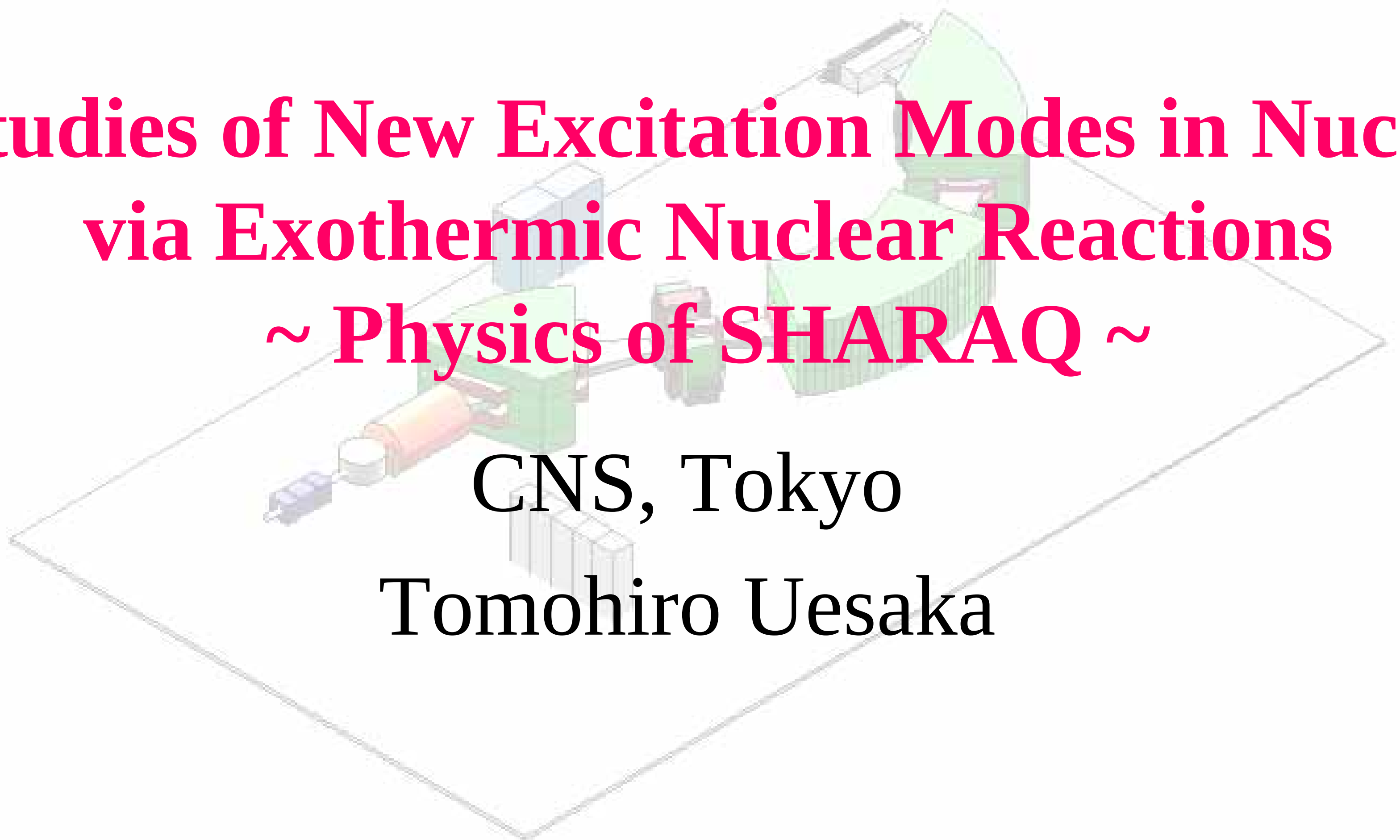
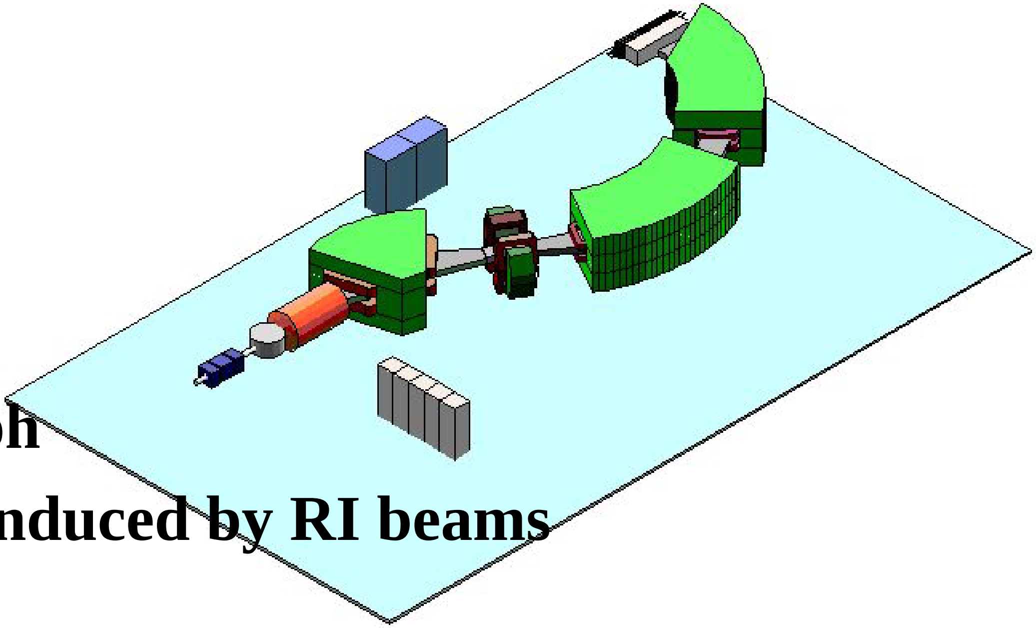
Studies of New Excitation Modes in Nuclei via Exothermic Nuclear Reactions ~ Physics of SHARAQ ~



CNS, Tokyo

Tomohiro Uesaka

Outline



New SHARAQ Spectrograph

EXOTHERMIC reactions induced by RI beams

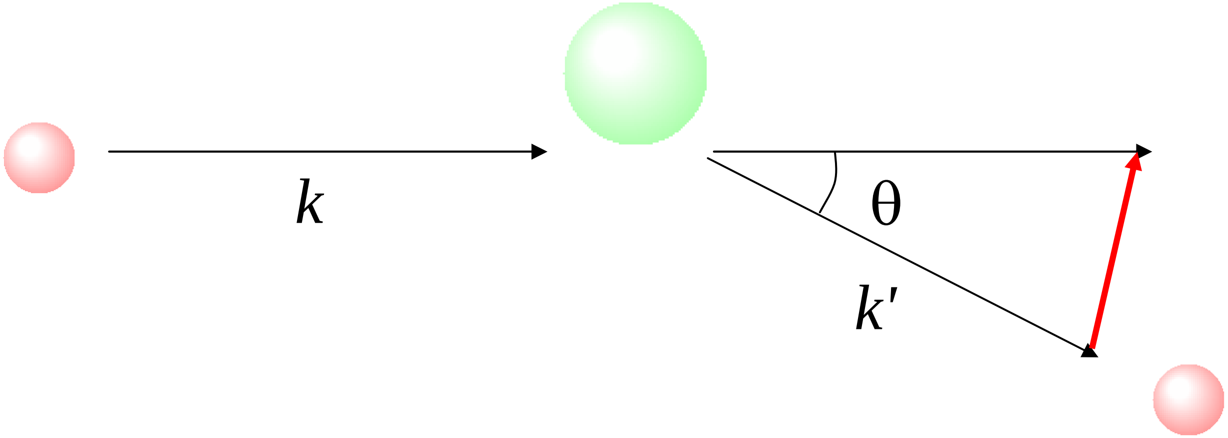
LECTURE:

- **Introduction to momentum transfer (*q*) in nuclear reactions**
- ***q*-dependences of nuclear transitions**
- **Idea of exothermic reactions**
- **New excitation modes in nuclei reachable by the reactions**
- **Overview of SHARAQ spectrograph**

What is Momentum Transfer

momentum given to the target nucleus through nuclear reaction

= difference of momenta of projectile and ejectile.



$$q = k - k'$$
$$\sim 2k \sin(\theta/2) \text{ if } |k| \sim |k'|$$

angular distribution → *q*-dependence

***q* takes its minimum value at 0°**

Nuclear Reaction in Momentum Space

Transition amplitude by (DW) Born Approximation

$$\begin{aligned} T(k_f, k_i) &= \langle \Psi_f \chi^-(k_f) | V_{\mathrm{residual}} | \chi^+(k_i) \Psi_i \rangle \\ &= \int \mathcal{D}(Q; k_f, k_i) \mathcal{V}(Q) \rho_{fi}(Q) dQ \end{aligned}$$

$\mathcal{D}(Q; k_f, k_i)$ Fourier transform of DW

$\mathcal{V}(Q)$ Fourier transform of interaction

$\rho_{fi}(Q)$ Fourier transform of transition density

In the plane wave limit

$$\mathcal{D}(Q; k_f, k_i) = \int e^{i(k_f - k_i)r} dr = \delta(Q - q)$$

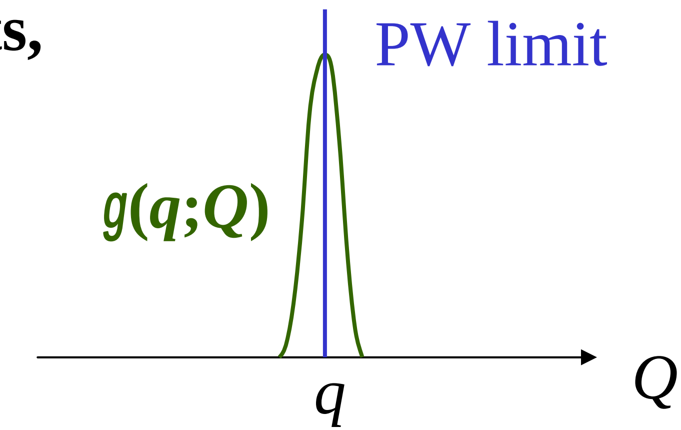
$$\rightarrow \quad T(k_f, k_i) \xrightarrow{\mathrm{PW}} \mathcal{V}(q) \rho_{fi}(q)$$

$q = k_i - k_f$ momentum trasnfer

Nuclear Reaction in Momentum Space (*cont.*)

even in the presence of distortion effects,

T depends mostly on q



distortion depends only weakly on Q

interaction also, if it is short-range

$$T(k_f, k_i) \quad \sim \quad \mathcal{D}(q; k_f, k_i)\mathcal{V}(q) \int \underline{g(q;Q)}\rho_{fi}(Q)dQ$$

smearing function

Nuclear structure dependences of transition amplitude

can be clearly seen through momentum transfer $q = k_i - k_f$

Angular Momentum and *q*

Relation between orbital angular momentum and *q*

transition density in momentum space

$$\rho_{fi}(q) = \int \tilde{\rho}_{fi}(\boldsymbol{r}) e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} d\boldsymbol{r}$$

$$\tilde{\rho}_{fi}(\boldsymbol{r}) \sim \mathcal{R}_\ell(r) Y_{\ell m}(\hat{\boldsymbol{r}})$$

Rayleigh expansion

$$e^{-i\boldsymbol{q}\cdot\boldsymbol{r}} = \sum_{\ell=0}^{\infty} \sum_m (2\ell+1) i^\ell j_\ell(qr) Y_{\ell m}(\hat{\boldsymbol{k}}) Y^*_{\ell m}(\hat{\boldsymbol{r}})$$

Using orthogonality of spherical harmonic

$$\rho_{fi}(q) \sim \int \mathcal{R}_\ell(r) j_\ell(qr) dr$$

If the reaction is sensitive to nuclear surface,

$$\frac{d\sigma}{d\Omega} \sim |j_\ell(qR)|^2$$

$$\frac{d\sigma}{d\Omega} \propto T^2 \sim \rho^2_{fi}(q)$$

Spherical Bessel Function

for R=4 fm

L=0 j_0(qr)

peak at *qr* = 0

1st minimum at *qr* = π

q ~ 0.8 fm^{-1} = 160 MeV/c

L =1 j_1(qr)

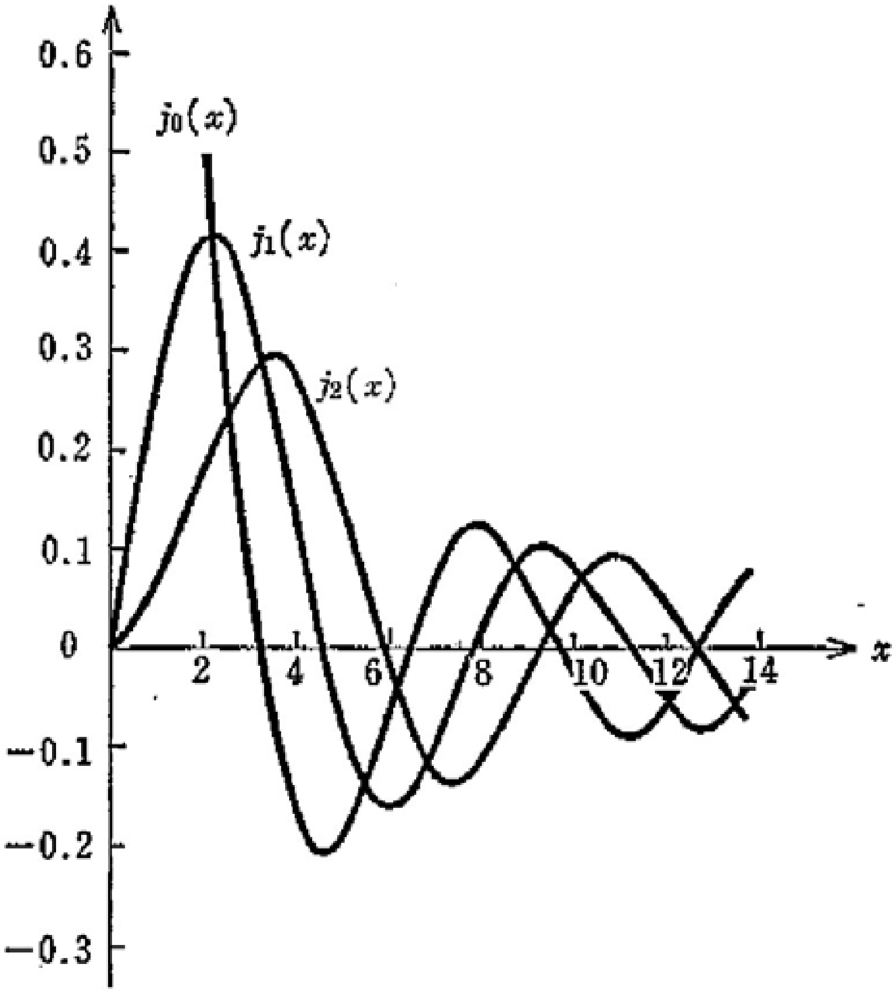
1st peak at *qr* ~ 2

q ~ 0.5 fm^{-1} = 100 MeV/c

L =2 j_2(qr)

1st peak at *qr* ~ 4

q ~ 1.0 fm^{-1} = 200 MeV/c

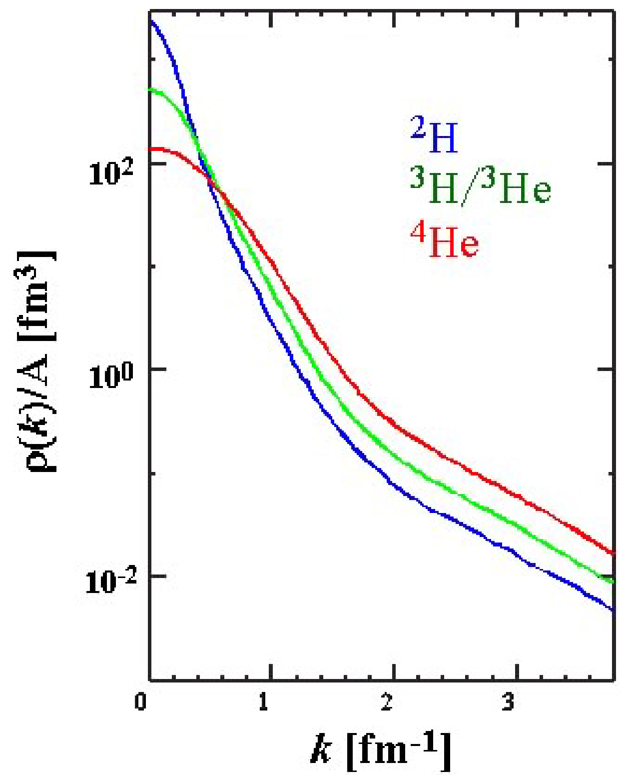


q-region and related physics

Large momentum transfer

high momentum states → Ideguchi-san's talk

short-range phenomena



R.Schiavilla et al., Nuclear Physics A **449** (1986) 219

Small momentum trasnfer

ΔL = 0 transitions

Gamow-Teller transtion

weakly bound states

$$k \sim \sqrt{2\mu B}$$

neutron rich nuclei

pionic atom

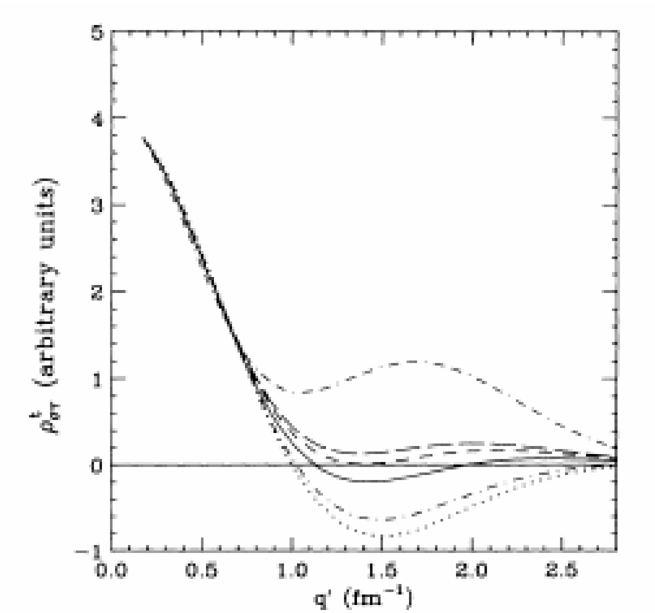
Examples of *q*-dependences

1) **Gamow-Teller excitation**

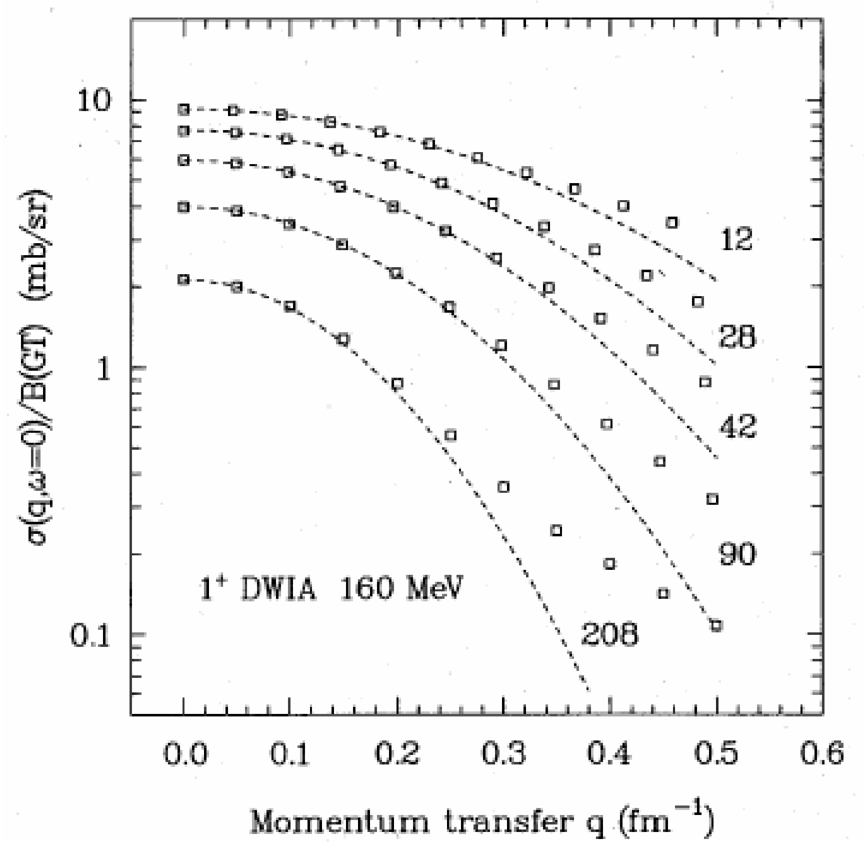
$\Delta S = 1$

$\Delta T = 1$

$\Delta L = 0$



F. Osterfeld et al., Phys. Rev. C 45 (1992) 2854.



T. N. Taddeucci et al.,
Nucl. Phys. A 469 (1987) 125.

Examples of *q*-dependences (*cont.*)

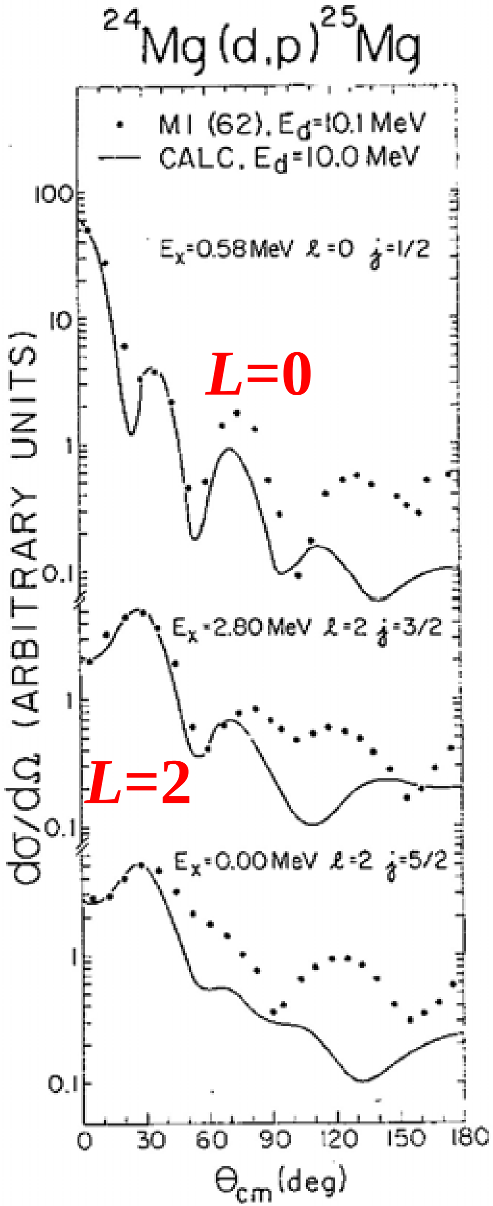
2) (*d*,*p*) reaction

$$T^{\mathrm{PW}} = \sum F_T(q) F_p(q')$$

$$q = k_p - \frac{A}{A+1} k_d$$

transition density of target part is w.f. of transferred neutron

$$\tilde{\rho}_{fi}(r) \sim \Psi_n(r) Y_{\ell m}(\hat{r})$$



T.J.Yule and W. Haeberli, Nucl. Phys. A 117 ('68) 1.

What' beyond?

spectroscopy of low excitation energy levels with small L

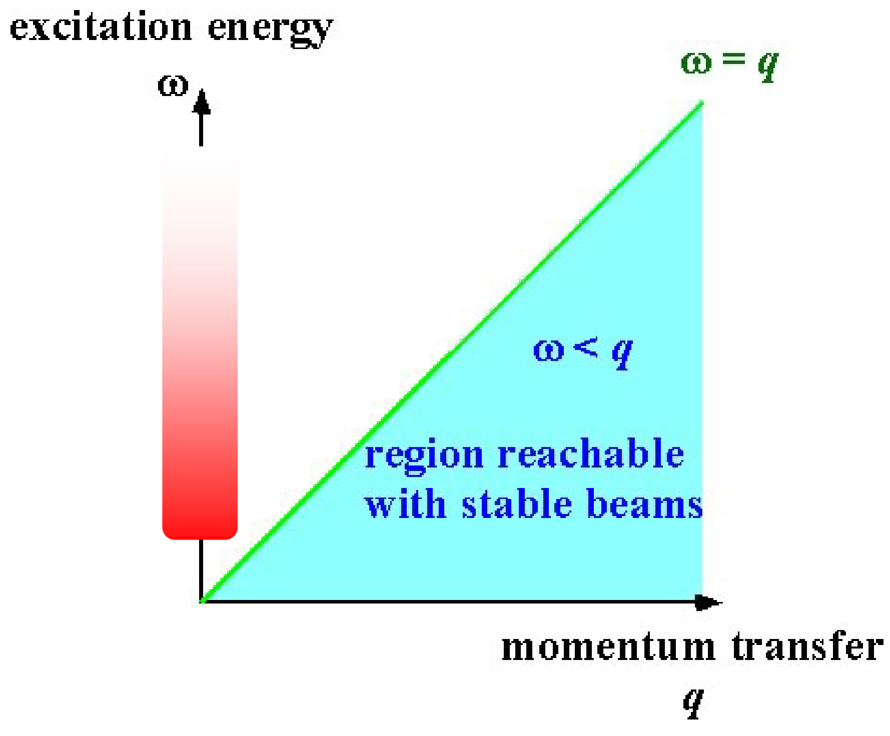
→ reactions with stable beams work well.

BUT this is not the case for highly excited states with small L!

WHY limited?

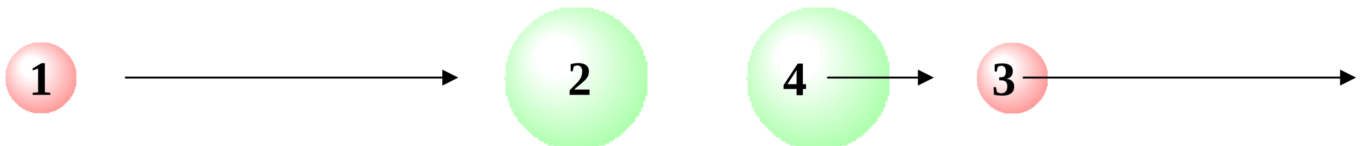
HOW we can break the limitation?

What we can expect in the unexplored region



Excitation energy and momentum transfer

Consider binary reaction at 0°.



Energy Conservation $$E_1 + m_2 = E_3 + E_4$$

Momentum Conservation $$p_1 = p_3 + p_4$$

since $q << m_4$ in the case considered, $T_4 \sim 0$.

Energy transfer $$\omega = E_1 - E_3 \sim M_4 - M_2$$

Momentum transfer $$q = p_1 - p_3$$

ω and *q* (*cont.*)

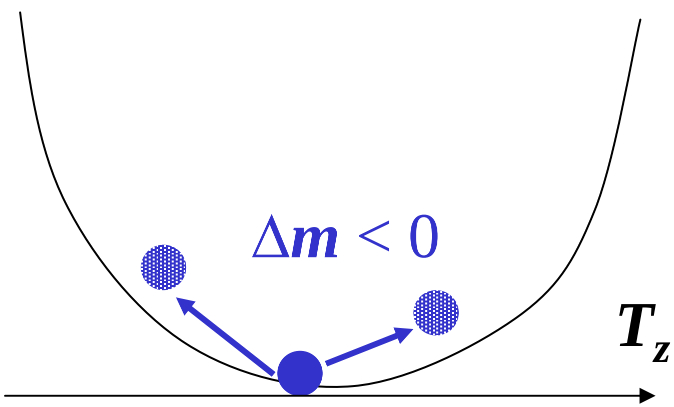
Solving the equations and taking small *q* approximation,

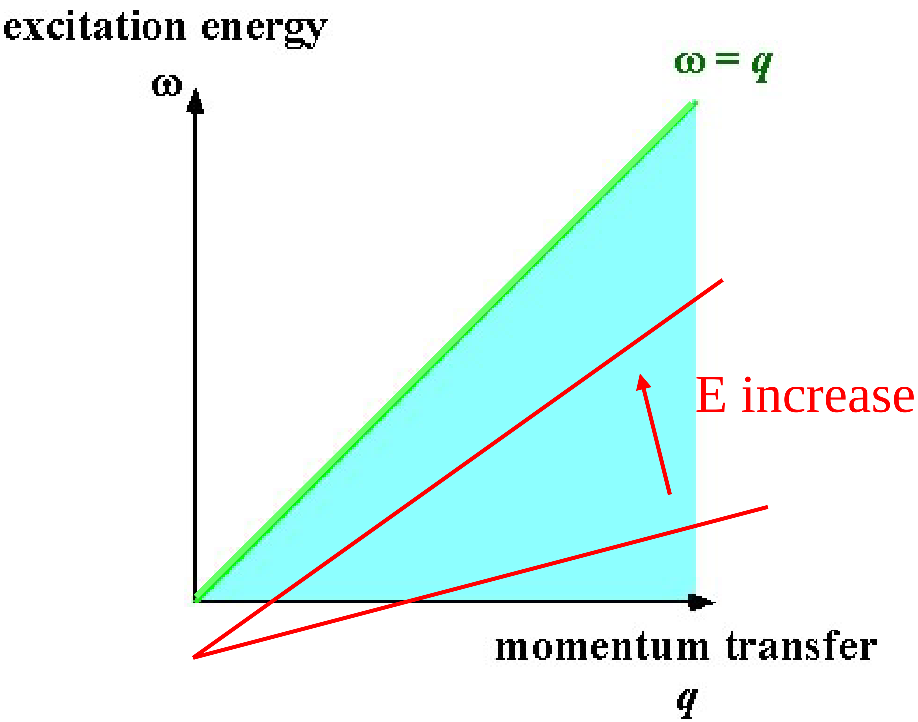
$$\omega \sim \frac{m_1 - m_3}{\gamma} + \beta q$$

In stable beam induced reactions

$$\Delta m = m_1 - m_3 \leqq 0$$

stable nucleus has the smallest mass among its isobars



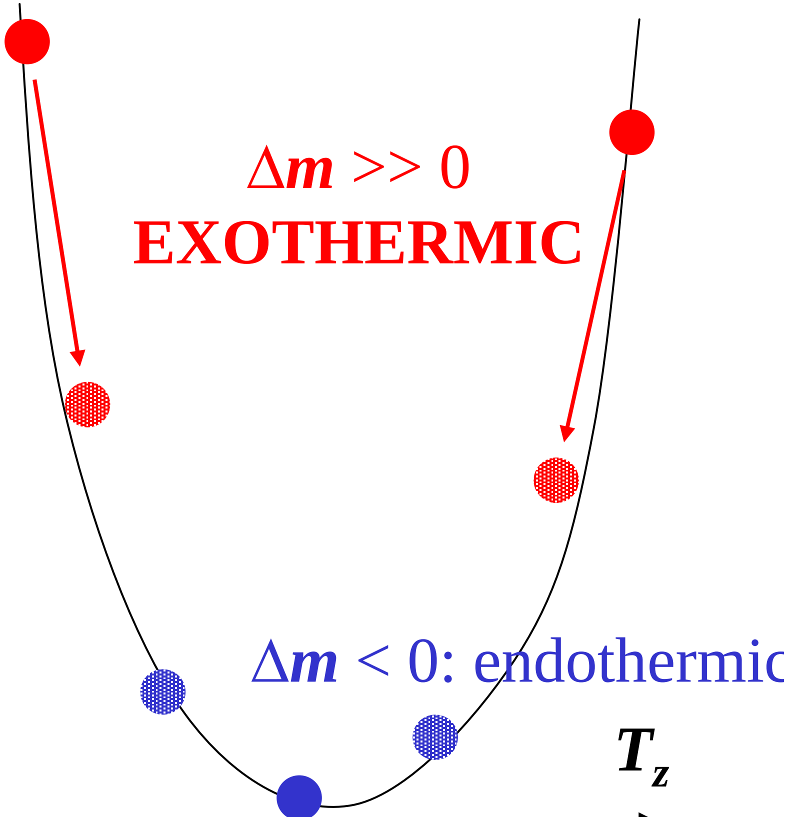


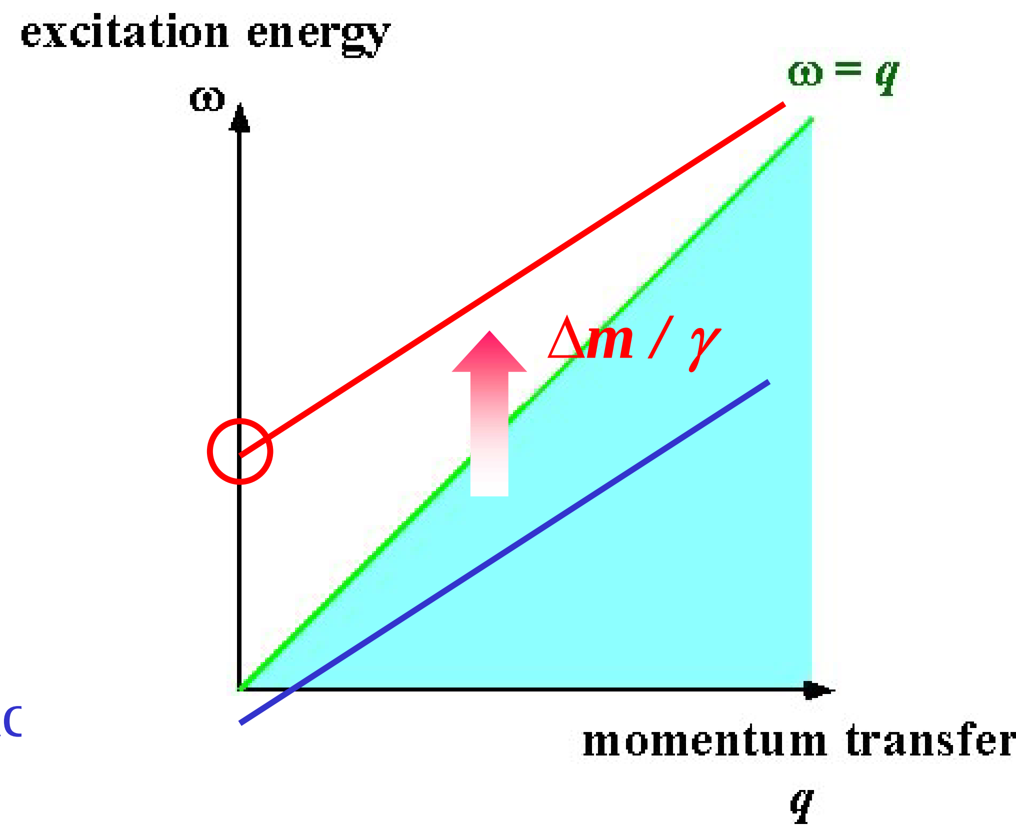
New Idea to use unstable nuclei

with stable beam

with unstable beam

$$\omega \sim \frac{m_1 - m_3}{\gamma} + \beta q$$





New Excitation modes at large ω & small *q*

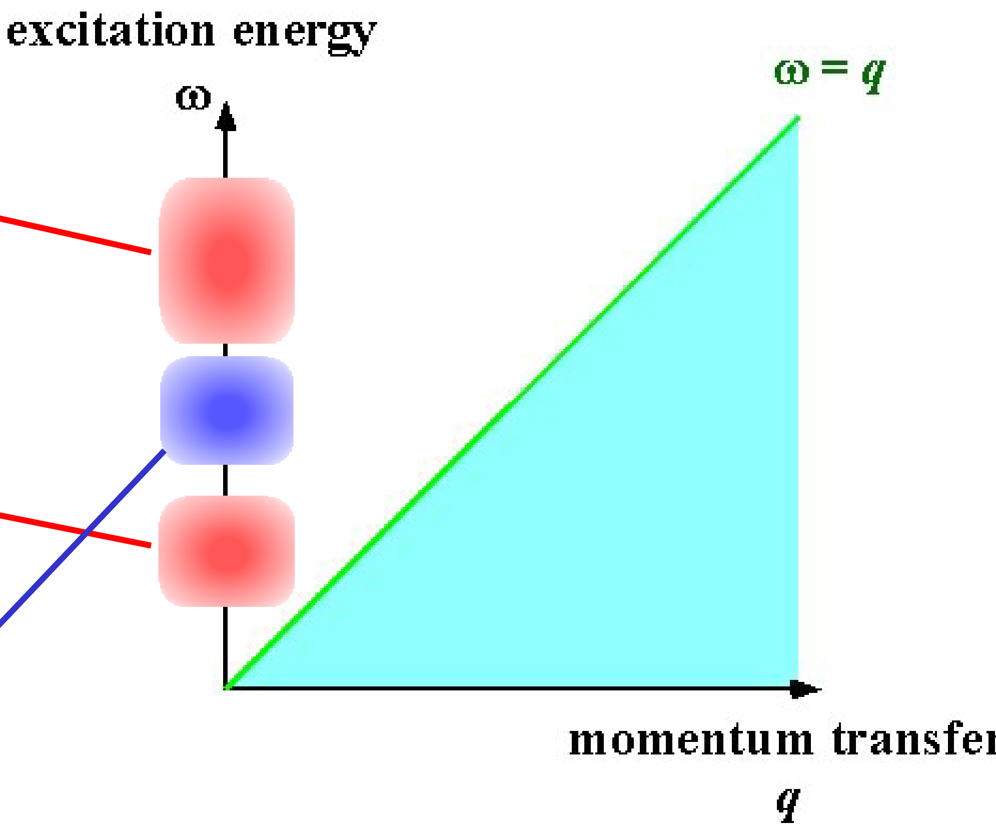
ΔL=0 Excitations

2) Isovector Spin Monopole Resonances
ω = 30 – 40 MeV

1) Double Gamow-Teller resonance
ω = 20 – 25 MeV

Weakly interacting system

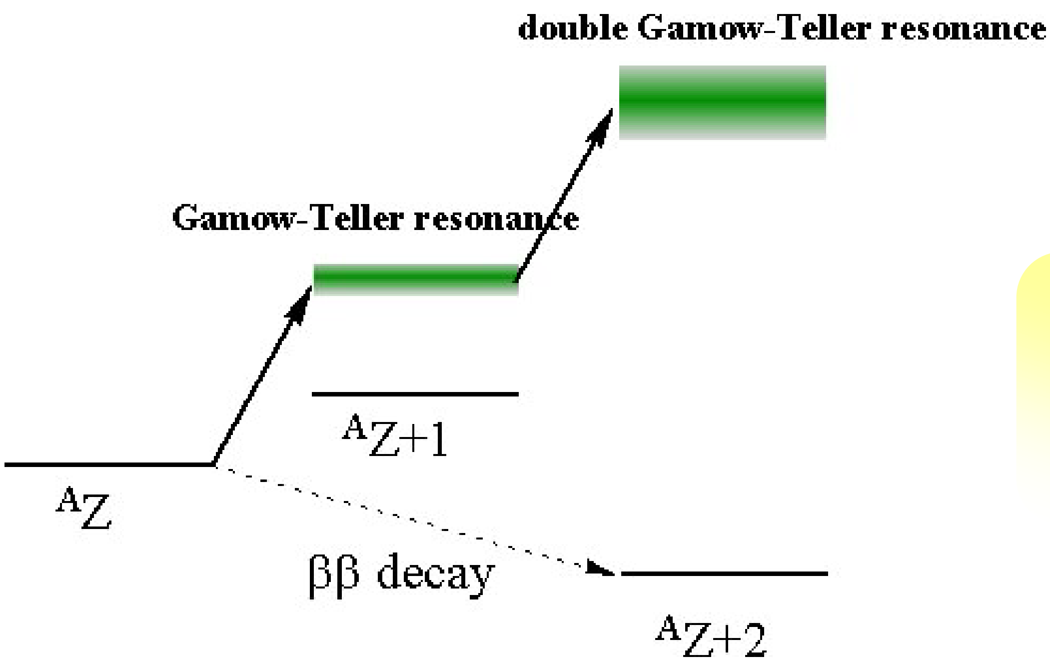
3) Multi-neutron states
ω ~ 30 MeV



Double Gamow-Teller resonance

GT resonance laid on GT resonance

NOT YET DISCOVERED



$E_{DGTR} = 2\ E_{GTR}$?

$\Gamma_{DGTR} = \sqrt{2}\ \Gamma_{GTR}$?

irreplaceable "calibration standard" of ββ-decay nuclear matrix element

Heavy-ion double charge exchange reactions

(^{18}O,^{18}Ne), (^{11}B, ^{11}Li) → no successful results

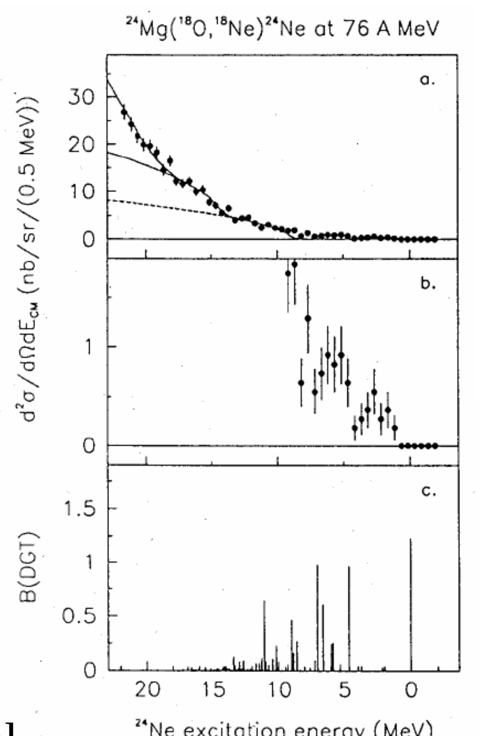
Momentum transfer in candidate reactions

(^{18}O,^{18}Ne) @76MeV/A , GANIL

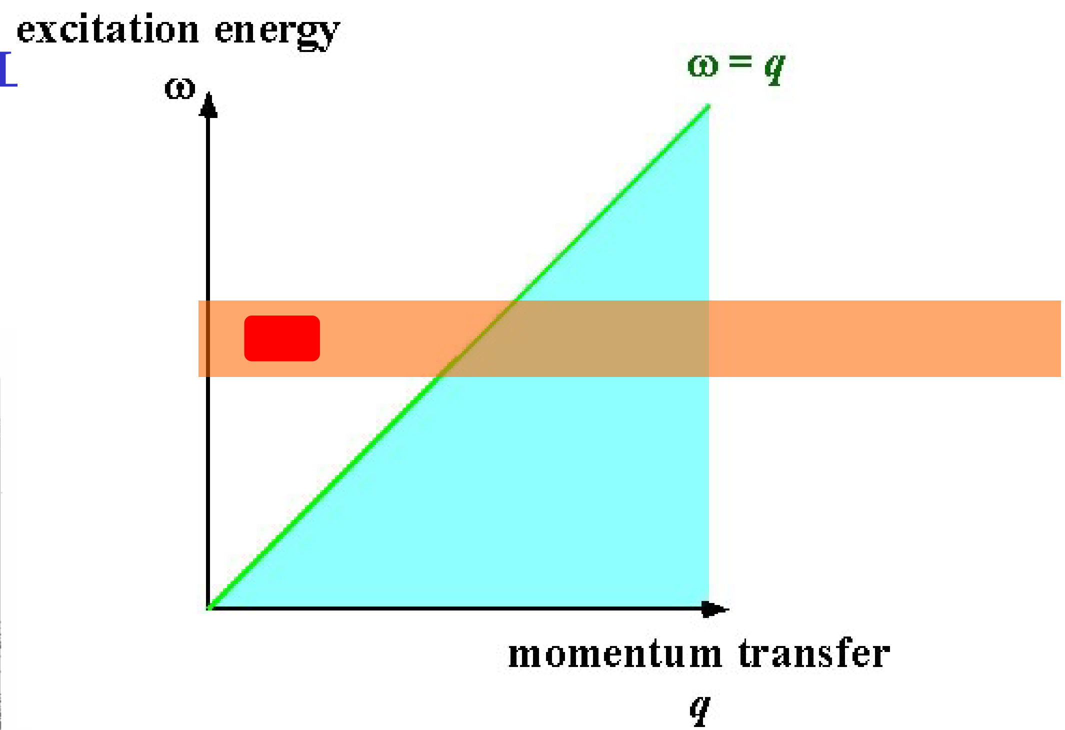
→ q = 90MeV/c

(^{11}B, ^{11}Li) @69MeV/A, RCNP

→ q = 174MeV/c



J. Blomgren et al.,
Phys. Lett. B **362** (1995) 34.



^{100}Mo(^{20}Mg,^{20}Ne) @150MeV/A , RIBF

→ q = 8MeV/c

most promising reaction

Isovector Spin Monopole Resonance

Breathing (compressive) mode

spin-isospin density ($\langle\sigma\tau\rangle$) oscillates

⇔ "spin-isospin compressibility"

propagation velocity of "spin-isospin sound"

$$\mathcal{O}_{\mathrm{IVSMR}} = \sum r_i^2 \sigma_i \tau_i$$

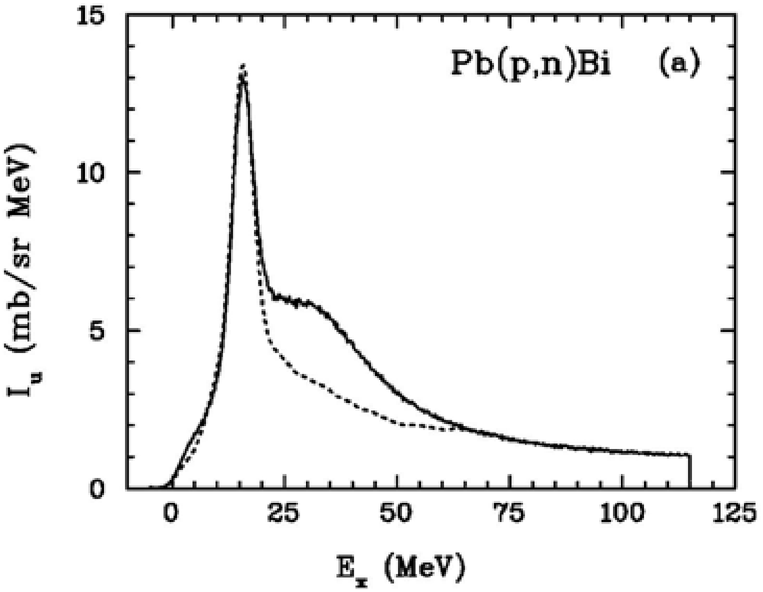
One data indicative of its existence

^{208}Pb(*p*,*n*) @795MeV (LAMPF)

D.L. Prout et al., PRC **63** (2000) 014603.

(^{3}He,t) data from RCNP

R.G.T.Zegers et al. PRL **90** (2003) 202501.



Probes to IVSMR

L=0 resonance

→ small *q*

spin-isospin excitation

→ 150 – 300MeV/A

surface sensitivity

$$\int \rho_{\mathrm{IVSMR}}(r) r^2 dr = 0$$

→ heavy ion reaction

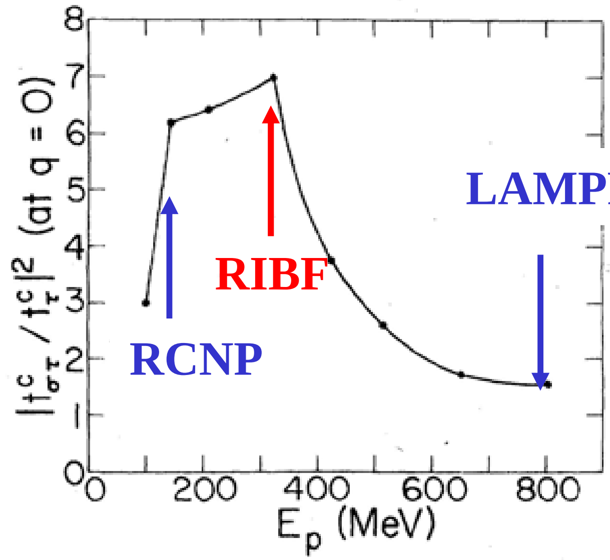
(^{12}N,^{12}C), (^{12}B,^{12}C) reaction at RIBF

possible probes to IVSMR

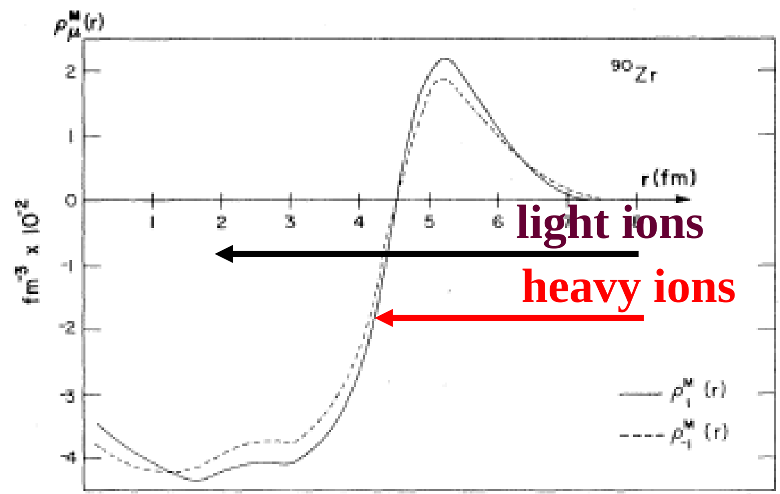
q ~ 40 MeV/c

E/A ≦ 350 MeV/A

sensitivity to στ mode



W.G.Love and M.A.Franey, Phys. Rev. C **24** (1981) 1073.



N. Auerbach et al., Phys. Rev. C **28** (1983) 280.

Multi-neutron states

extreme of neutron-rich, weakly interacting "nuclei"

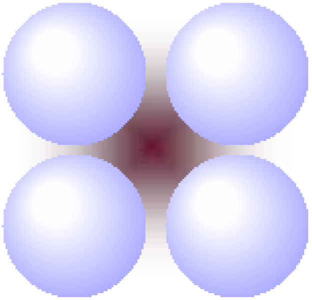
many body correlation in neutron matter

three-, four- nucleon force

4-neutron bound state:"tetra-neutron"

B≦1MeV

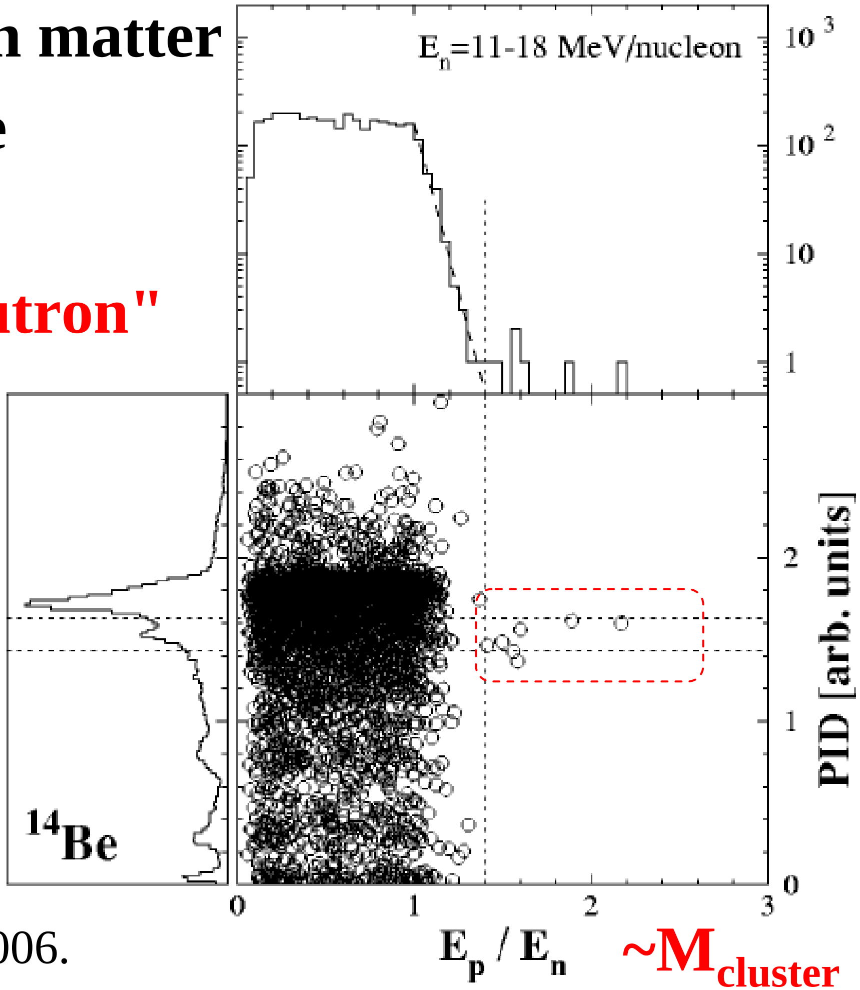
if bound



Candidates?

7 events in ^{14}Be breakup

in coincidence with ^{10}Be



F.M. Marques et al., Phys. Rev. C **65** (2002) 044006.

(^{8}He,^{8}Be) Reaction

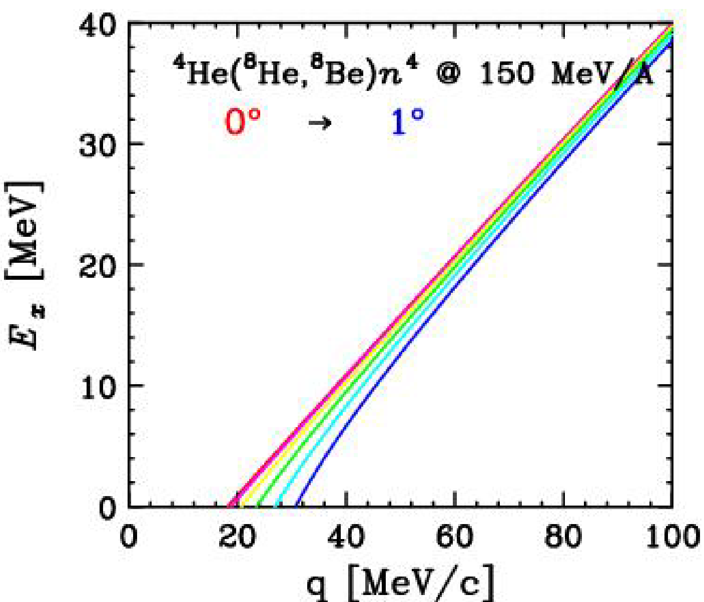
n^4**-state: weakly interacting system**

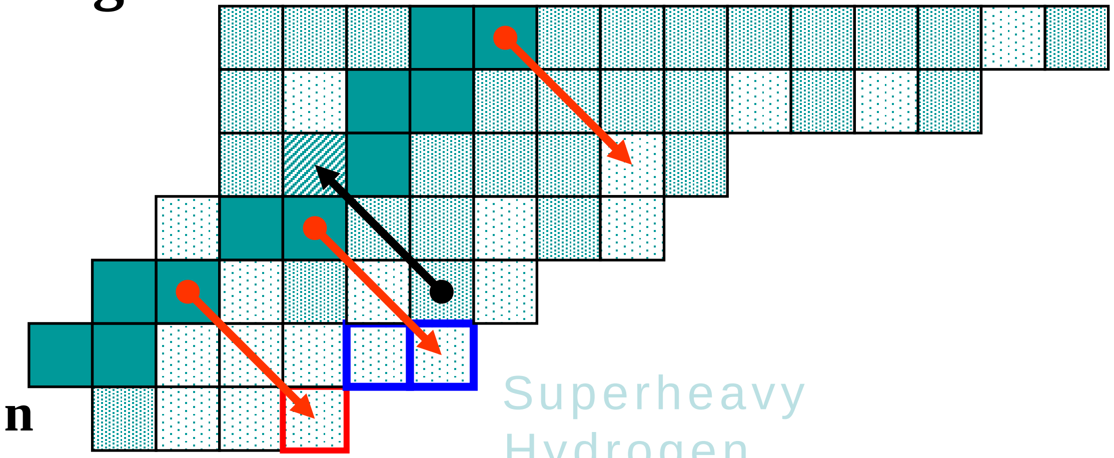
→ **should be softly produced, i.e. with small *q***

$\omega \sim 4m_n - m_{^4He} \sim 30\text{MeV}$

(^{8}He,^{8}Be) reaction

double charge exchange



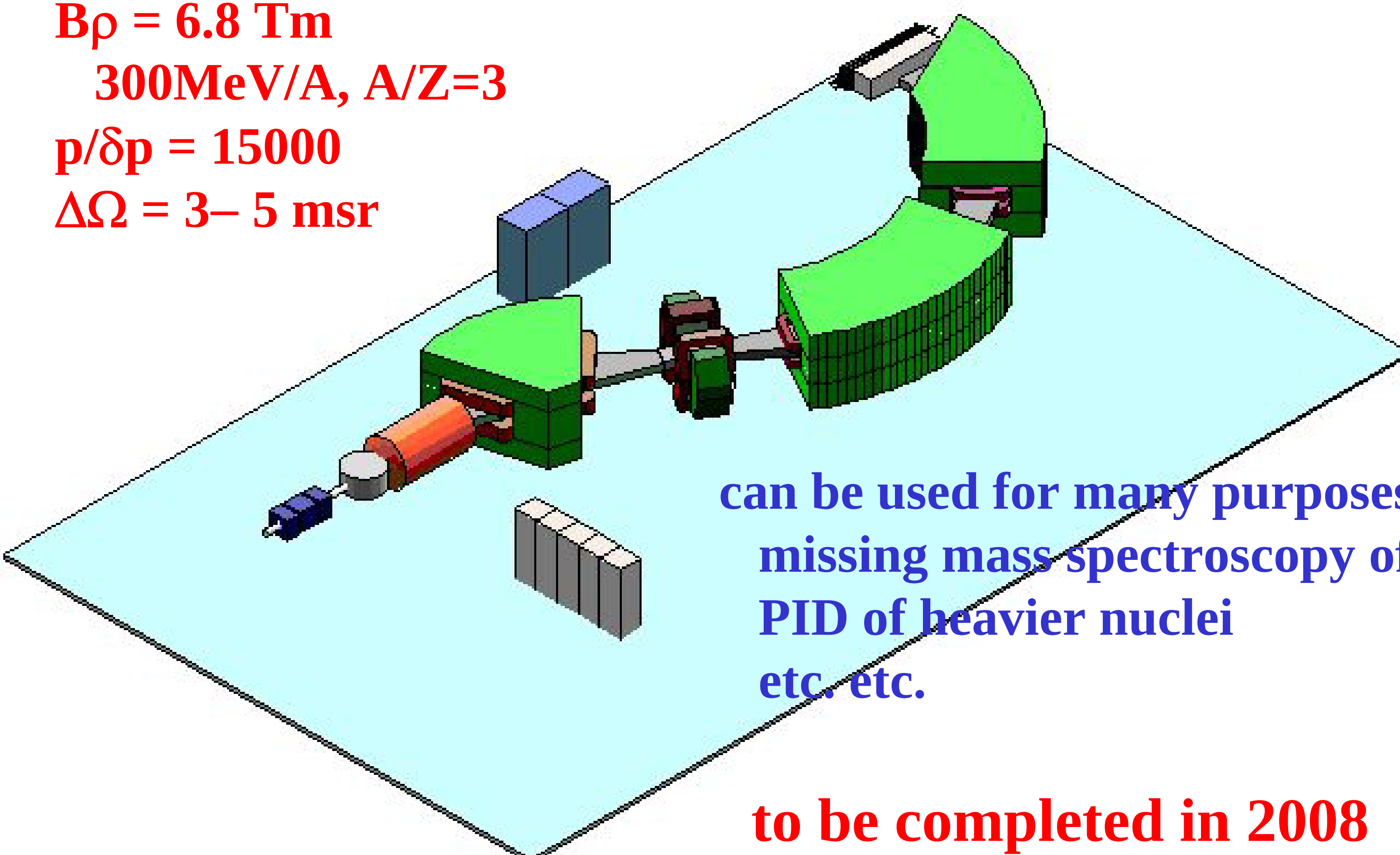


$^{3,4}n$: ^{3,4}He(^{8}He,^{8}Be)

^{6,7}H: ^{6,7}Li(^{8}He,^{8}Be)

SHARAQ spectrograph at RIBF

$B\rho = 6.8$ Tm
  300MeV/A, A/Z=3
$p/\delta p = 15000$
$\Delta\Omega = 3\text{–}5$ msr



can be used for many purposes
- missing mass spectroscopy of RI
- PID of heavier nuclei
- etc. etc.

to be completed in 2008

Summary

1. momentum transfer is an important key to understand nuclear reaction.
2. stable-beam induced reaction can probe only q > ω region. while several interesting subjects are sitting in q < ω.
3. RI beam can provide new experimental approaches to explore the unexplored region in q-ω plane.
   - double Gamow-Teller resonances
   - isovector spin monopole resonances
   - multi-neutron states
4. Combination of RI beams from RIBF and SHARAQ spectrograph can give us much.

YOUR NEW IDEAS OPEN THE POSSIBILITY!