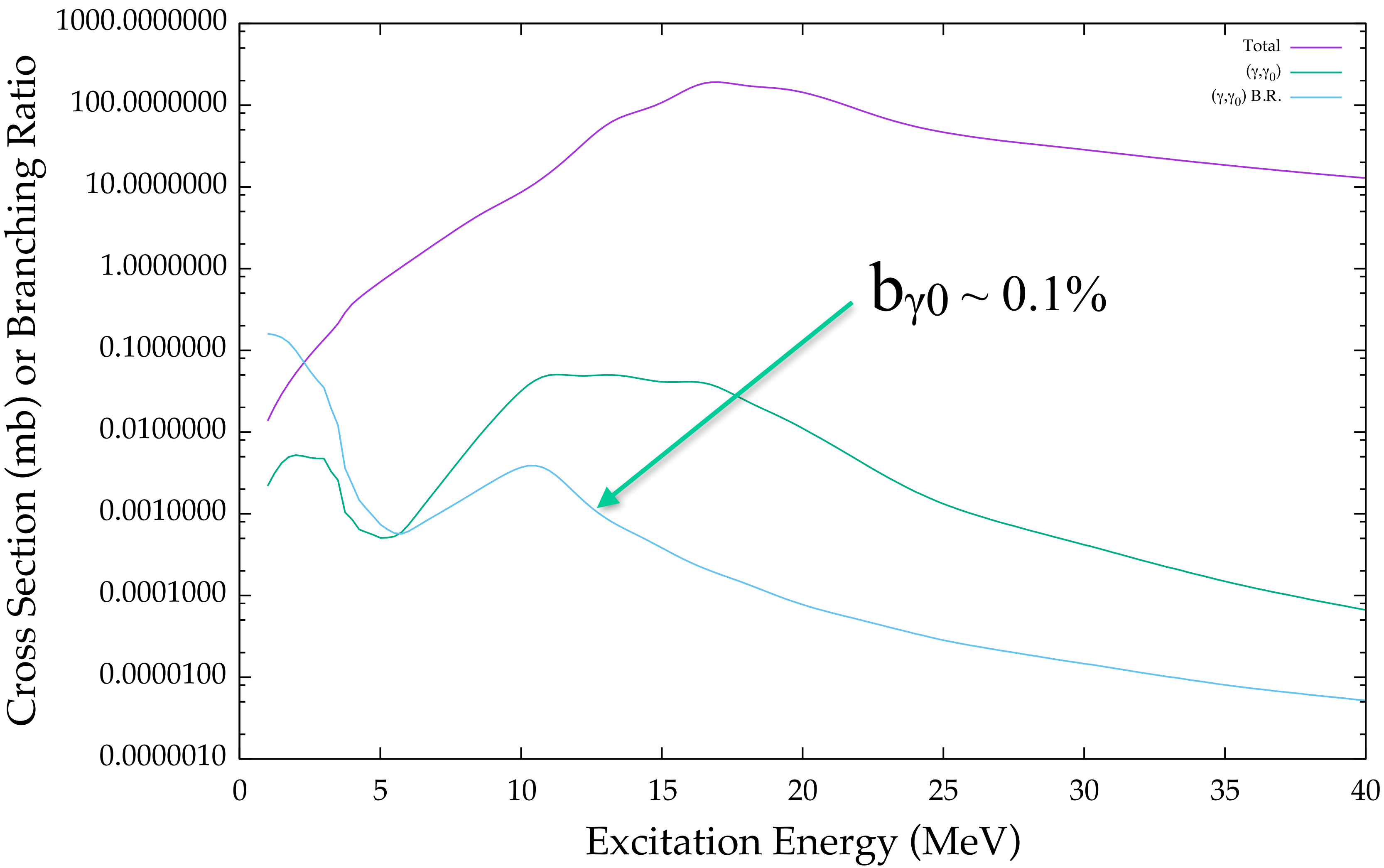
The IVGDR in ^{208}Pb also seems to have nearly a flat b.r.





90Zr

Preliminary



TALYS predicts g.s. gamma branching ratio of the order of $b_{\gamma 0}$~0.1%.

Since the excitation c.s. (and thus $\Gamma_{\gamma 0}$) is well predicted, pre-equilibrium contributions are underestimated or particle decay widths are over-predicted.

Physical Interpretation (open question)

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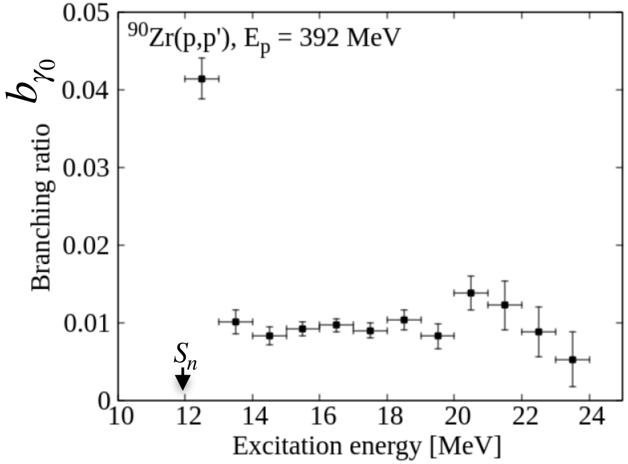
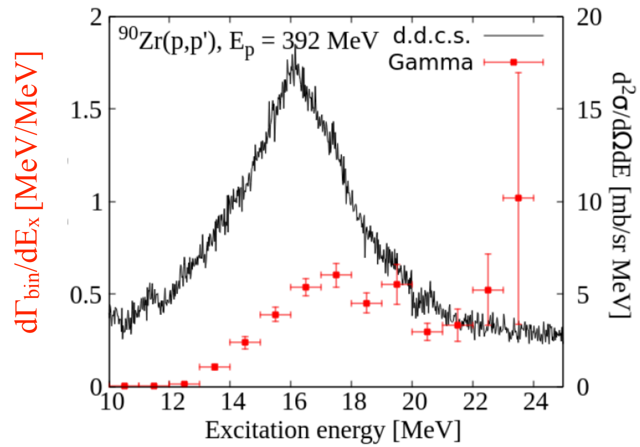


<u>Why Γ_{bin} increases as E_x increases?</u>

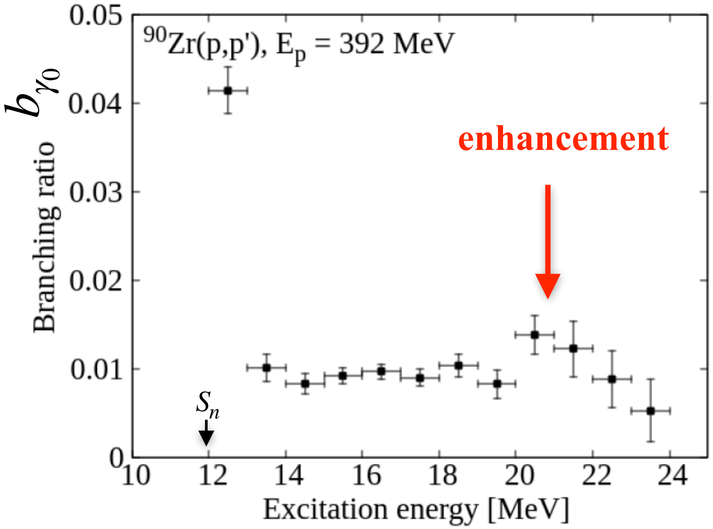
Probably due to the increase of the particle decay width and of the spreading width.

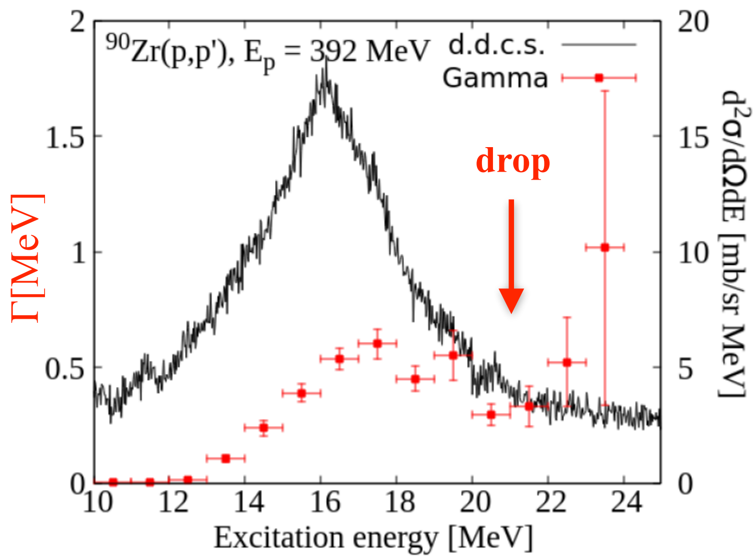
Γ_{bin} sums up more-or-less to the resonance width Γ.

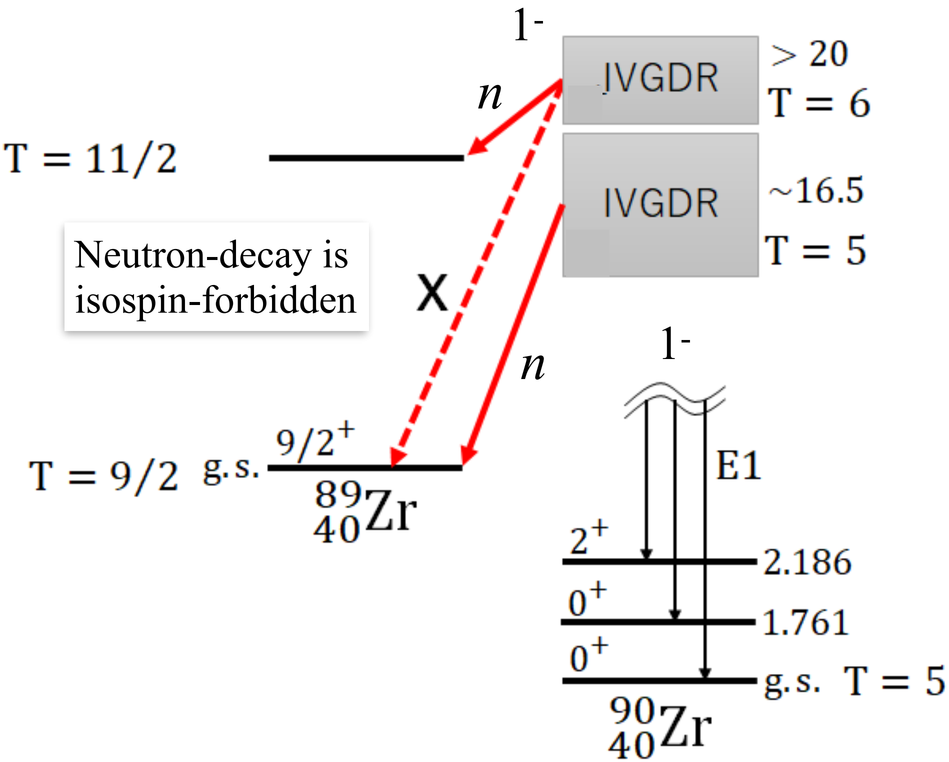


Effect of the Isospin Upper IVGDR

Preliminary







Ex is consistent with the work by ^{89}Zr(p,γ)

S. Nakamura, master thesis

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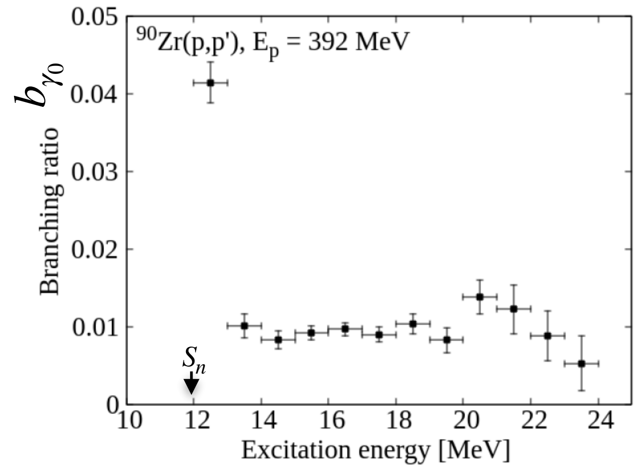

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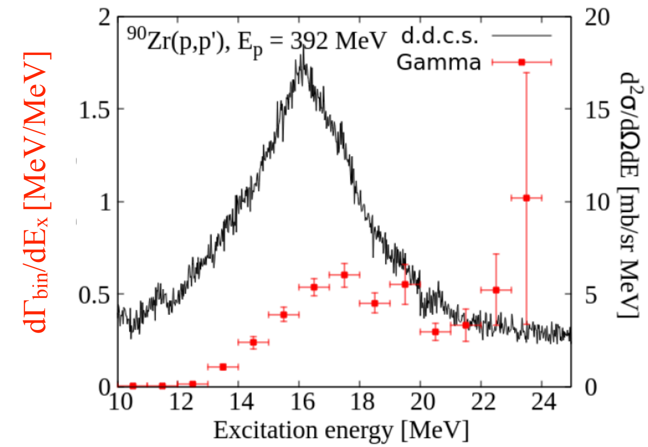

Further study for different nuclei and for the other decay channels in the PANDORA project and in other dedicated experiments.

Summary

I picked up the following subjects in my lectures.

- Overview of Giant Resonances
- Experiment using High-Resolution Spectrometer
- Electric Response of Nuclei, Sum Rule
- Nuclear Equation of State, Neutron Stars
- Photo-nuclear reaction of light nuclei and ultra-high-energy cosmic rays
- Spin-Magnetic Response of Nuclei, Damping of GDR, Fine Structure

A nucleus is very complicated system. Many interesting features appear depending on the way of your study. Also the knowledge on nuclear structures and reactions is important for applications e.g. to nuclear astrophysics, particle physics and industries.

I hope you will enjoy nuclear physics researches and I hope to have collaborative work together.

Thank you

No Conclusion.
Our research will continue!