Experimental Studies of Neutrino Nuclear Responses
Nuclear Probes

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Neutrino Nuclear Responses (NNR05)

Charge-exchange probes

(p,n)-type (DT_z= -1)

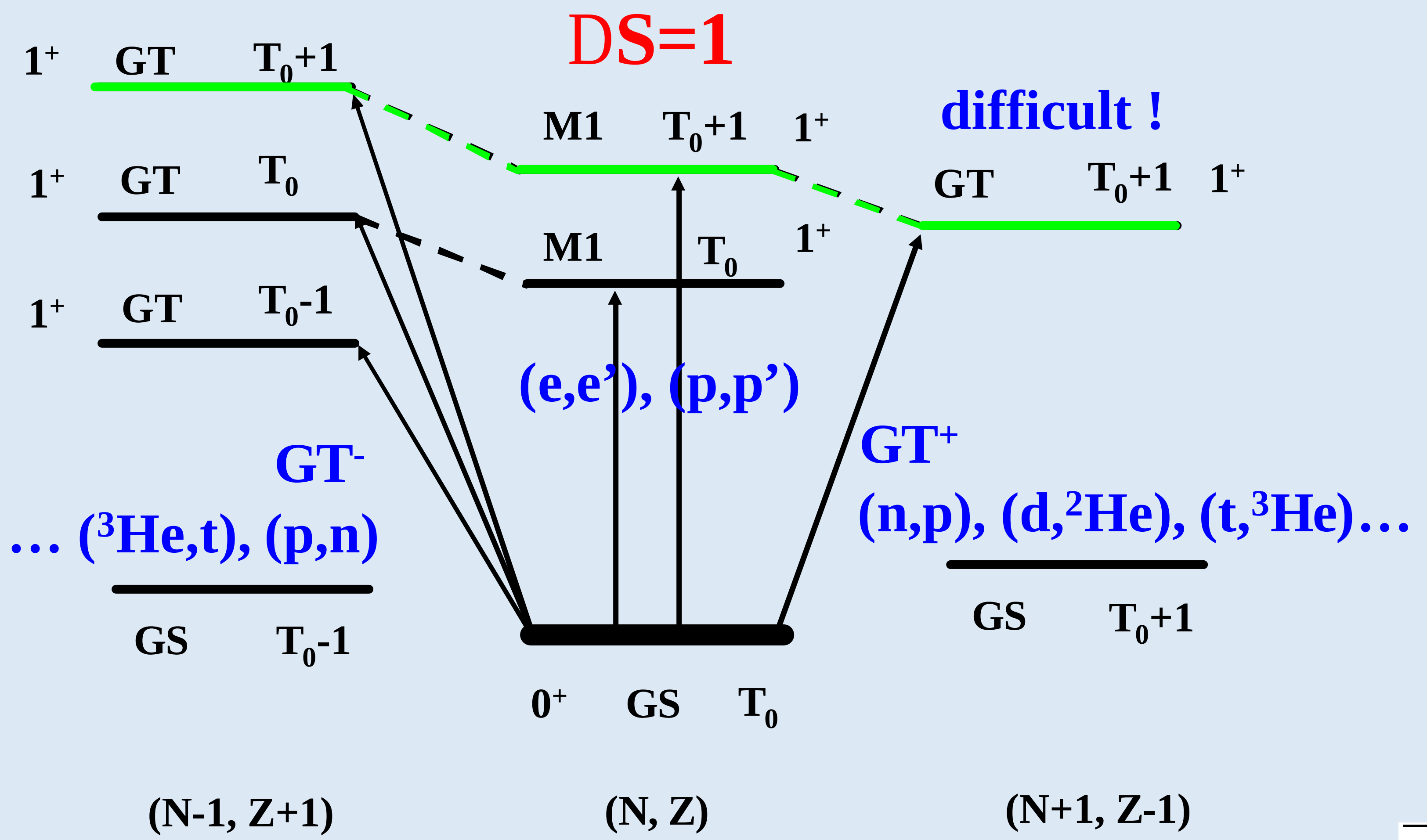
- b^{-}**-decay**
- **(p,n)**
- **(^{3}He,t)**
- **heavy ion**
- (p^{+},p^{0})

(n,p)-type (DT_z= +1)

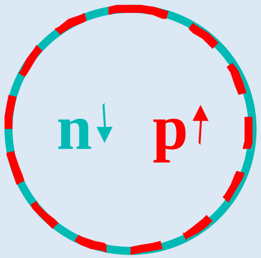
- b^{+}**-decay**
- **(n,p)**
- **(d,^{2}He)**
- **(t,^{3}He)**
- **heavy ion (^{7}Li,^{7}Be)**
- (p^{-},p^{0})

•Energy per nucleon (>100 MeV/n)
•Spin-flip vs non-spin-flip
•Complexity of reaction mechanism
•Experimental considerations

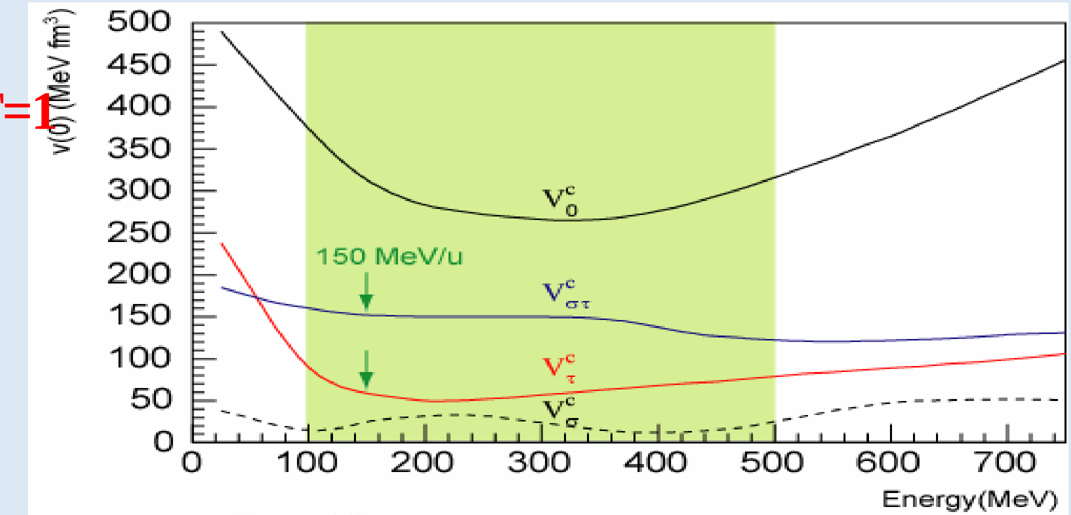
Spin-flip & GT transitions



Spin-isospin excitations



ΔL=0 ΔS=1 ΔT=1
GTR



- Gamow-Teller transitions;
  Isospin (ΔT=1)
  Spin (ΔS=1)

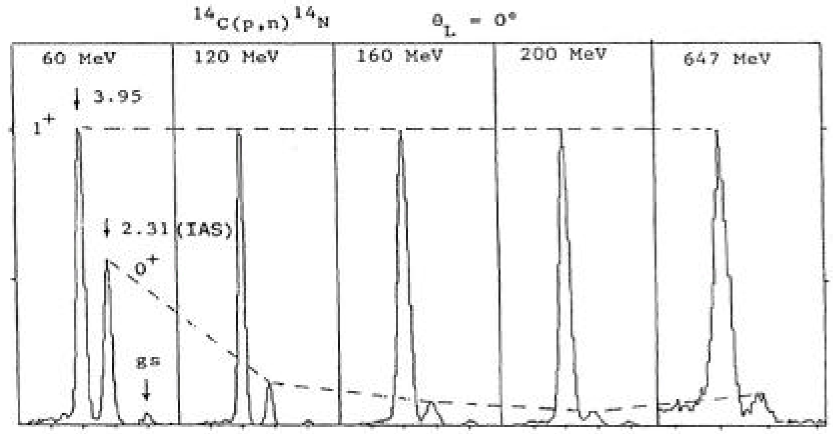


FIG. 4. Zero-degree cross-section spectra for the $^{14}C(p,n)^{14}N$ reactions at the indicated bombarding energies. The spectra have been arbitrarily normalized. From Gaarde (1985) and Rapaport (1989).

Advantages

- Cross section peaks at q=0 deg. (ΔL=0)
- Strong excitation of GT states at E/A=100-500 MeV/u

KVI

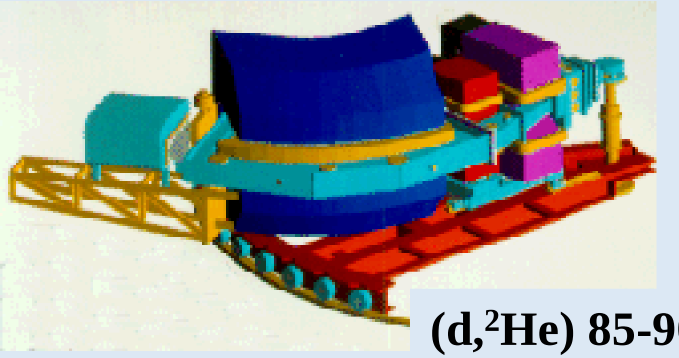
Outline

- **Isovector charge-exchange modes**

  (^{3}He,t), (t,^{3}He) & (*d*,^{2}He) charge-exchange reactions

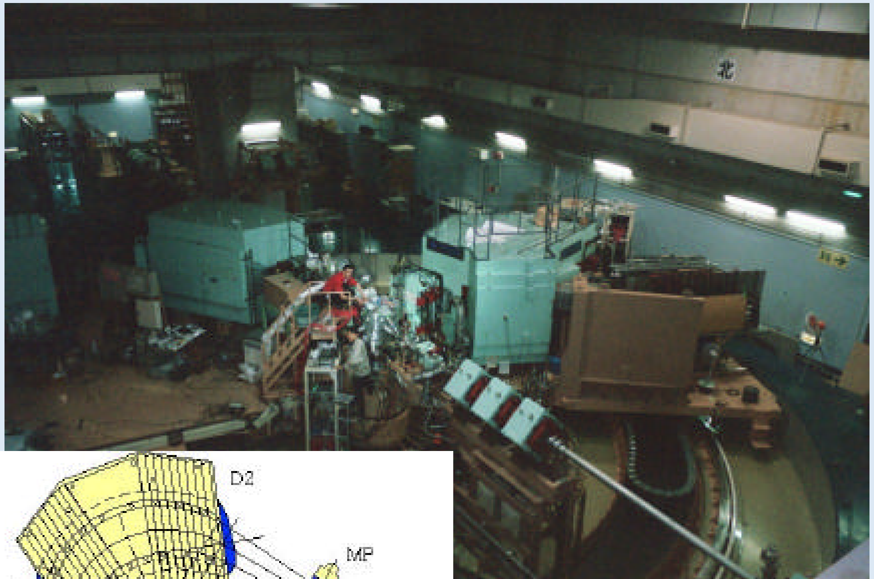
  Þ Low-lying GT$^-$ & GT$^+$ Strength, Spin-dipole & Collective modes

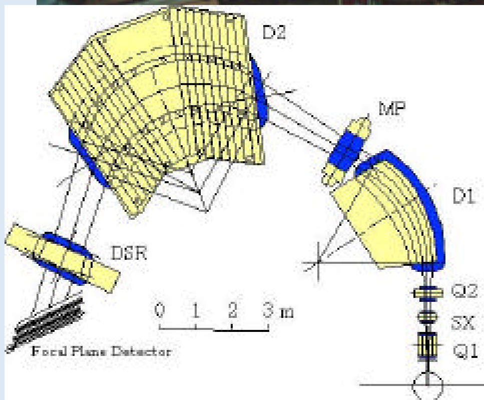
- **Outlook**



BBS@KVI

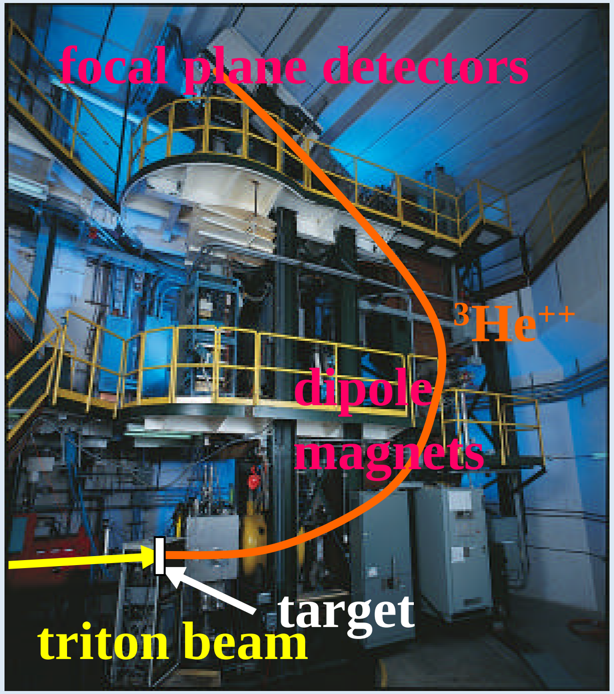
(d,^{2}He) 85-90 MeV/u
(^{3}He,t) 60 MeV/u
(t,^{3}He) 43 MeV/u





Grand Raiden@ RCNP

(^{3}He,t) 140-150 MeV/u
Also
(p,n) (n,p) 300 MeV



TRIUMF (n,p) (p-CEX)
IUCF (p,n) (^{3}He,t) K600
iThemba (p,p) K600

S800@NSCL (t,^{3}He) 115 MeV/u

Experiments at KVI

Equipment

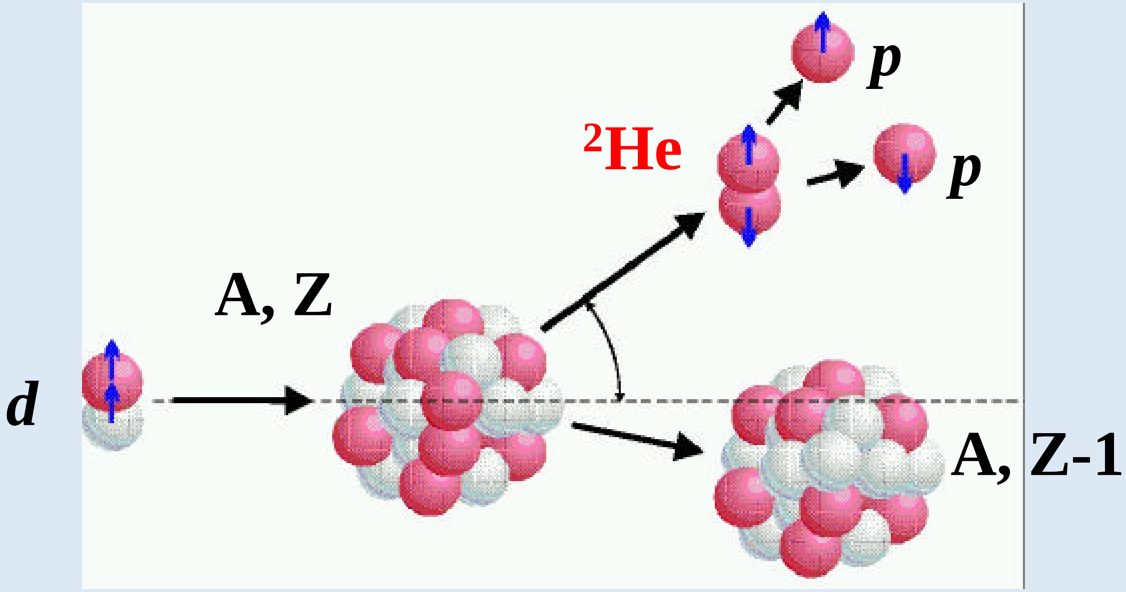
- Big momentum Bite magnetic Spectrometer (BBS)

- Its associated Focal-Plane Detectors (FPD)

  Contructed by the EuroSupernova Collaboration

  $\Rightarrow$ Allows study of **(d, ^{2}He)**

Exclusive excitations DS=DT=1: (*d*, ^{2}He)

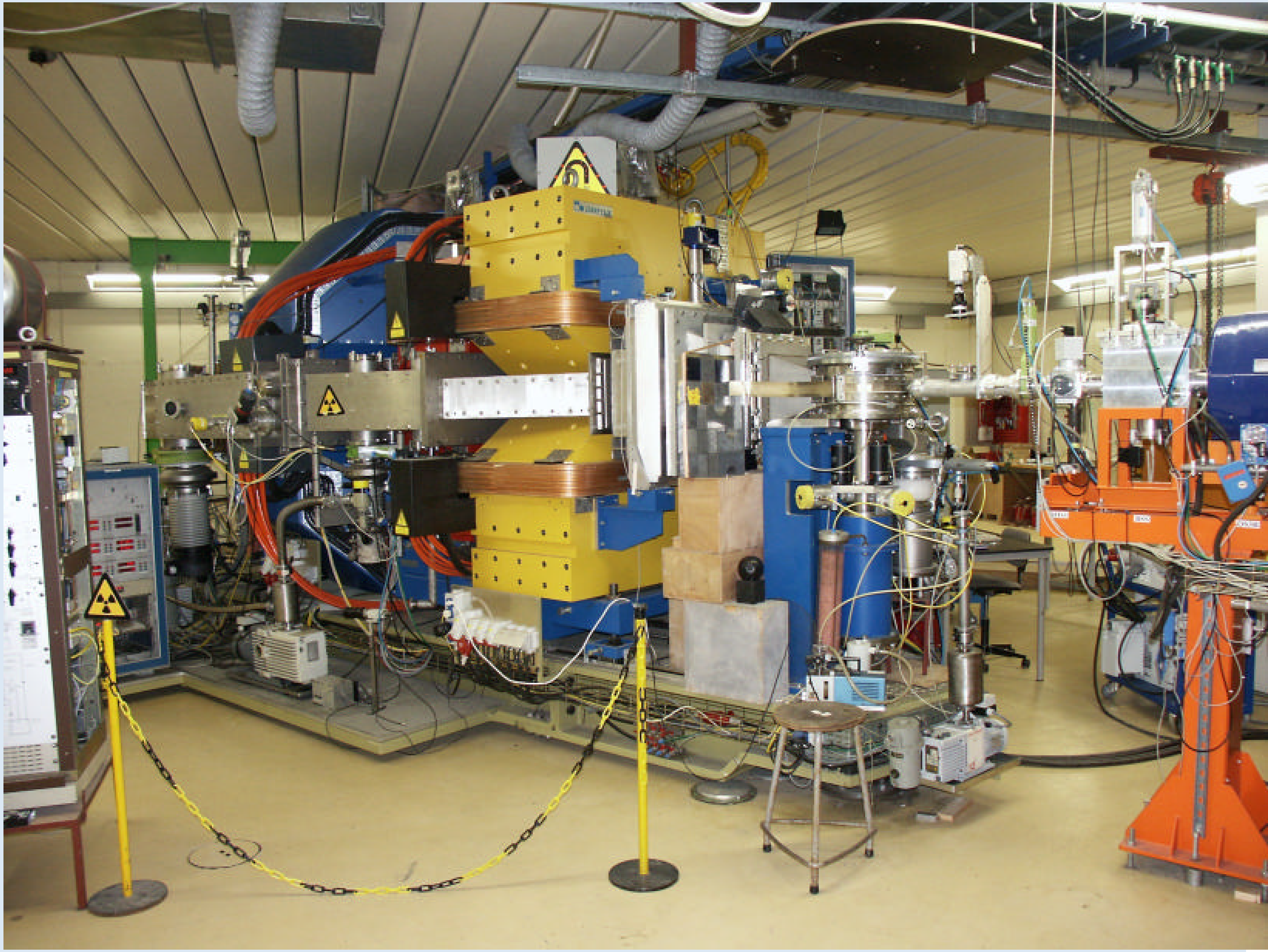


$^3S_1$ deuteron Þ $^1S_0$ di-proton (^{2}He)

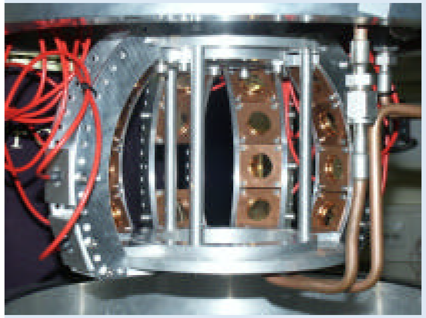
$^1S_0$ dominates if (relative) proton kinetic energy e < 1 MeV

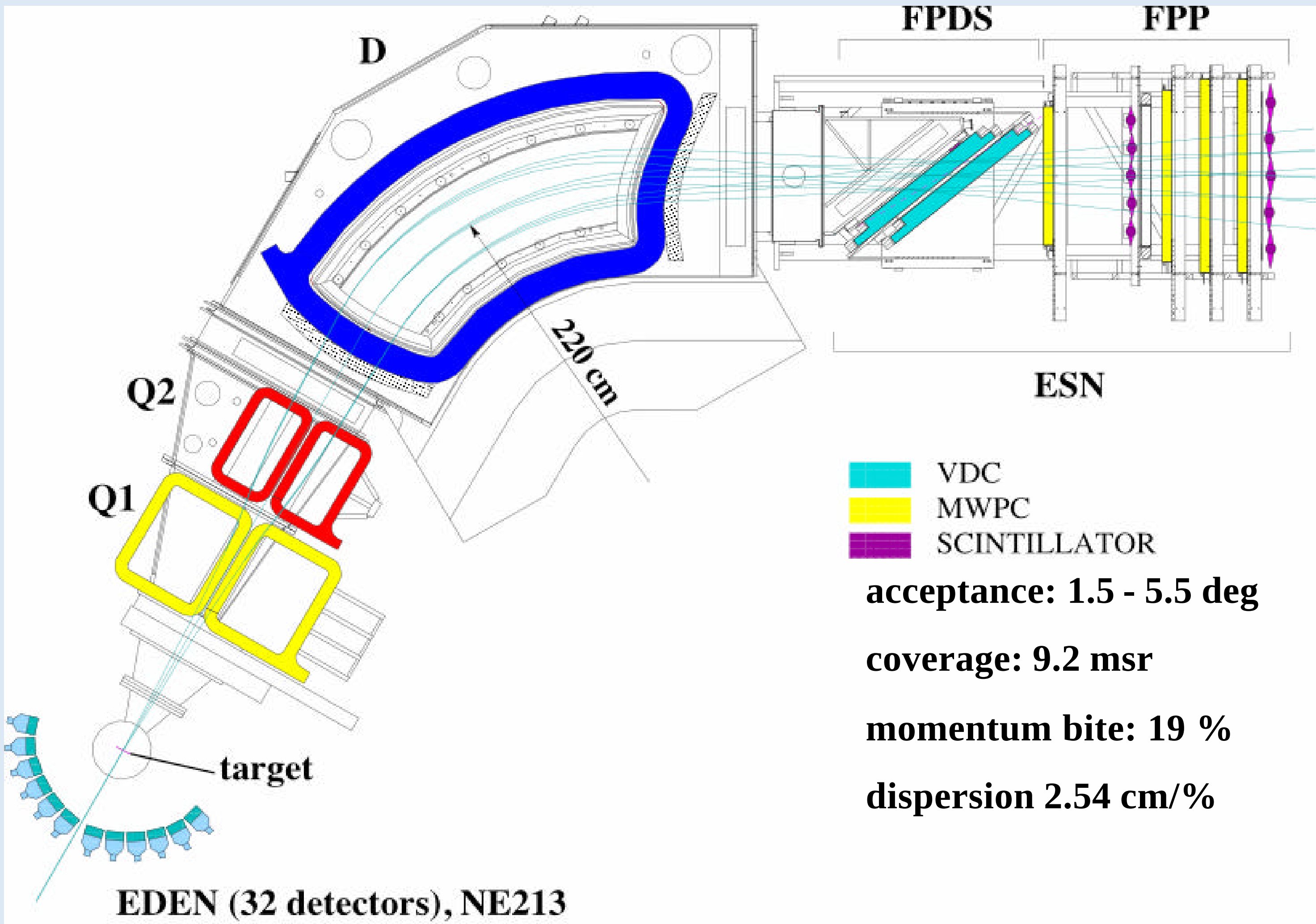
(*n*,*p*)-type probe with exclusive DS=1 character (GT$^+$ transitions)

But near 0°: tremendous background from *d*-breakup



Si-ball
16 Si-detectors at
10 cm from the target
total solid angle: 1 sr





acceptance: 1.5 - 5.5 deg

coverage: 9.2 msr

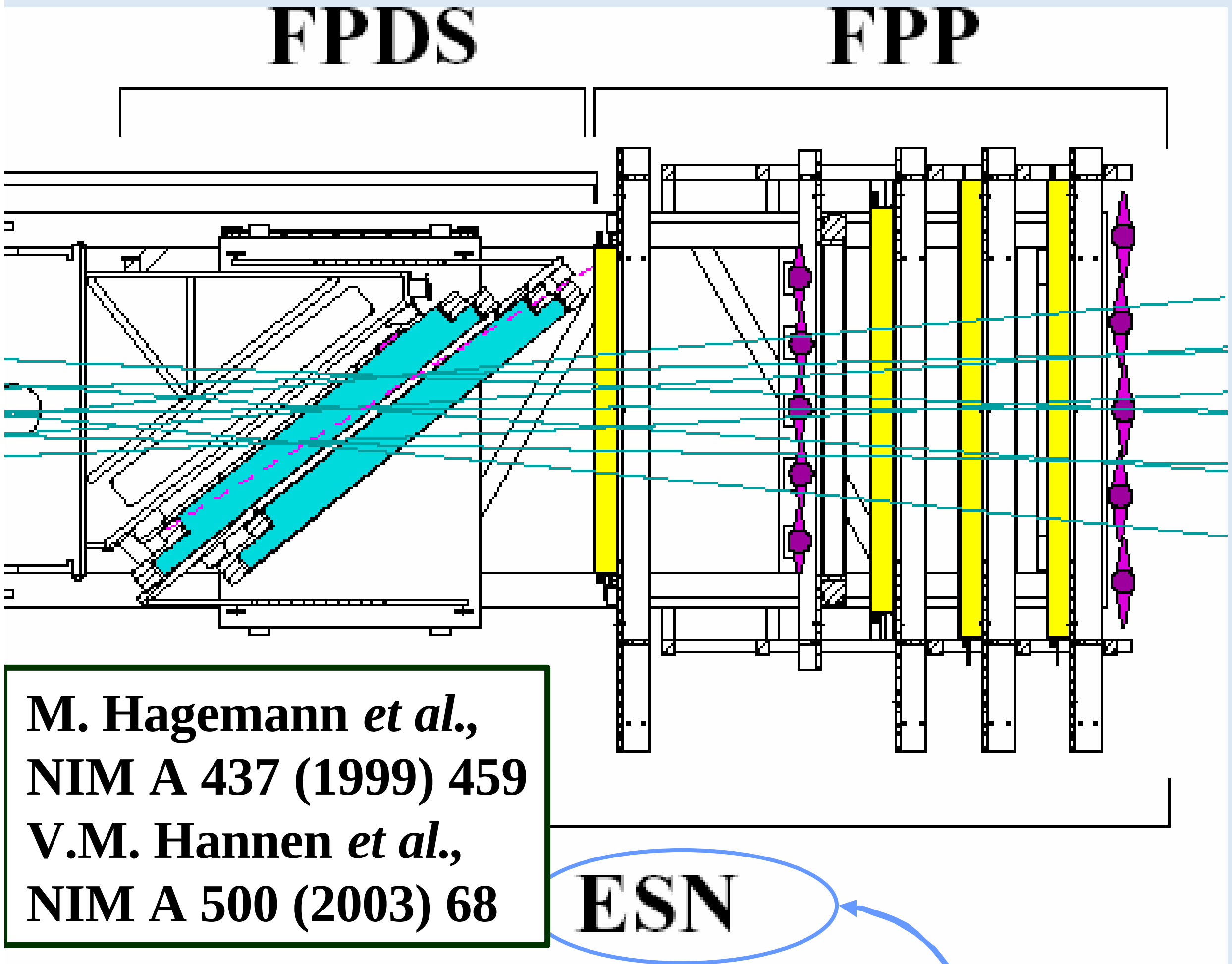
momentum bite: 19 %

dispersion 2.54 cm/%

total solid angle: 0.37 sr

KVI Big-Bite Spectrometer (BBS)

Setup: ESN detector



M. Hagemann *et al.*,
NIM A 437 (1999) 459
V.M. Hannen *et al.*,
NIM A 500 (2003) 68

Focal-Plane Detector:
(FPDS): 2 VDCs

Focal-Plane Polarimeter:
(FPP): 4 MWPCs & graphite analyzer

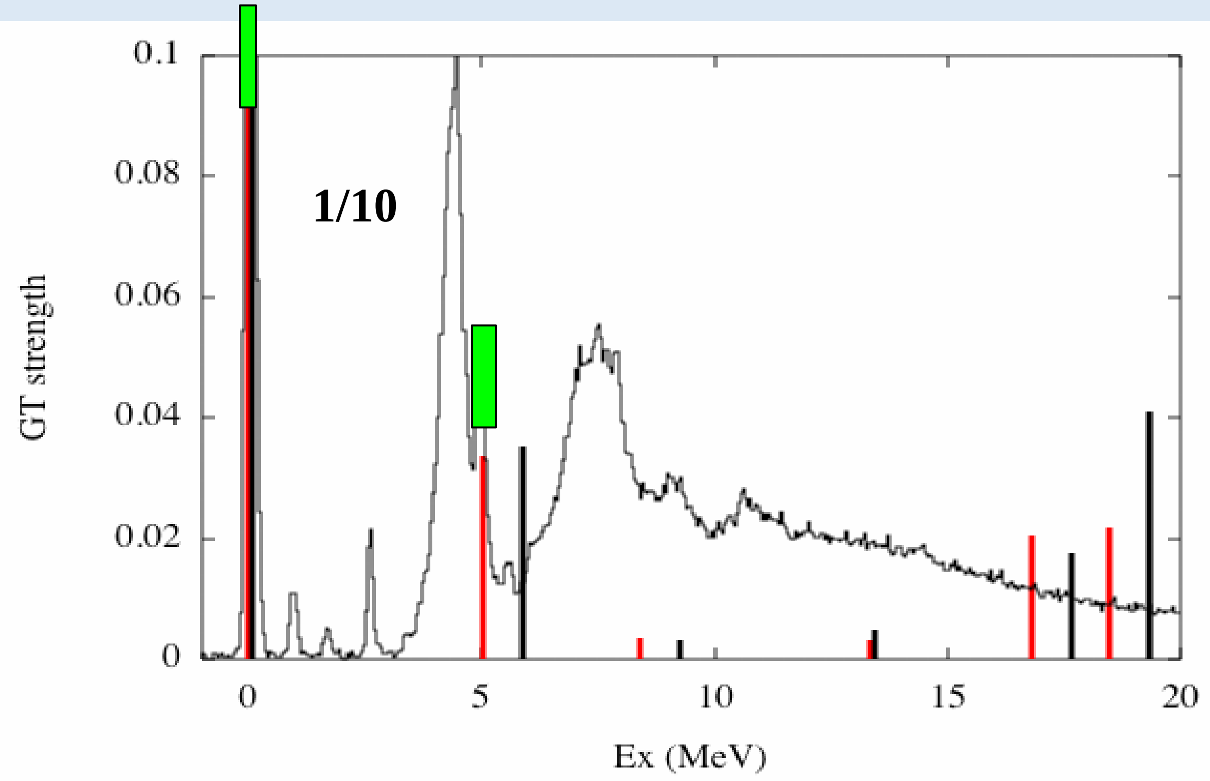
features a.o.:
fast readout
VDC readout pipeline
TDC's
VDC decoding using imaging techniques
DSP based online analysis

Bari, Darmstadt, Gent, Iserlohn, KVI, Milano, Münster, TRIUMF

KVI

Exclusive measurement of DS= DT =1 strength: ^{12}C(*d*, ^{2}He)^{12}B

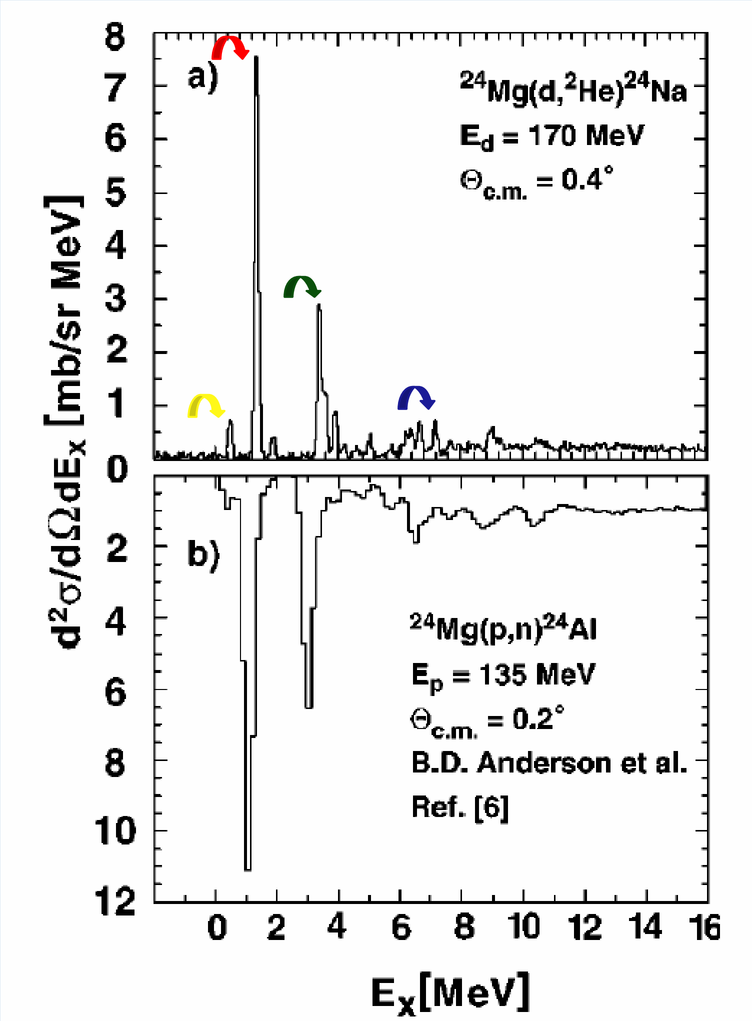
E_0 = 171 MeV, q = 0°

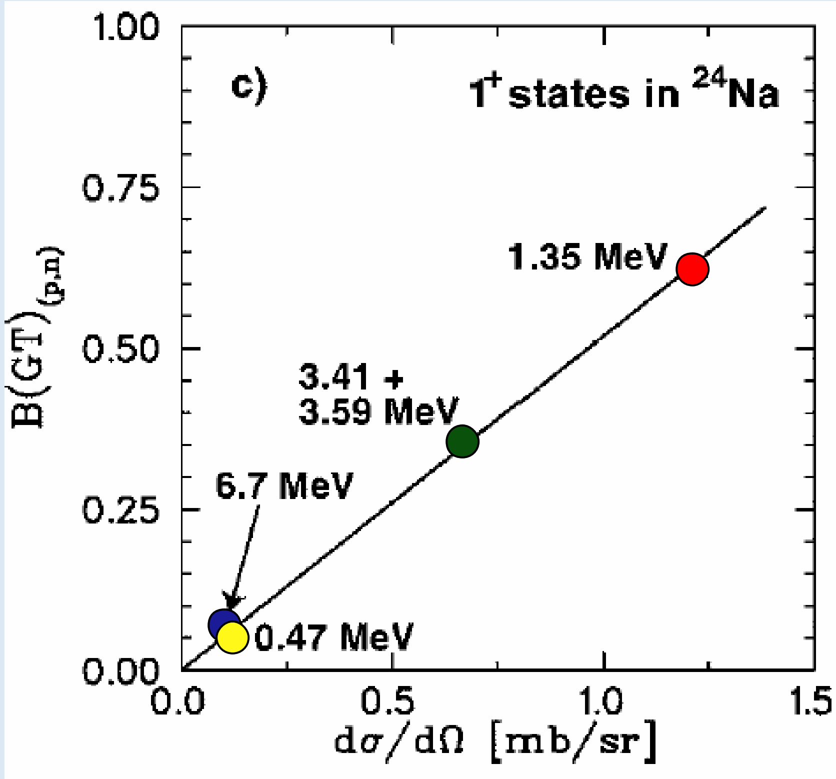


- **shell model calculations 4 ?w & 6 ?w (G. Martinez-Pinedo)**
- **B (GT^{+}) (S. Rakers)**

KVI

(p,n) vs (d,^{2}He): calibration



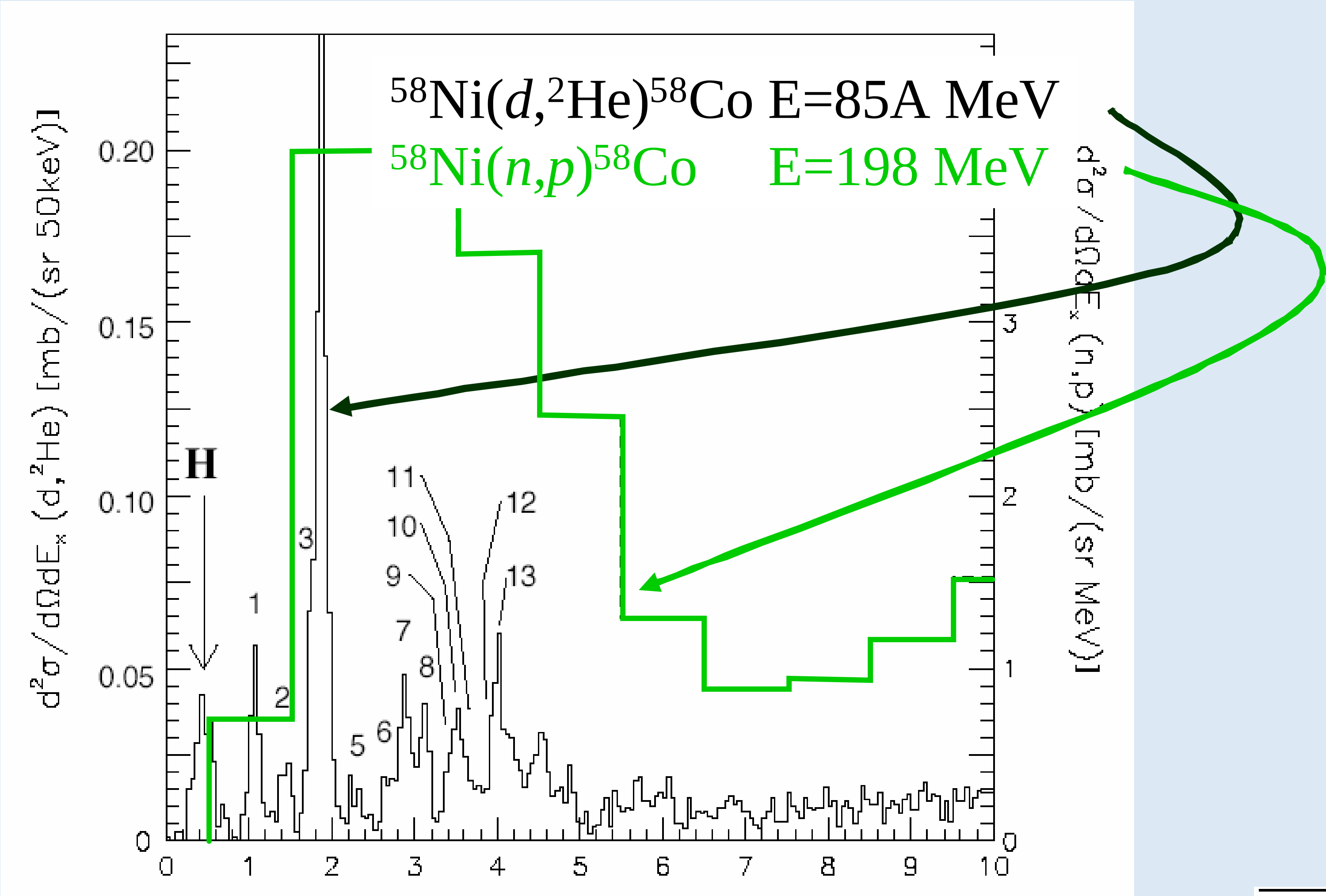


Self-conjugate ^{24}Mg

S. Rakers *et al.*
PRC **65** (2002) 044323

KVI

(d,^{2}He) as GT$^+$ probe in *fp* shell nuclei

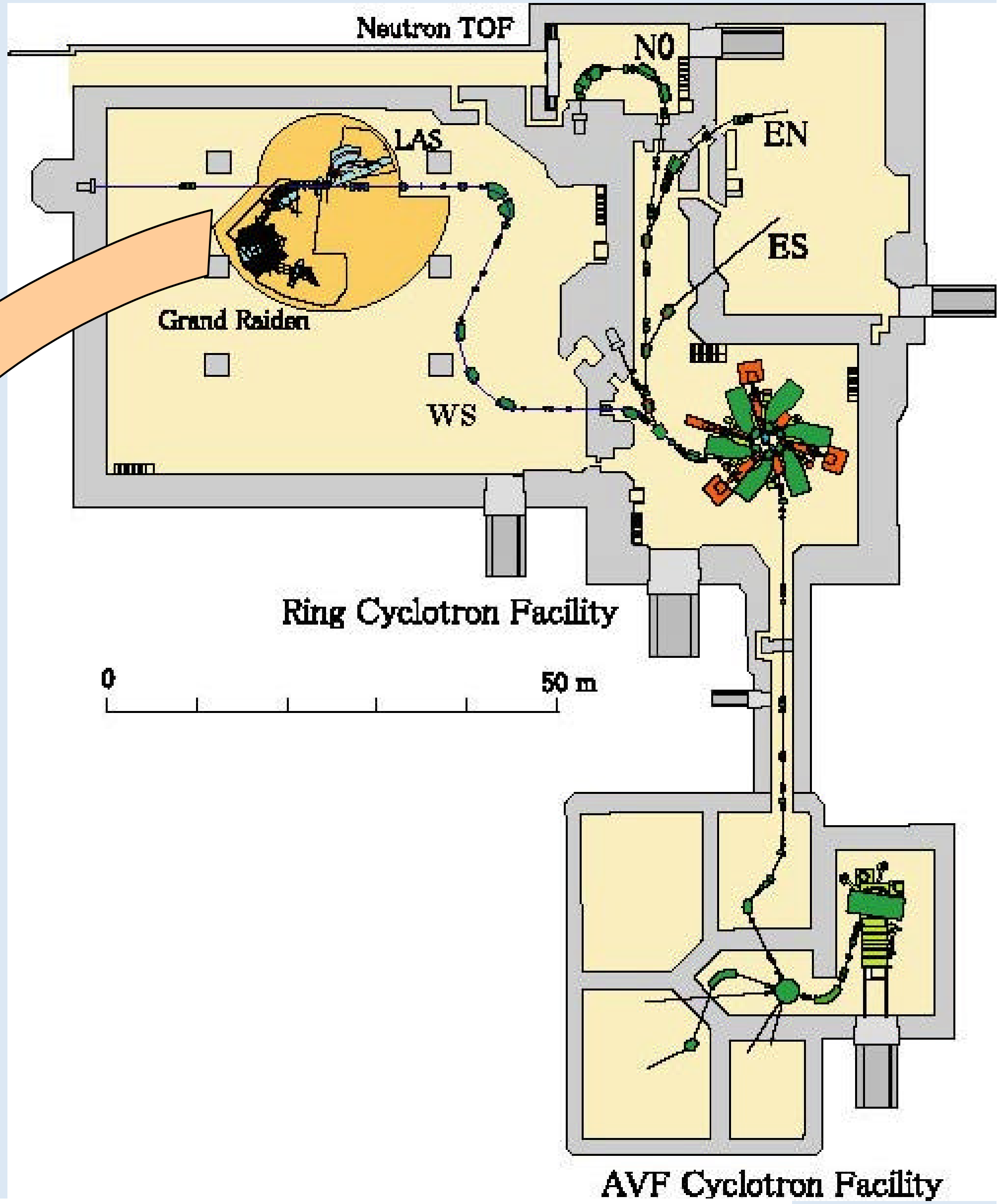


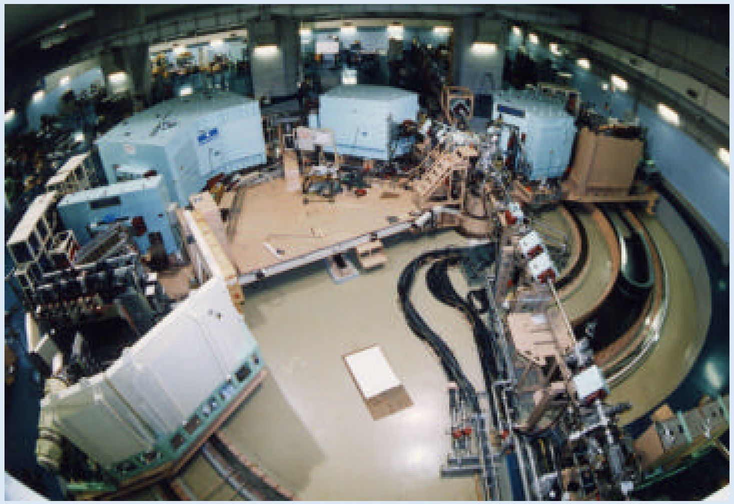
Experiment

- RCNP facility

  K=400 MeV ring cyclotron

  Grand Raiden spectrometer
- Beam: $^{3}He^{++}$, 450 MeV
- Target: ^{208}Pb foil



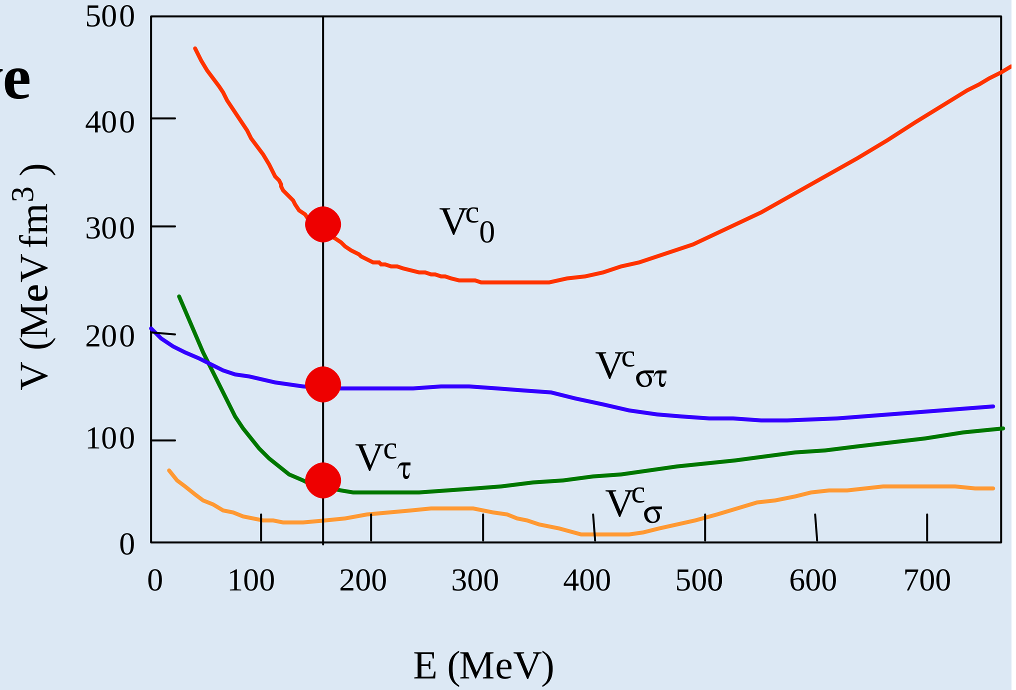


M. Fujiwara et al., NIM A 422 (1999) 484

(^{3}He,*t*) Reaction above 150 MeV/u

- **Energy dependence of effective interactions.**

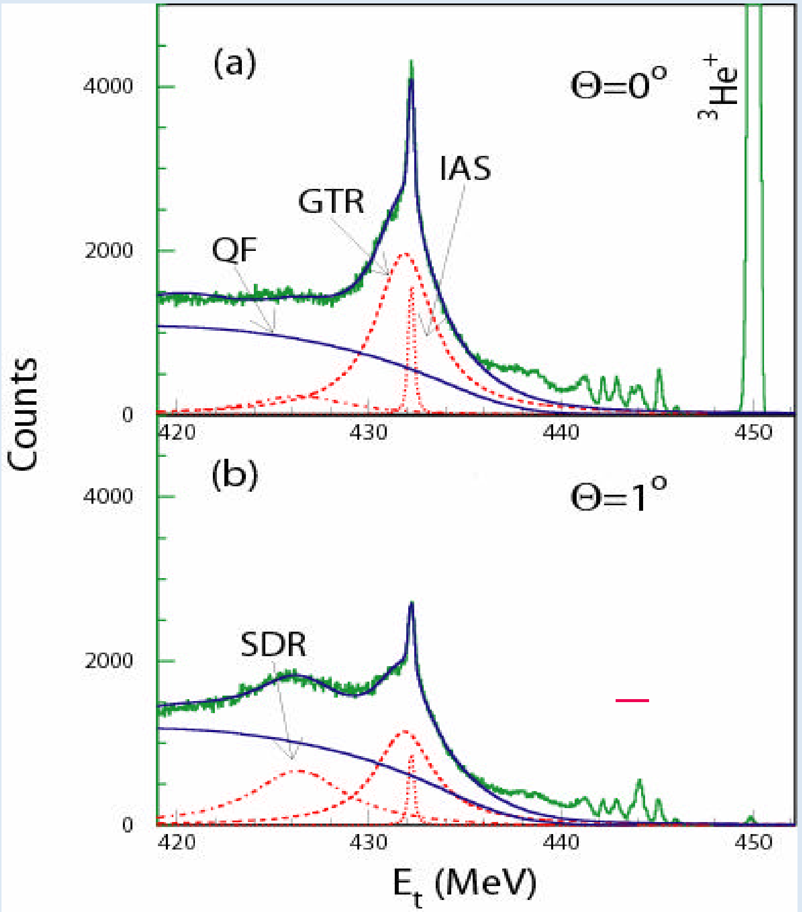
- **150 MeV/A**
  - **V_0 part: Minimum.**
  - **$V_{s\,t}$ part: Relatively large.**
  - **V_t part: Minimum.**



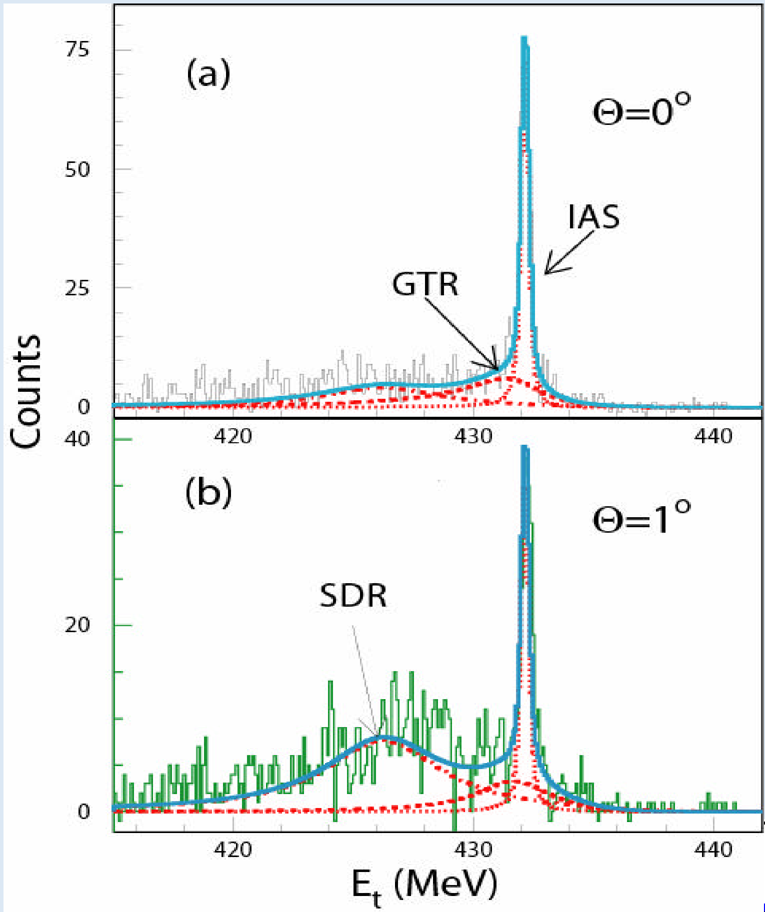
Spin-isospin-flip transitions in charge-exchange reactions and proton decay

A. Krasznahorkay et al., PRC 64 (2001) 067302.
A. Krasznahorkay et al., PRL 82 (1999) 3216.
H. Akimune et al., PRC 52 (1995) 604.
H. Akimune et al., Phys. Lett. B 233 (1994) 107

208Pb(^{3}He,t) reaction at E(^{3}He)=450 MeV



(^{3}He,tp) Coincidence data



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The (^{3}He,t) reaction at 0 degree.

- **Cross sections at E(^{3}He)=450 MeV, q=0 for (^{3}He,t) reactions**

$$\frac{ds}{d\Omega} = \frac{m_i m_f}{(p\hbar^2)^2}\left(\frac{k_f}{k_i}\right)(N_\tau^D \,|\, J_t \,|^2\, B(F) + N_{st}^D \,|\, J_{st} \,|^2\, B(GT))$$

T. N. Taddeucci et al., Nucl. Phys. A469, 125 (1987)
I. Bergqvist et al., Nucl. Phys. A469, 648 (1987)

- **Neutrino absorption cross sections**

$$\sigma = \frac{1}{\pi \hbar^4 c^3}\left[G_V^2 B(F) + G_A^2 B(GT)\right] \times F(Z, E_e)\, p_e E_e$$

Importance of charge-exchange reactions at intermediate energies

Measuring GT strengths

$$\frac{ds}{d\Omega}(q=0) = KN_D \left| J_{st} \right|^2 B(GT)$$

kinematic factor

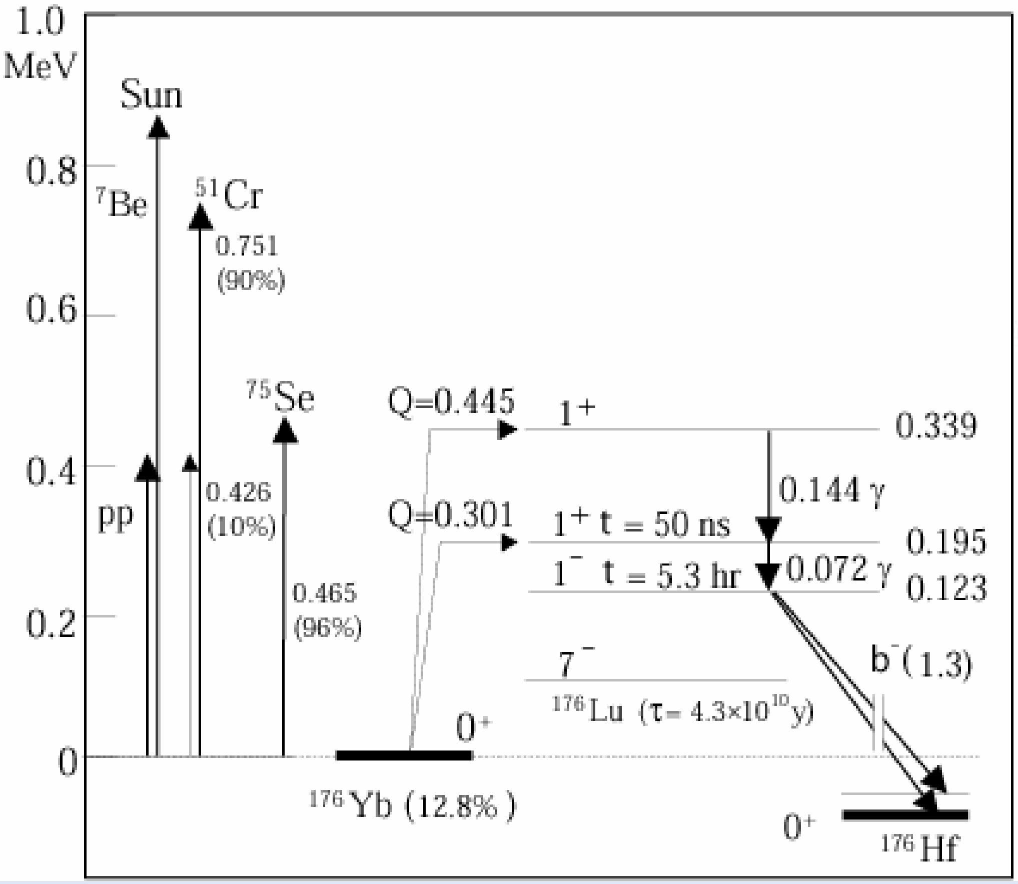
distortion factor

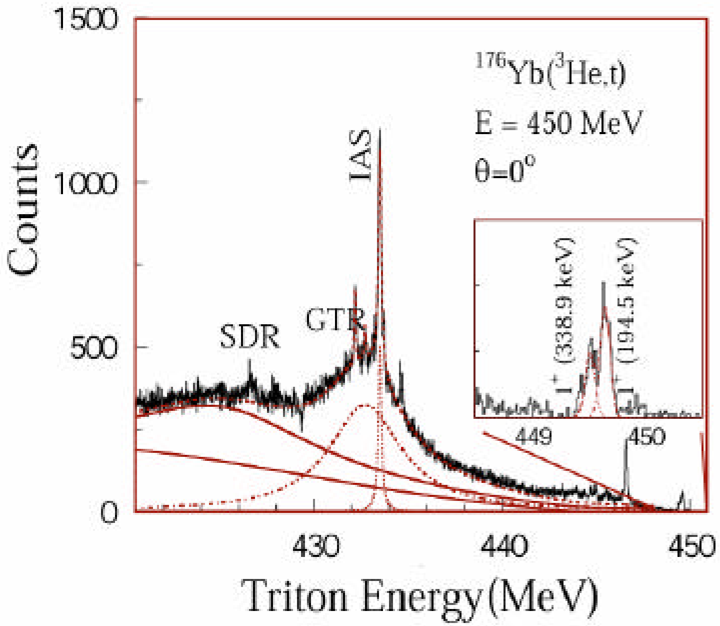
nucleon-nucleus interaction

Gamow-Teller strength

Calibration of B(GT) to cross section for known transitions (e.g. from b-decay)

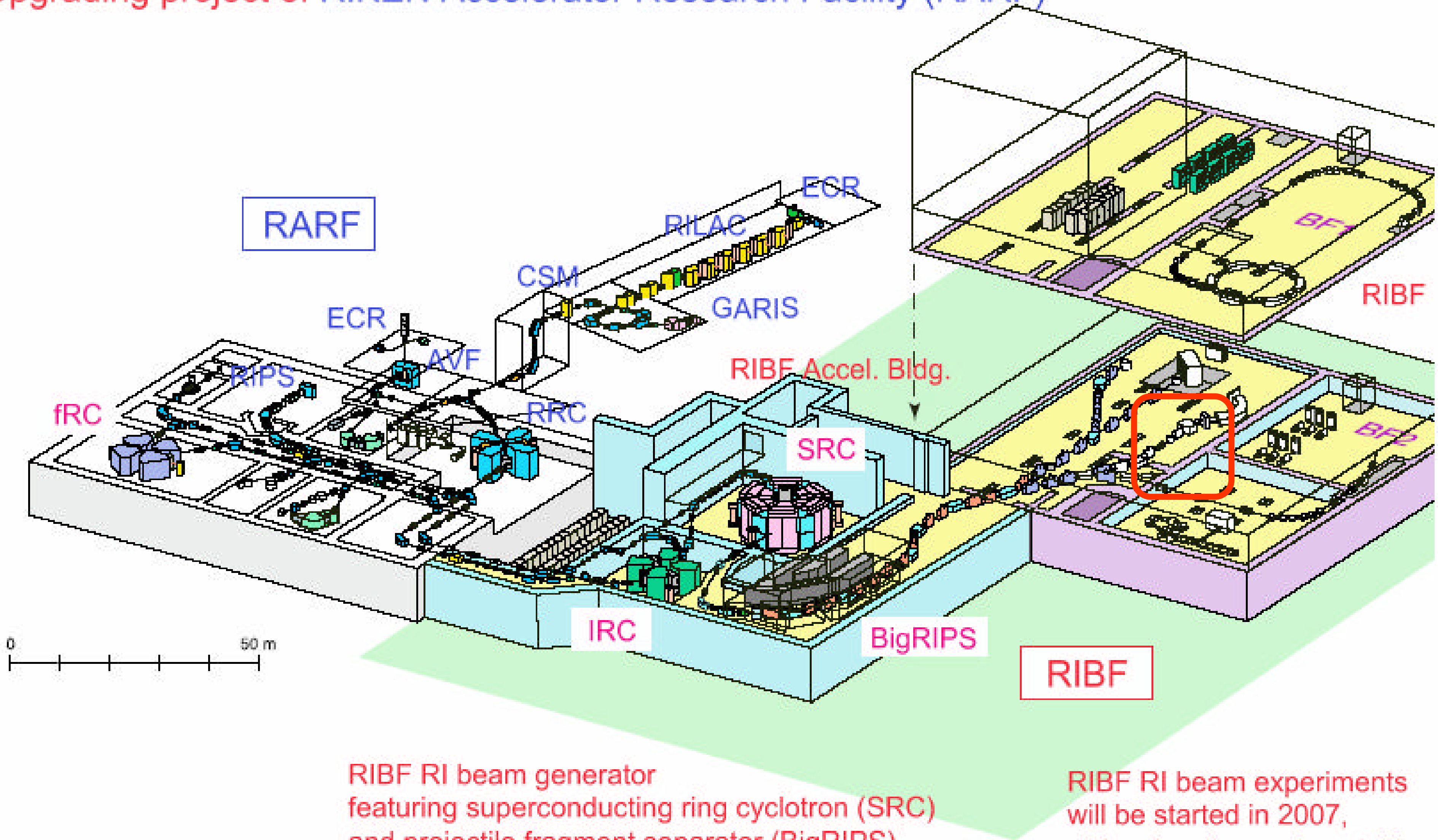
M. Fujiwara et al. PRL 85 (2000) 4442.





E_x (MeV)	0.195+0.339 (*p,n*)	0.195 (^{3}He,*t*)	0.339 (^{3}He,*t*)
B(GT)	0.32±0.04	0.20±0.04	0.11±0.02

RI Beam Factory (RIBF):
Upgrading project of RIKEN Accelerator Research Facility (RARF)



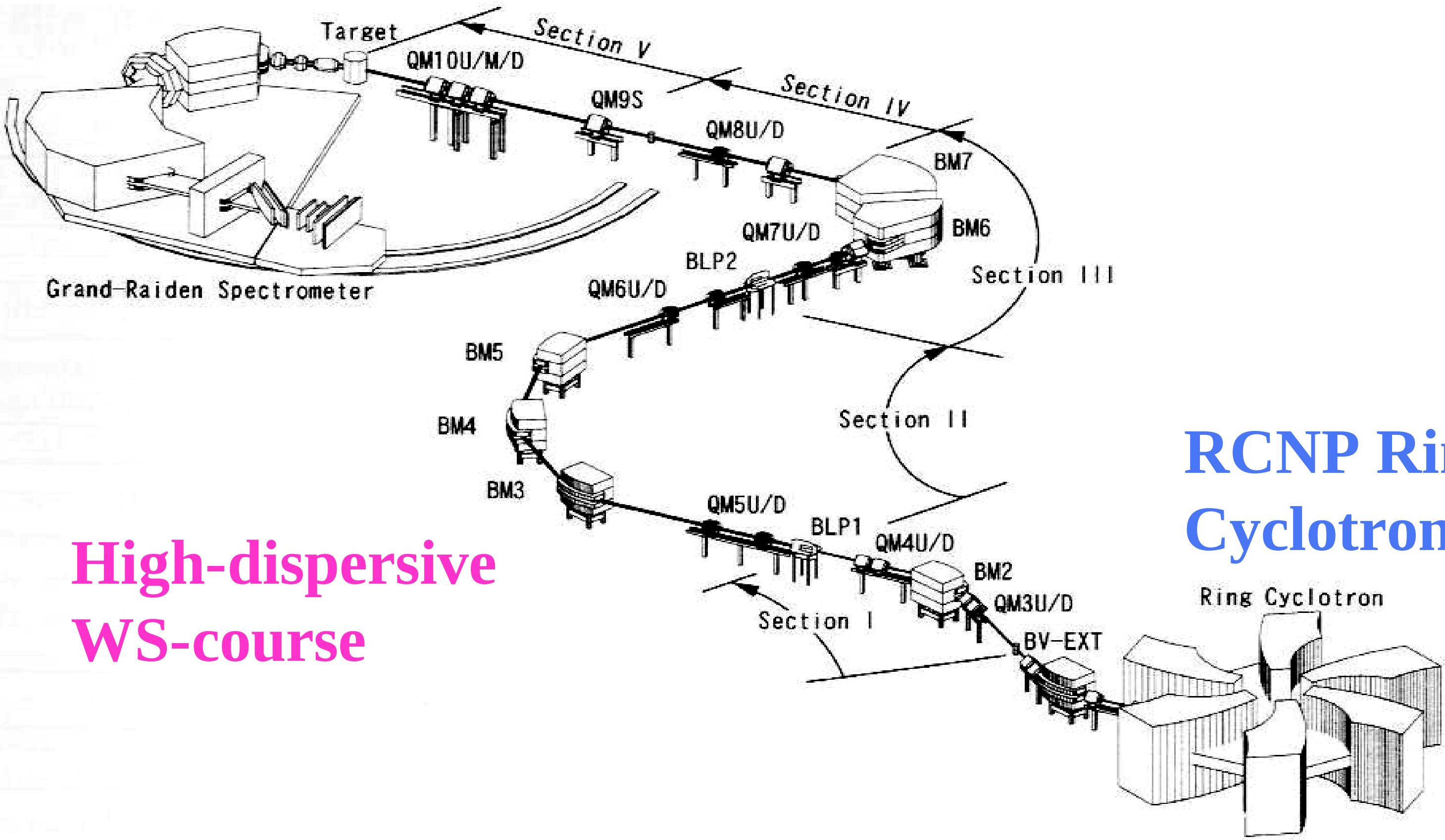
RIBF RI beam generator
featuring superconducting ring cyclotron (SRC)
and projectile fragment separator (BigRIPS)
will be commissioned late in 2006.

RIBF RI beam experiments
will be started in 2007,
with colored experimental inst

Beam line WS-course

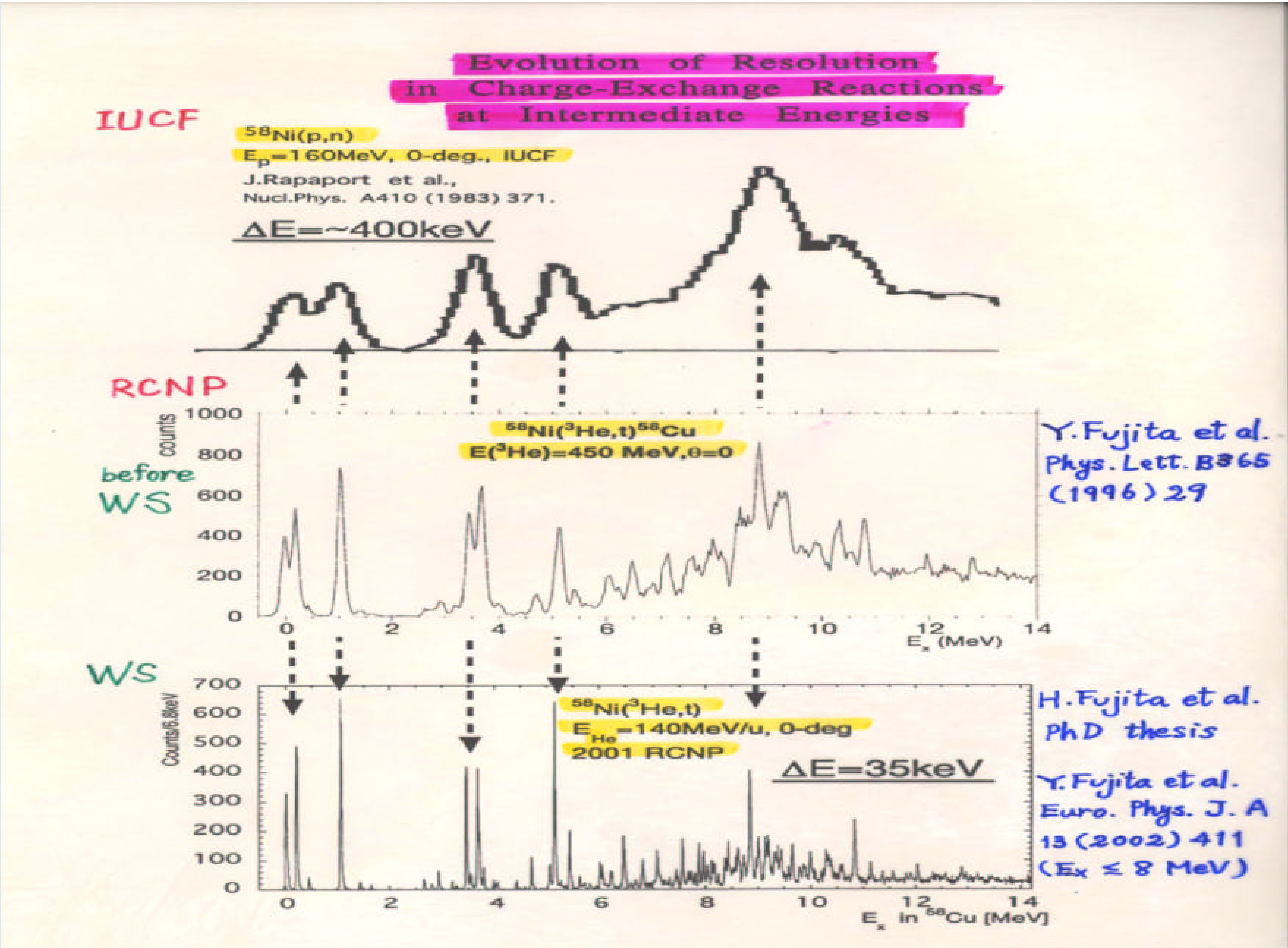
Grand-Raiden Spectrometer

T. Wakasa et al., NIM A482 ('02) 79.



High-dispersive WS-course

RCNP Ring Cyclotron



Evolution of Resolution in Charge-Exchange Reactions at Intermediate Energies
IUCF
58Ni(p,n)
Ep=160MeV, 0-deg., IUCF
J.Rapaport et al., Nucl.Phys. A410 (1983) 371.
ΔE=~400keV
RCNP
before WS
58Ni(3He,t)58Cu
E(3He)=450 MeV,θ=0
Y.Fujita et al. Phys.Lett.B365 (1996) 29
Ex (MeV)
WS
58Ni(3He,t)
EHe=140MeV/u, 0-deg
2001 RCNP
ΔE=35keV
H.Fujita et al. PhD thesis
Y.Fujita et al. Euro.Phys.J.A 13 (2002) 411 (Ex ≤ 8 MeV)
Counts/6.8keV
Ex in 58Cu [MeV]

Decomposition of the isospin component of the excited state in ^{58}Cu.

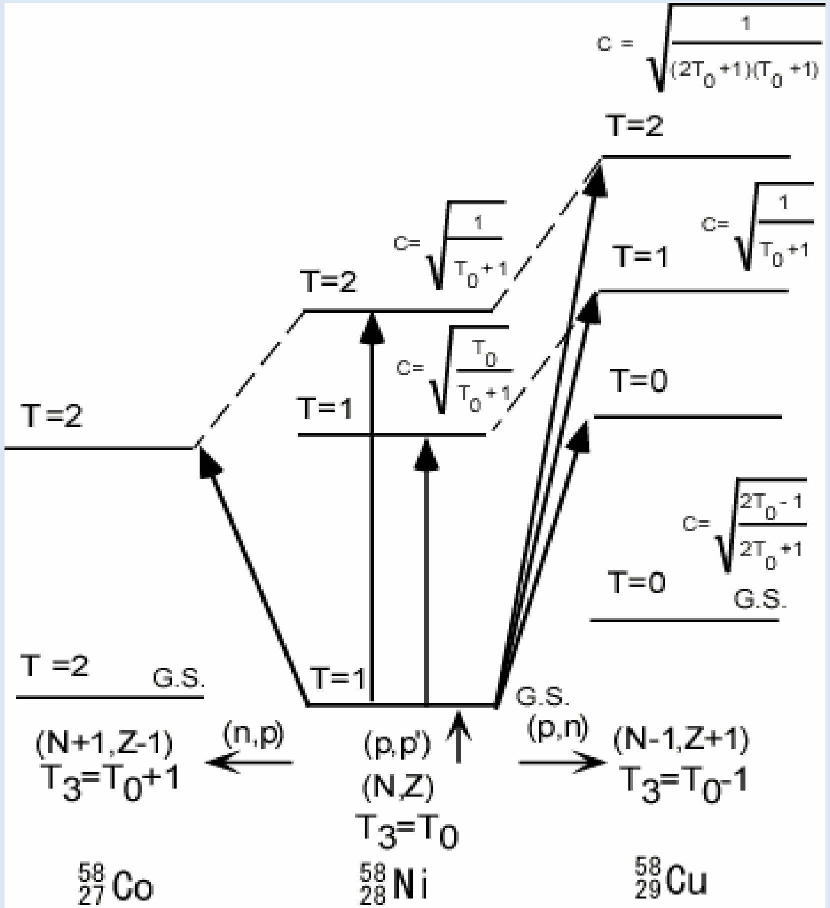
- Isospin of ^{58}Ni g.s. : T_0=1

- In principle, comparison among (n,p), (p,p), (p,n) spectra
  →separates isospin components

But, very difficult in practice
because of high level density for
T=1 and T=2 states.

- **CG**

$\sigma_{T=0} : \sigma_{T=1} : \sigma_{T=2} = 2:3:1$
(T_0=1)

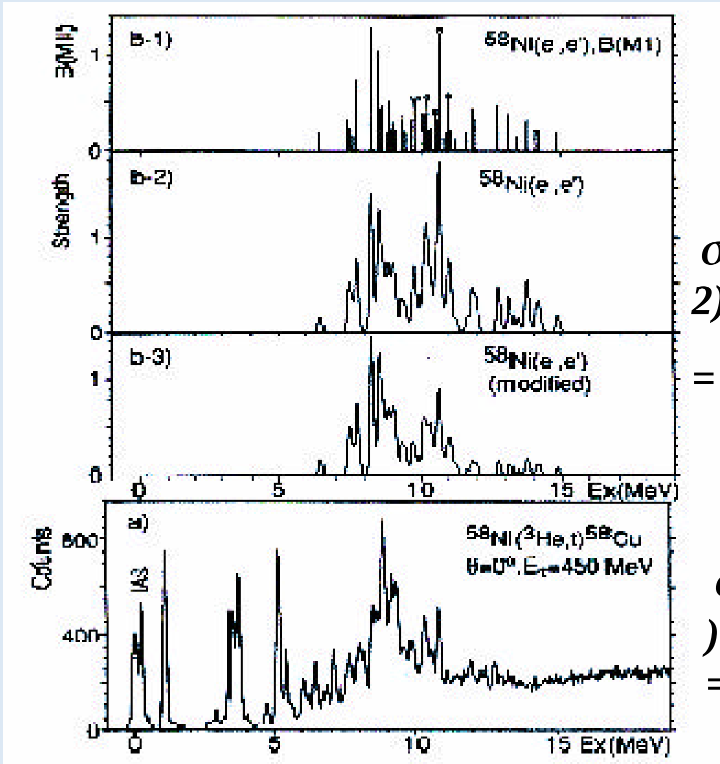


Comparison of (^{3}He,t) and (e,e') spectra

- **Comparison of (^{3}He,t) with (e,e') spectra ➔ Try to separate isospin components**
- **At E_x= 6-10 MeV (T=1 region)**
  - **Rather good correspondence**
- **At E_x=10-15 MeV (T=2 region)**
  - **No good correspondence**

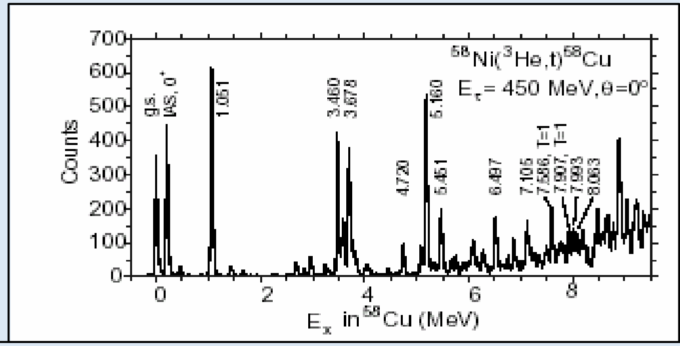
Fujita et al., Phys. Lett. B 365, 29 (1996).

Fujita et al., Eur. Phys. J A13, 411 (2002).

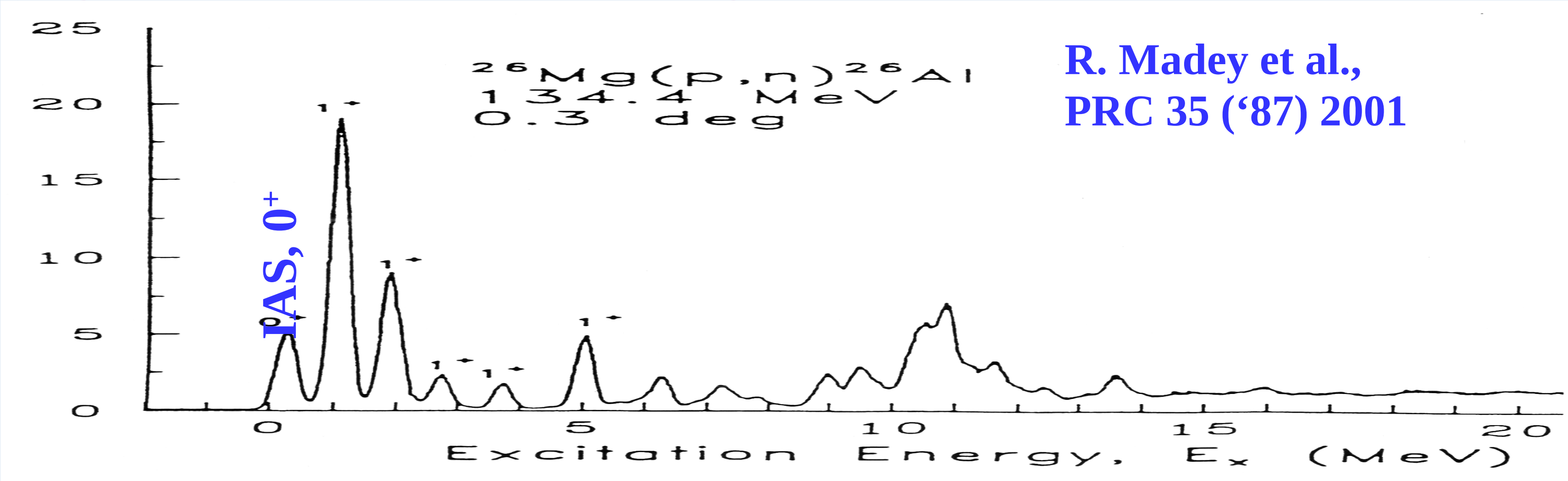


σ (T=1): σ (T=2)
= 1 : 1

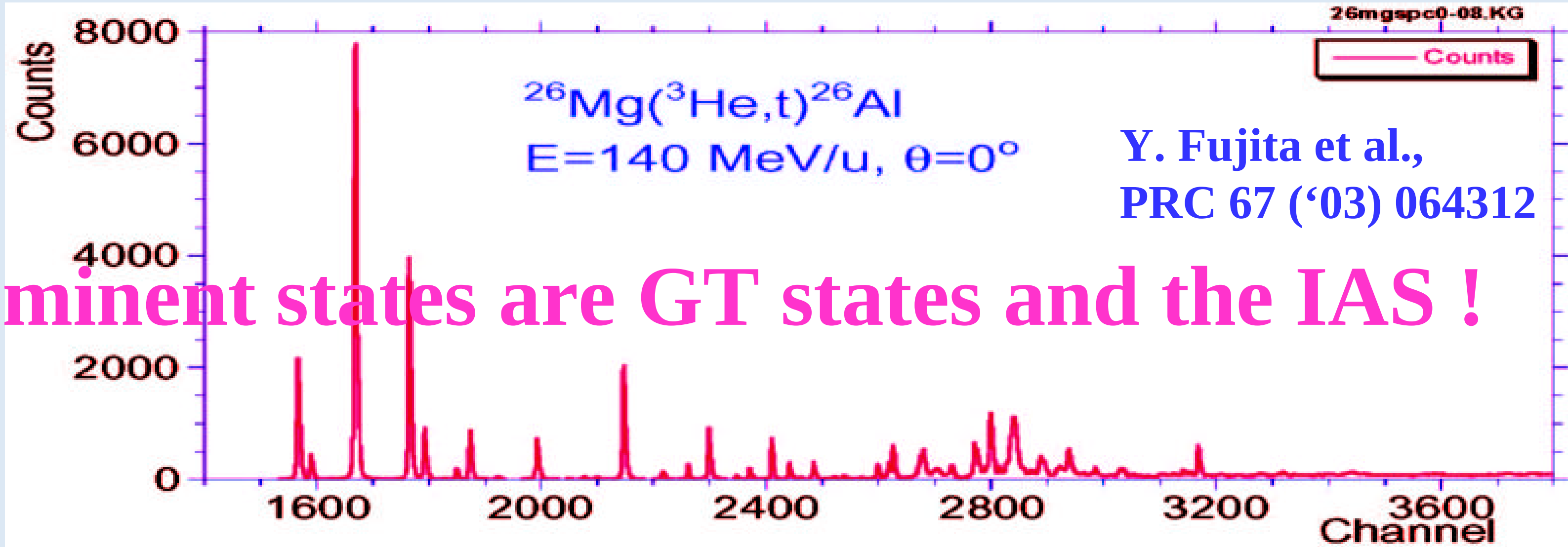
σ (T=1): σ (T=2)
= 3 : 1



$^{26}Mg(p, n)^{26}Al$ & $^{26}Mg(^{3}He,t)^{26}Al$ spectra



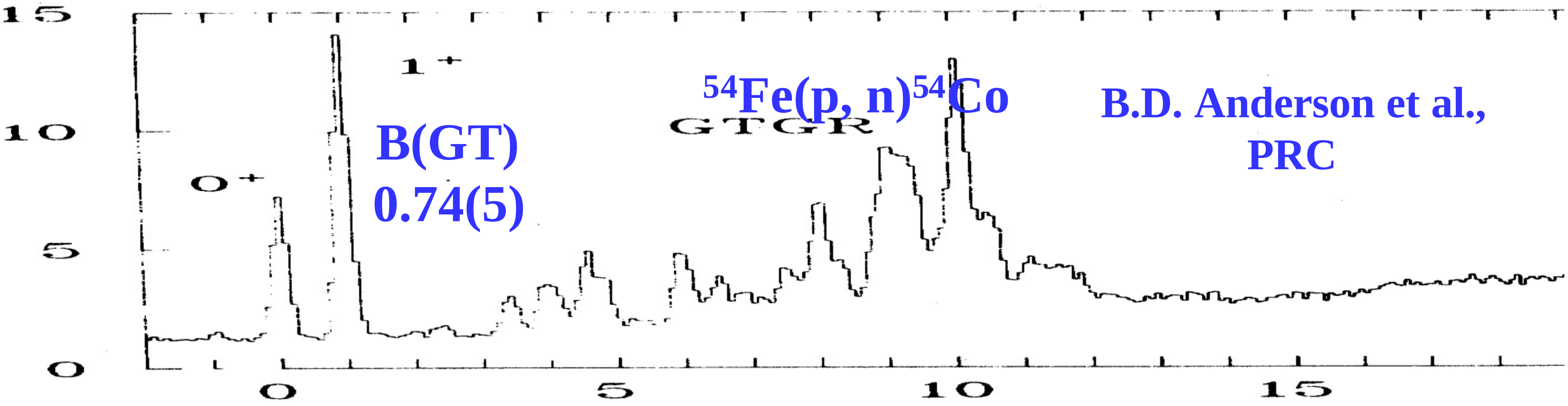
R. Madey et al., PRC 35 ('87) 2001

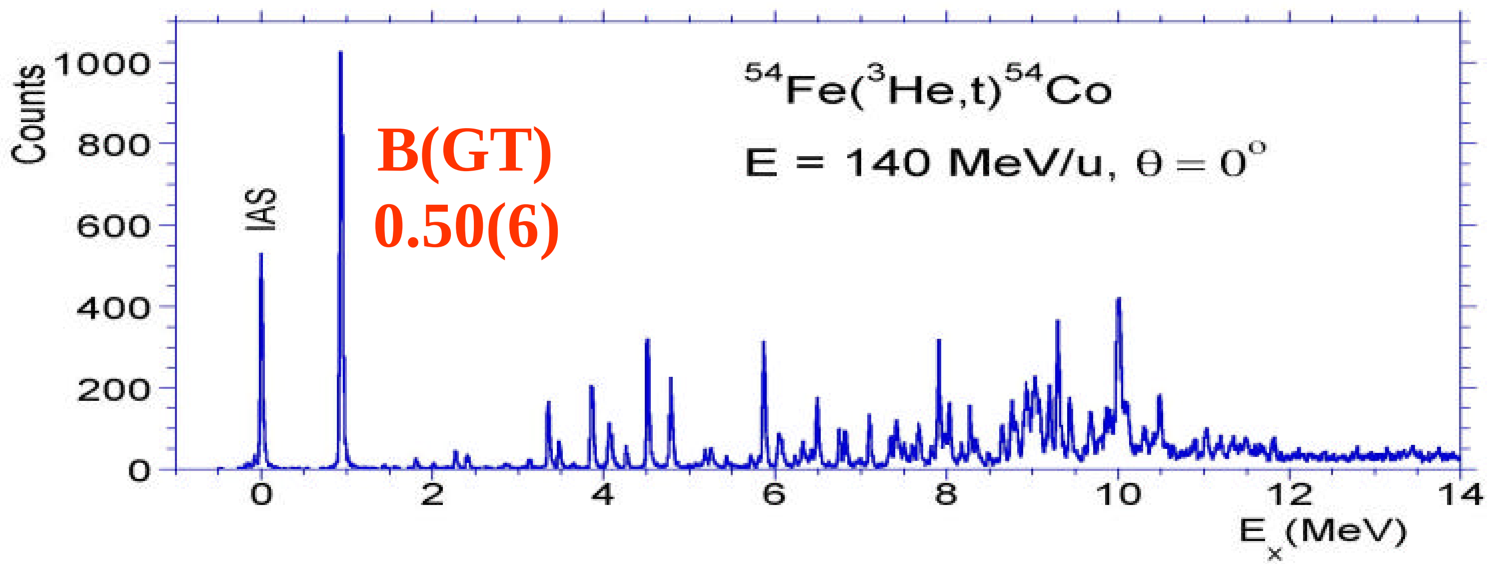


Y. Fujita et al., PRC 67 ('03) 064312

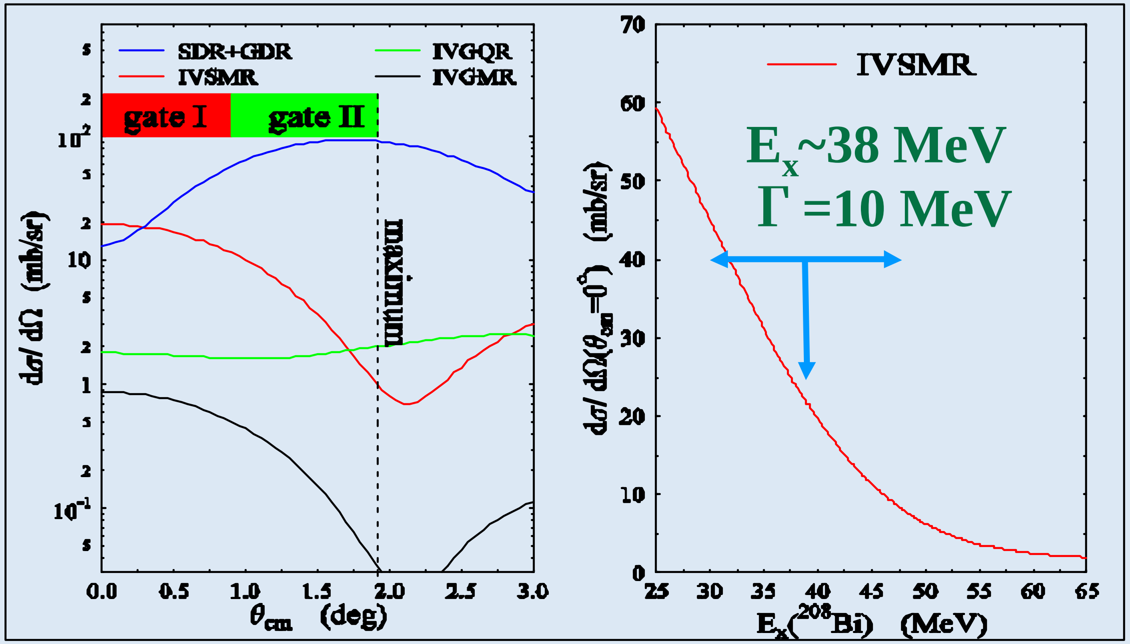
Prominent states are GT states and the IAS !

^{54}Fe(p,n) & ^{54}Fe(^{3}He,t)

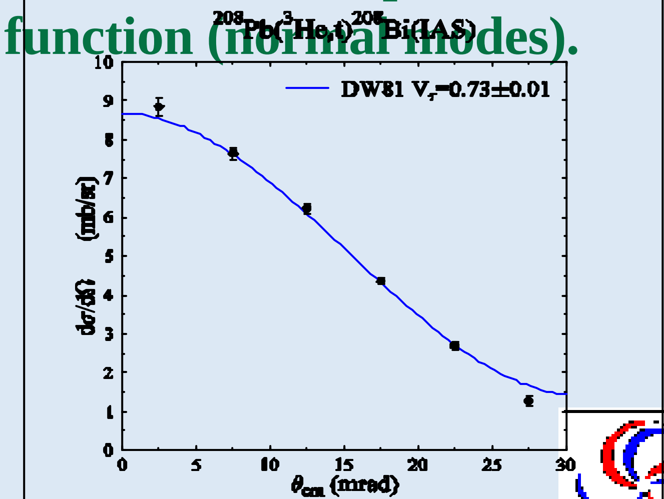




Measurement of IVSGMR via $^{208}Pb(^3He,t+p)$



- DW81 (Raynal)
- Effective ^{3}He-N potential
  - $V_\tau = 0.73 \pm 0.01$ MeV (IAS)
  - $V_{\sigma\tau} = -2.1 \pm 0.2$ MeV (known ratio to V_τ)
  - $V_{T\tau} = -2.0$ MeV/fm^2
- most coherent 1p-1h wave-function (normal modes).

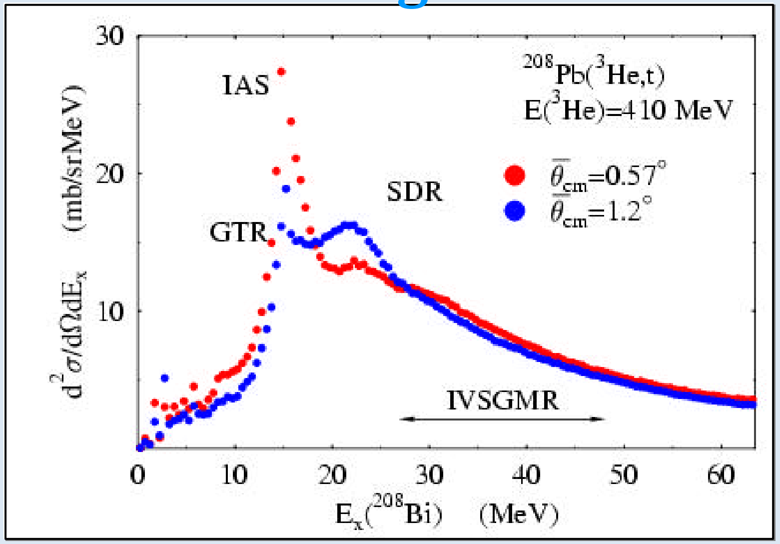


Use *difference-of-angle* to identify the monopole excitations

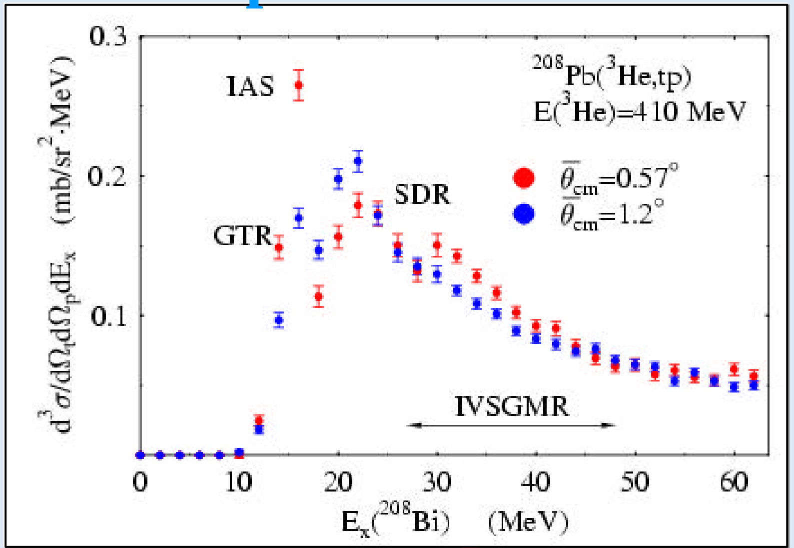
Results

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

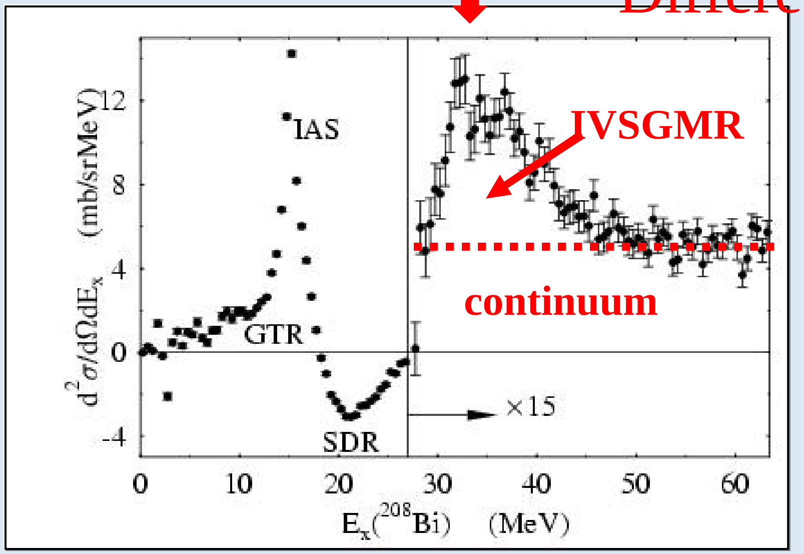
t singles

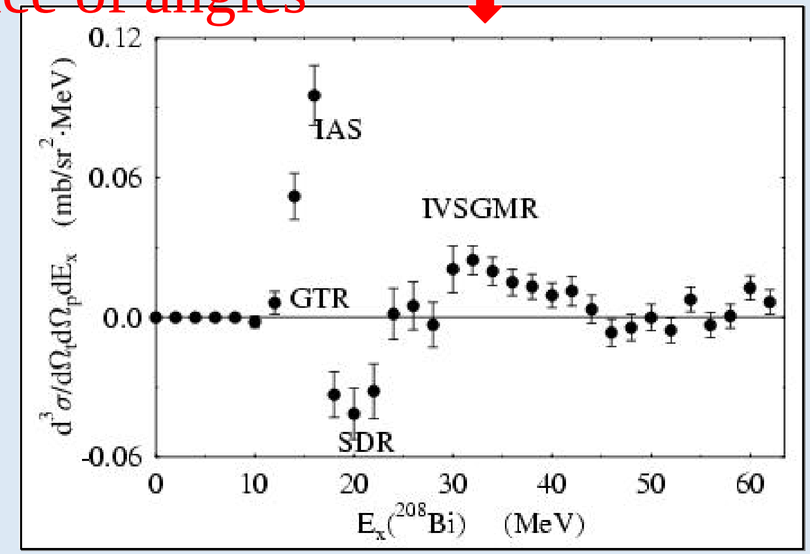


t-p coincidences



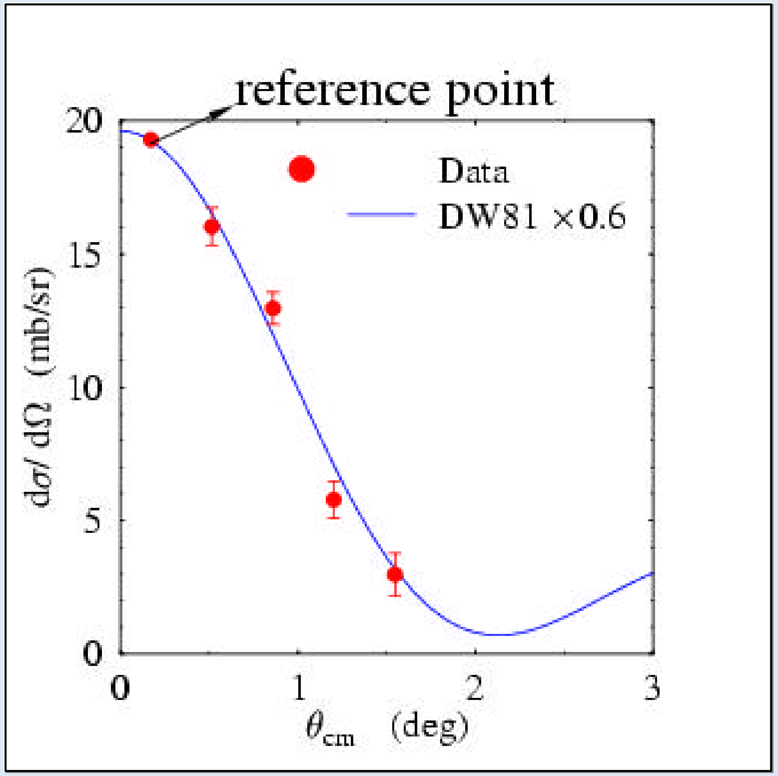
Difference of angles





Angular distribution

Use difference-of-angle method between narrow angular bins to extract angular distribution of the resonance



IVSGMR angular distribution confirmed

Outlook

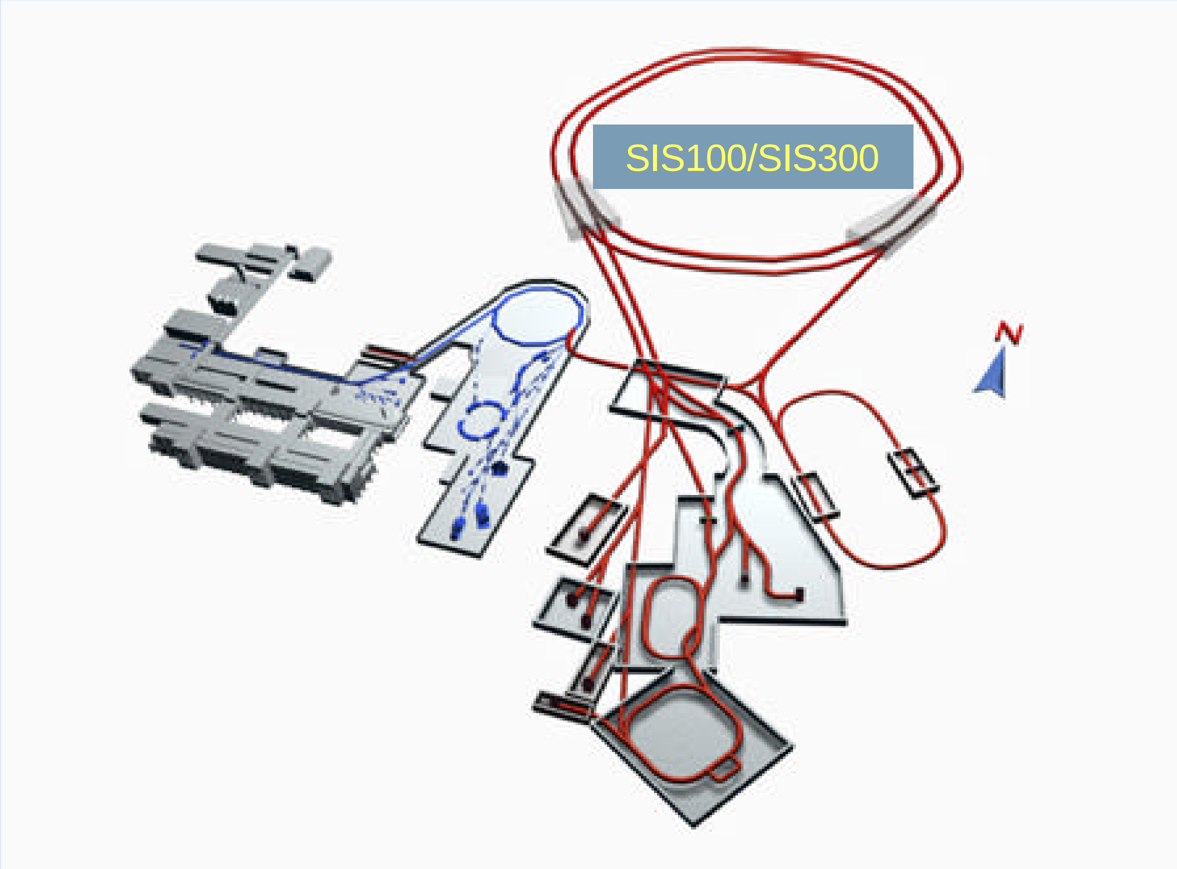
Radioactive ion beams will be available at energies where it will be possible to study (charge-exchange) multipole excitations (RIKEN, FAIR, RIA, EURISOL, NSCL)

- **Multipole strength functions in unstable n-rich nuclei**

  soft modes, pygmy resonances, low-lying non-collective strength, but also charge-exchange isospin & spin-isospin modes

- **Determine GT & spin-dipole strength in unstable nuclei**
- **Use GRs as tools to determine n-skin [IV(S)GDR]**
- **Exotic excitations such as Double GT**

NuPECC recommends as the highest priority for a new construction project the building of the international “Facility for Antiproton and Ion Research (FAIR)” at the GSI, Darmstadt



Primary Beams

- 10^{12}/s 1.5-2 GeV/u $^{238}U^{28+}$
- factor 100-1000 over present in intensity
- $2.5 \cdot 10^{13}$/s 29 GeV protons
- 10^{9}/s $^{238}U^{92+}$ up to 34 GeV/u

Secondary Beams

- broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- antiprotons 3 - 30 GeV

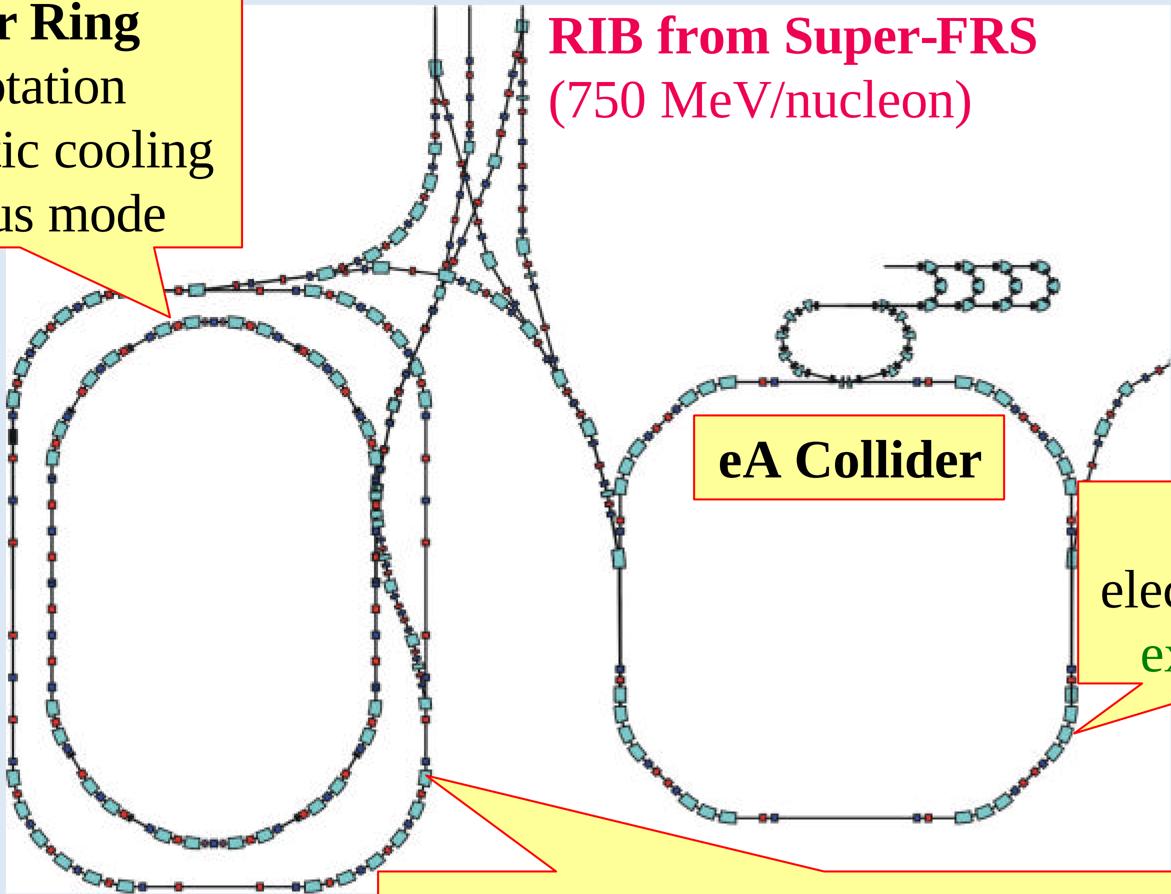
Storage and Cooler Rings

- radioactive beams
- e - A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons
- highly-charged ions and $\overline{p}$ at rest

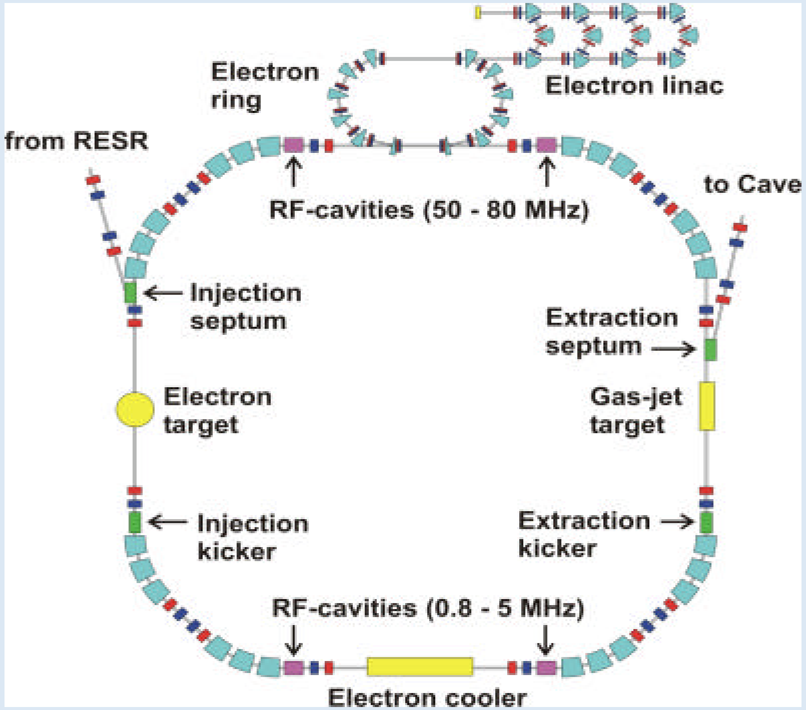
Key Technical Features

cooled and stored beams
rapidly cycling superconducting magnets
parallel operation

FAIR Storage Rings



NESR Versatile Storage Ring for Physics Experiments



Ions

storage and cooling of ion beams in the energy range 740®10 MeV/nucleon

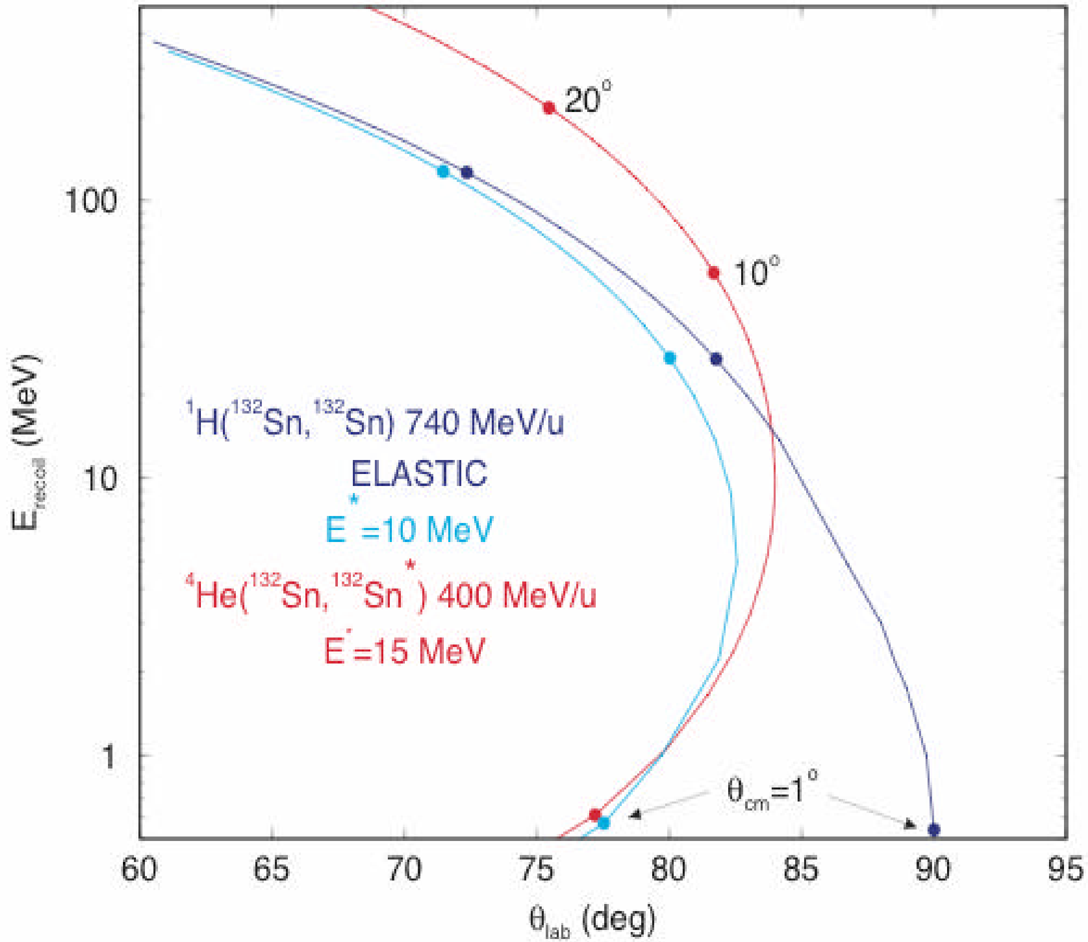
maximum deceleration rate ***1 T/s***

experiments with internal target

luminosity up to 10^{29} *cm*$^{-2}$*s*$^{-1}$

RIB accumulation by electron cooling

Energy range (Ramp Rate 1 T/s)	4 - 740 MeV/nucleon
Cooling time constant (for 10^7 U^{92+}-ions)	0.3 - 0.5 s
Transverse emittance after cooling	0.1 (h,v) mm mrad
Momentum spread after cooling	$\pm 1 \times 10^{-4}$
Number of stored ions / revolution frequency	up to ~ 10^9 / ~ 10^6 s^{-1}

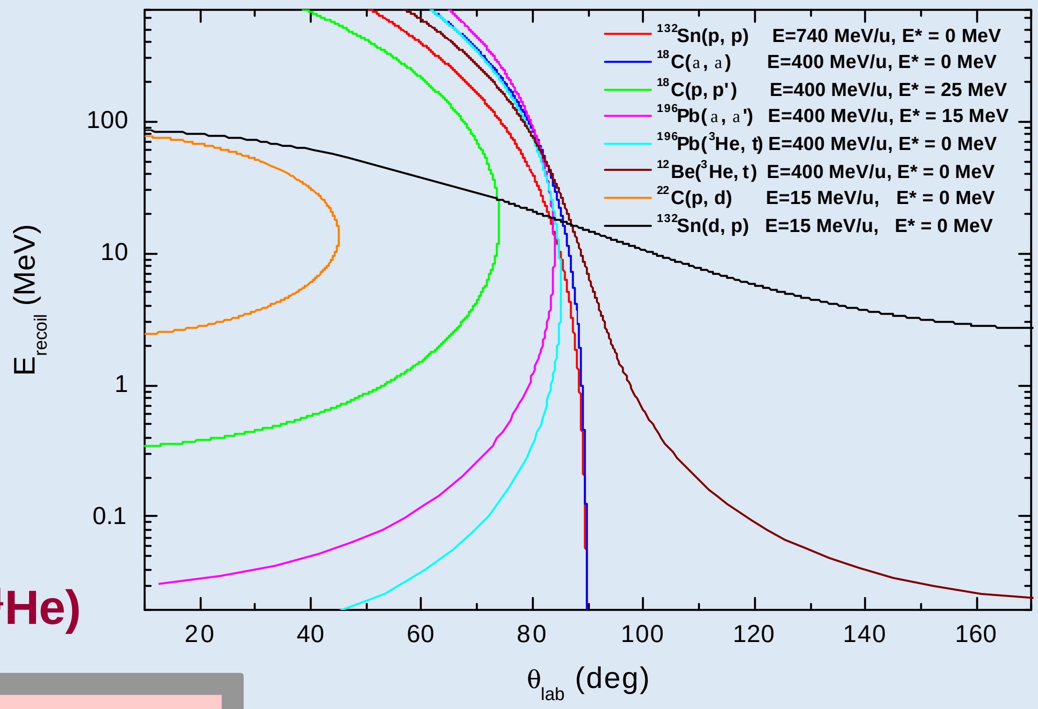

$^{1}H(^{132}Sn,^{132}Sn)$ 740 MeV/u
ELASTIC
E^{*}=10 MeV
$^{4}He(^{132}Sn,^{132}Sn^{*})$ 400 MeV/u
E^{*}=15 MeV
20°
10°
θ_{cm}=1°
E_{recoil} (MeV)
θ_{lab} (deg)
100
10
1
60
65
70
75
80
85
90
95

Light-ion scattering with Radioactive Ion Beams (RIB)

Rather limited applications to date

➢ **Heavy-ion storage ring**

➢ **Internal light target (e.g. ^{1,2}H, ^{3,4}He)**



- **Inverse kinematics**
- **Measurements at <u>low energy/momentum transfer</u>**

  → need very thin (windowless) target

  → need to regain luminosity

  from beam accumulation

  from beam recirculation (NESR ~ 10^6 s^{-1})

  → need high resolution (recoil kinematics)

  regain beam quality by electron cooling

Physics overlap with R^{3}B at the external target
(high-momentum transfer,
very-short lived nuclei,
active target)

Complementarity

EXL Set-up – Concept and Design Goals

Design goals

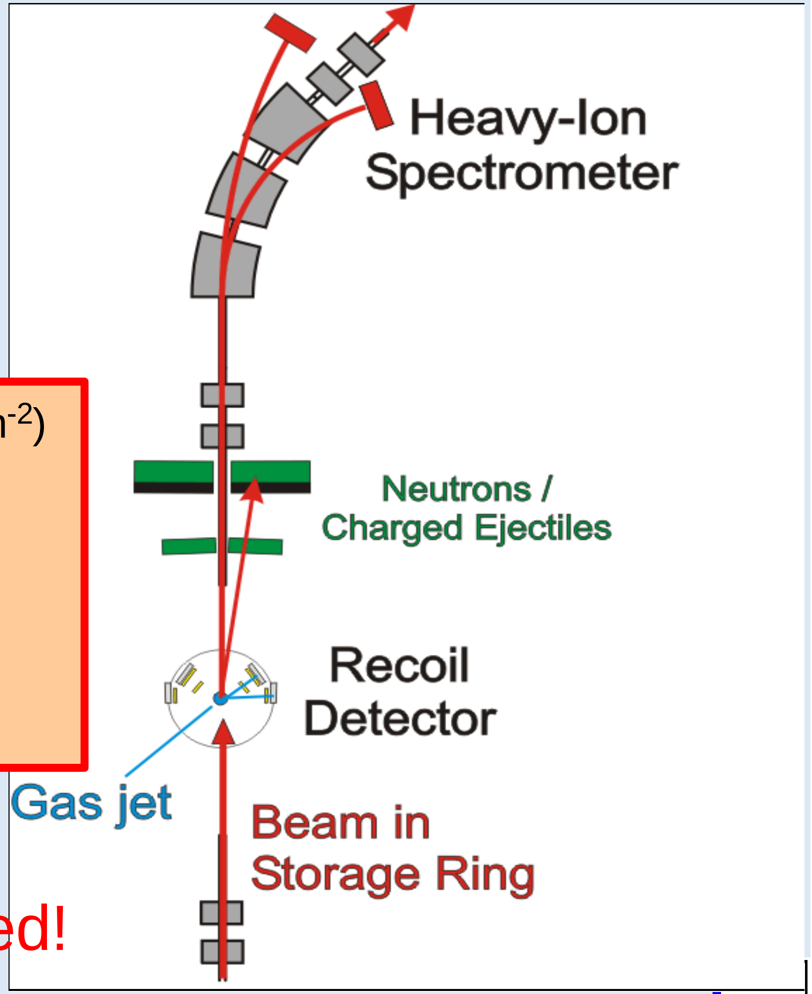
- Universality: applicable to a wide class of reactions
- High energy and angular resolution
- Fully exclusive kinematical measurements
- High luminosity (> 10^{28} cm^{-2} s^{-1})
- Large solid angle acceptance
- UHV compatibility (in part)

✓ Internal gas-jet target (>10^{14} cm^{-2})

✓ Detection systems for:

- Target recoils (p,α,n,γ…)
- Forward ejectiles (p,n,γ)
- Heavy fragments

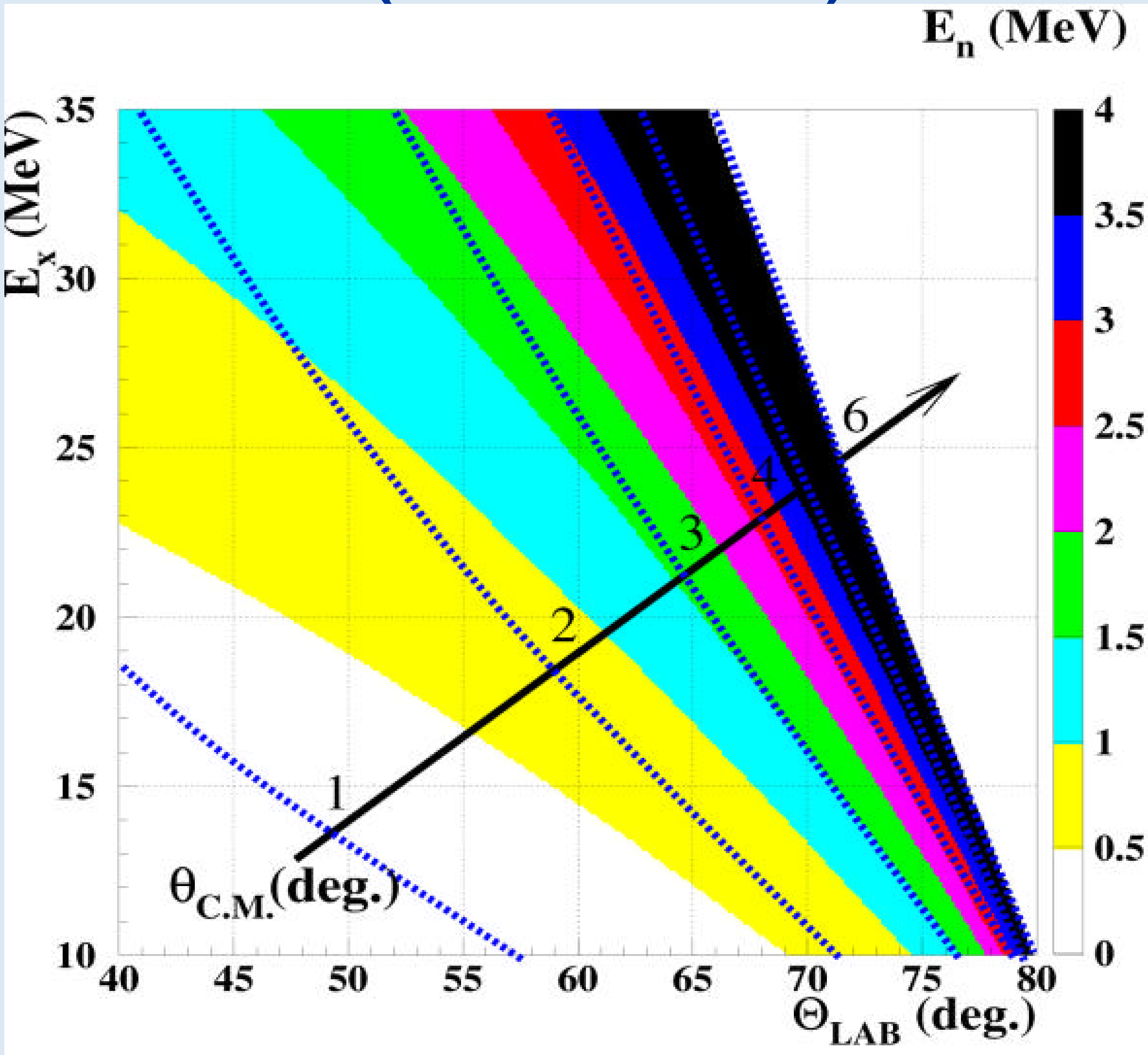
Big R&D effort needed!



KVI

New possibilities: p(^{132}Sn,n)

(E=400 AMeV)



ICHOR project

Isospin-spin responses in **CH**arge-exchange ex**O**thermic **R**eactions

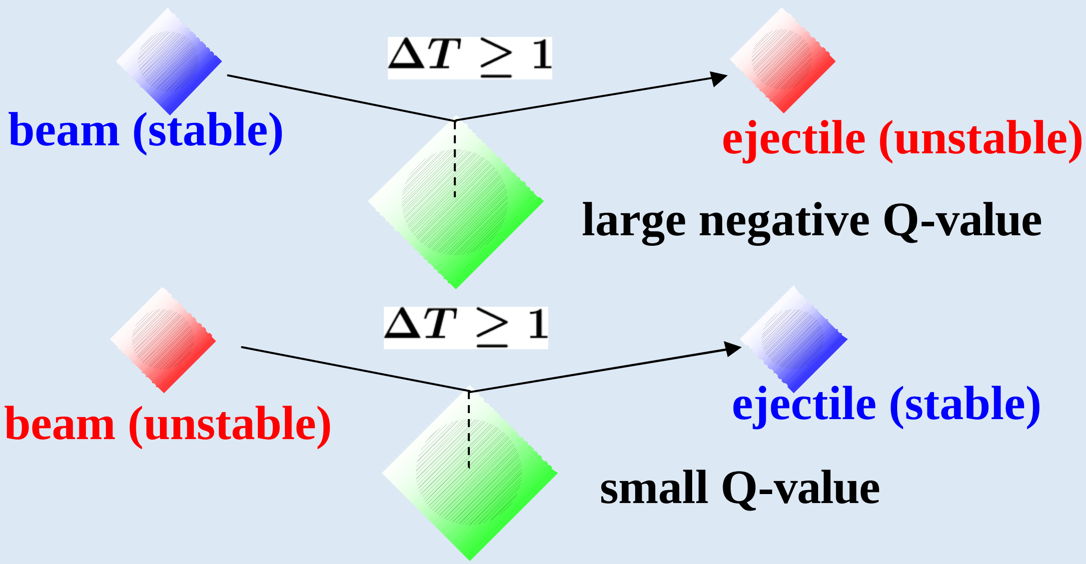
ICHOR

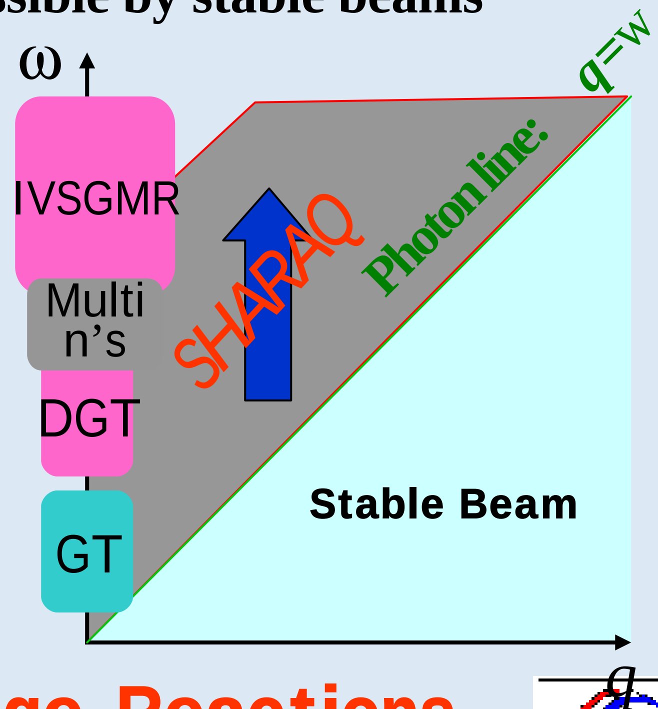
- ICHOR project approved by MEXT in 2005 to contruct SHARAQ

H Sakai, K Yako, S Shimoura, T Uesaka, E Ideguchi, T Kawabata

RI Beam (E = 150-400 MeV/A) as a new **PROBE** to nuclear systems

- Large Isospin — iso-tensor excitations
- Large internal energy — (q,w) inaccessible by stable beams





Exothermal Charge Exchange Reactions

SHARAQ Spectrometer

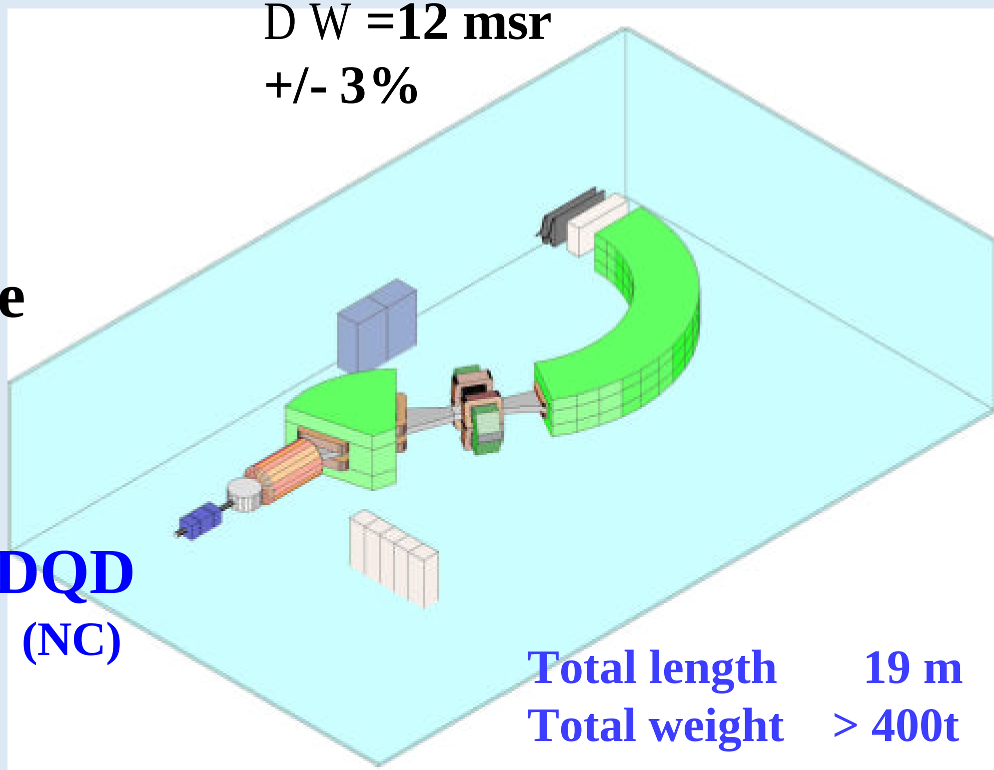
Spectroscopy of HAdron systems with RadioActive Quantum beams

Parameters

- **Momentum resolution** D*p*/*p* < 1/15000
  dE_x~300 keV for *A*=8, *E*=300MeV/u
- **Maximum rigidity** *B*r = 6.8Tm (r =4.8m)
- **Solid angle** D W =12 msr
- **Momentum acceptance** +/- 3%

High-quality RI beam-line

- **Dispersion matching**



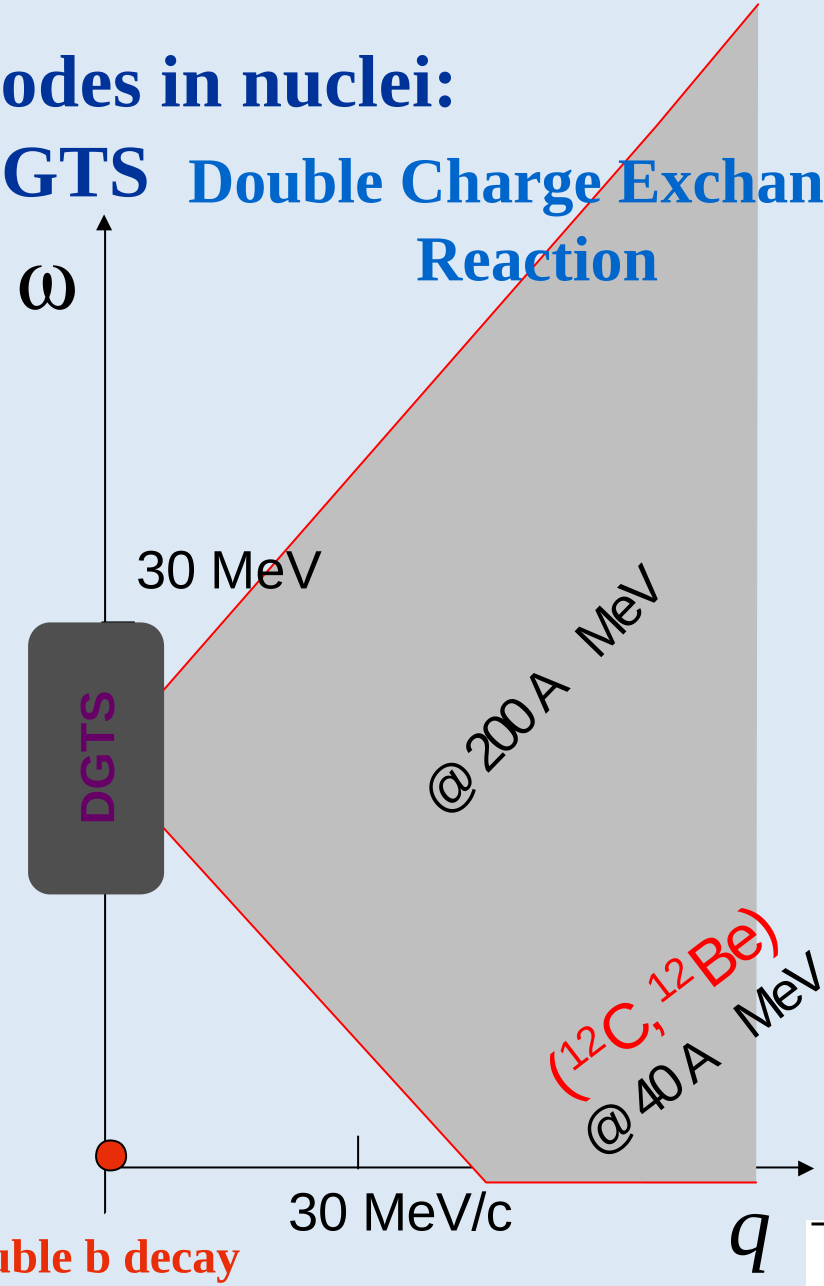
QQDQD
(SC) (NC)

Total length 19 m
Total weight > 400t

New Spin-Isospin Modes in nuclei: IVSMR, DGTS

Double Charge Exchange Reaction

- Double Gamow-Teller States (DGTS)
  - Two-phonon response
  - Nuclear matrix elements for double beta decay
  - $(^{20}Mg,^{20}Ne)$ $(^{9}C(3/2^{-}),^{9}Be(3/2^{-}))$



END