Gamow-Teller transitions from ^{56}Ni

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Charge-Exchange (CE) reactions: a tool for studying Gamow-Teller strengths

Gamow-Teller transition

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

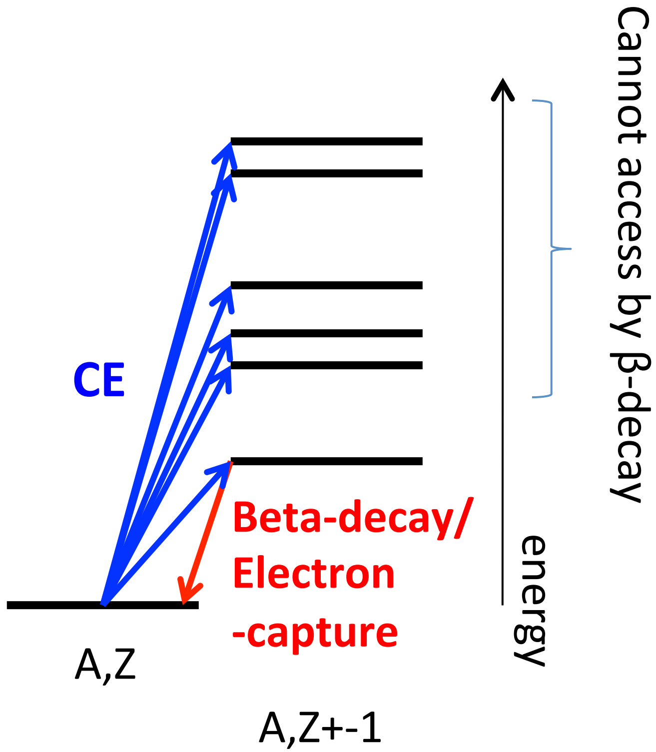
induced by $\boldsymbol{\sigma}\ \boldsymbol{t}_{\pm}$

strength : **B(GT)**

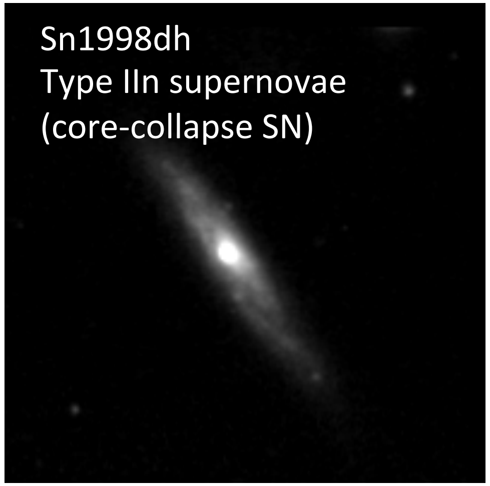
→ allowed β-decay

CE reaction at intermediate energies, e.g. (p,n) reaction

$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(p,n)} = \hat{\sigma}\ B(GT)$$



Weak reactions in astrophysics



Core-Collapse (Type II) Supernovae

- Collapse of massive star at the end of burning cycle electron-capture (EC) on Fe-region nuclei
  - reduces electron pressure
  - neutrinos by EC carry away energy from the star → collapse accelerates
  - affects the mass interior to the shockwave

Thermonuclear (Type Ia) Supernovae

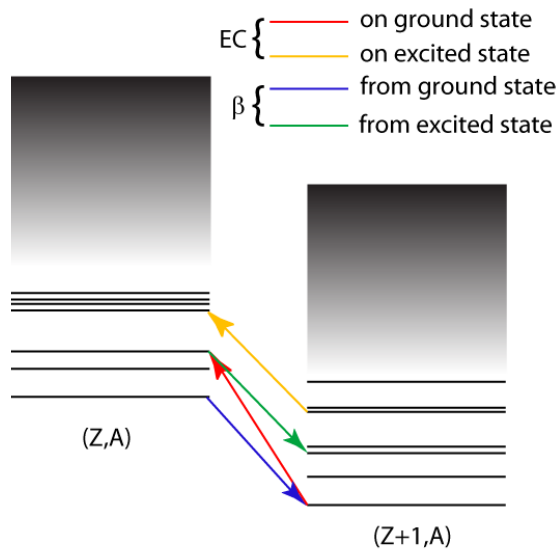
- source of large fraction of Iron group nuclei in the universe
- thermonuclear explosions of accreting white dwarfs in binary systems **Not well understood.**

- ECs strongly affect the flame propagation after ignition
- If ECs are well understood → models can be much better constrained

Key ingredient : Electron capture in Fe-region nuclei

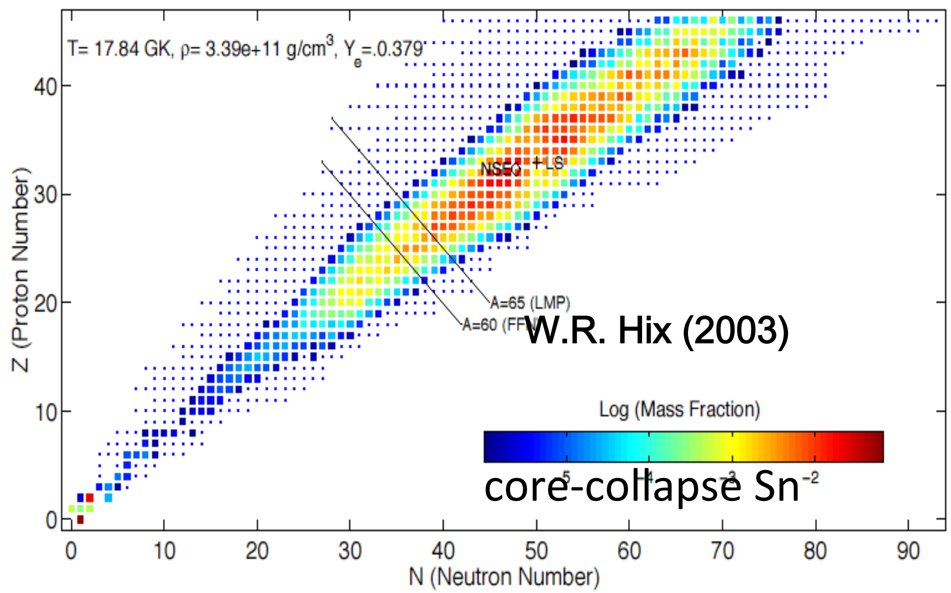
Weak reactions (electron capture) in supernovae

- Key ingredient: **Gamow-Teller strengths**
- Many nuclei play a role (A-40-120)
- Majority are unstable
- excitation can take place from excited nuclear states



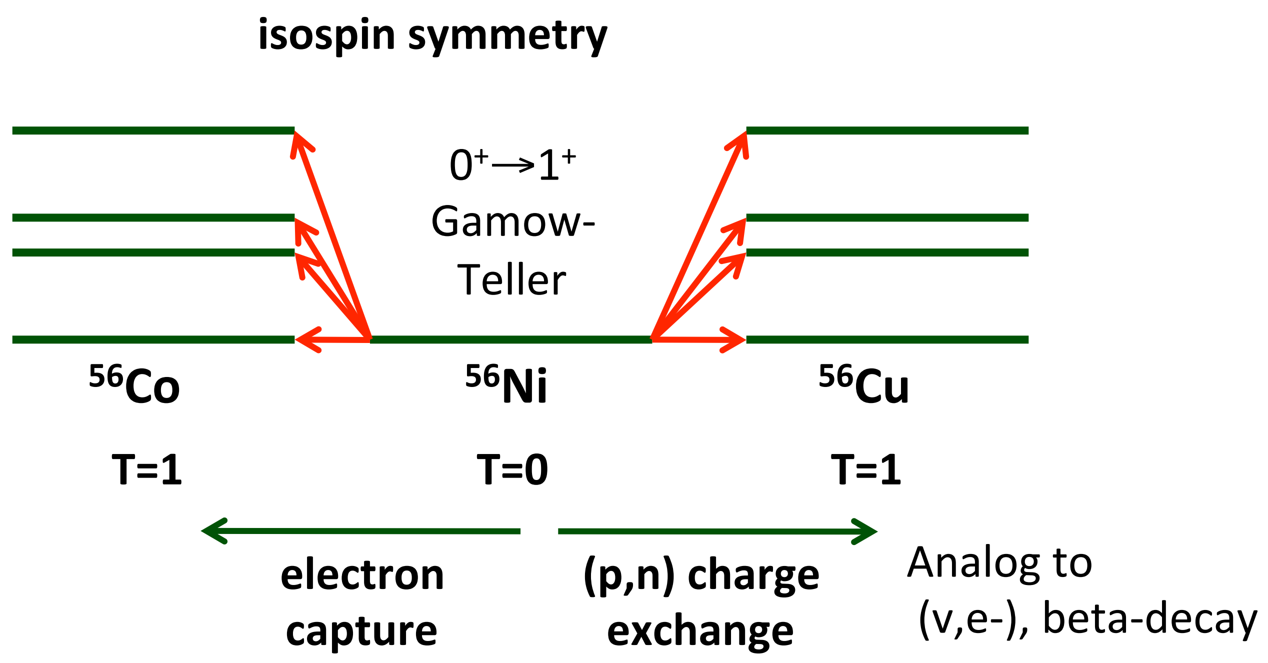
Impossible to measure even a sizeable fraction of cases

- Test theory with cases that constrain key model parameters
- Measure nuclei that are particularly abundant in supernovae



Electron capture in ^{56}Ni

One of the important cases
in core collapse super novae of massive stars
(Phys. Rev. Lett. 86, 1678 (2001))



B(GT) measured by the (p,n) reaction is directly connected with the EC rate.

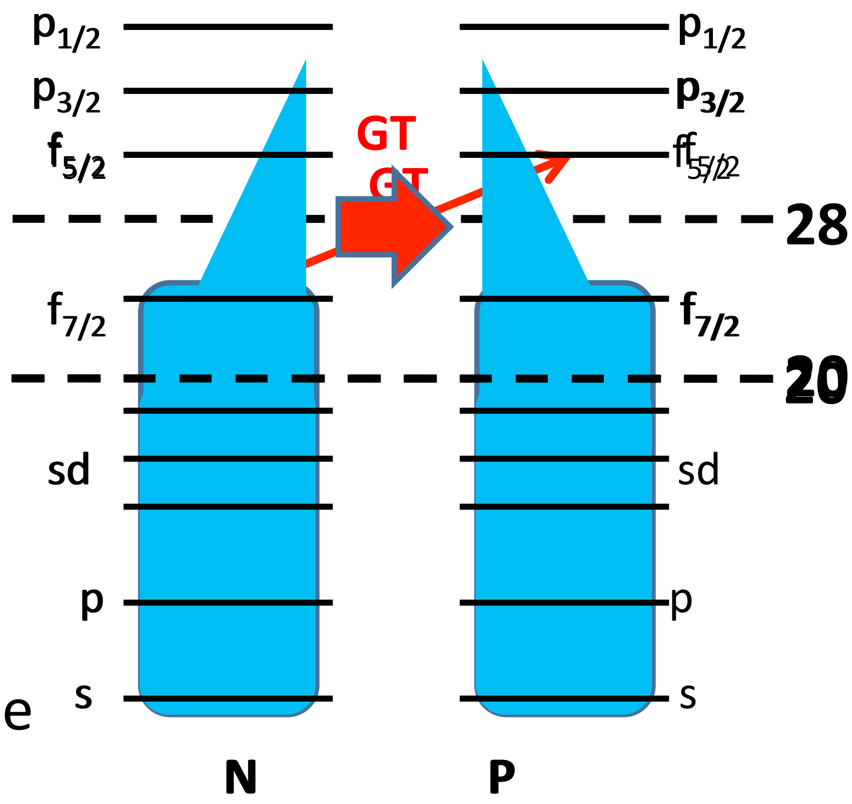
^{56}Ni is a key nucleus in Fe region

^{56}Ni (Z=N=28)

- independent particle model
  → ^{56}Ni is doubly magic
- Large p-n residual interaction
  → ^{56}Ni is not magic

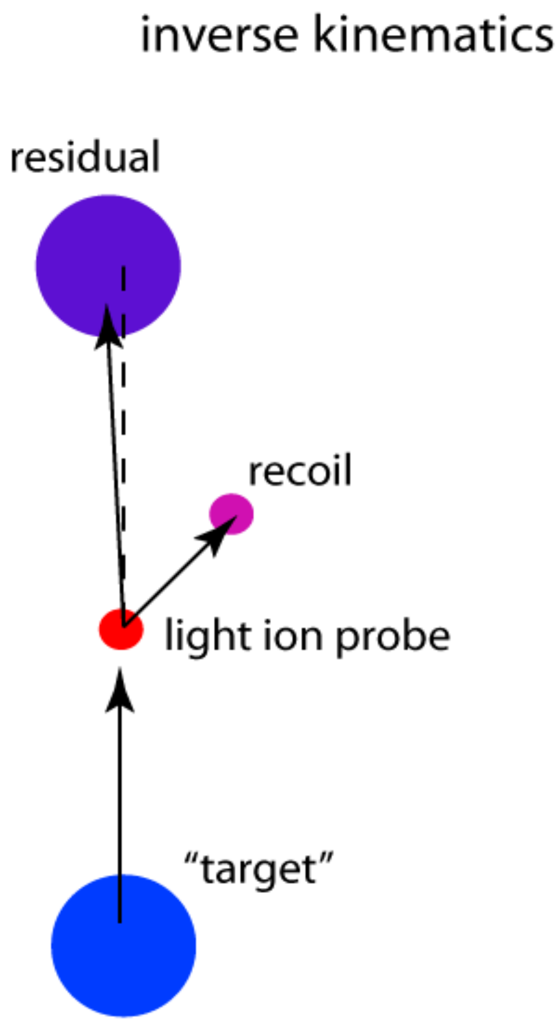
- **GT strength from ^{56}Ni**
  → key to bench mark nuclear model used for weak rates in the Fe region

Experimentally, challenging!



f7/2 70% in ^{56}Ni (GXPF1A, KB3G)
(e.g., Honma et al., Phys. Rev. C 69, 034335 (2004))

Existing CE studies using RI beams



^{34}P(^{7}Li,^{7}Be+gamma)

(Zegers et al., Phys. Rev. Lett. 104, 212504 (2010)

^{12}B(^{7}Li,^{7}Be+gamma)^{12}Be

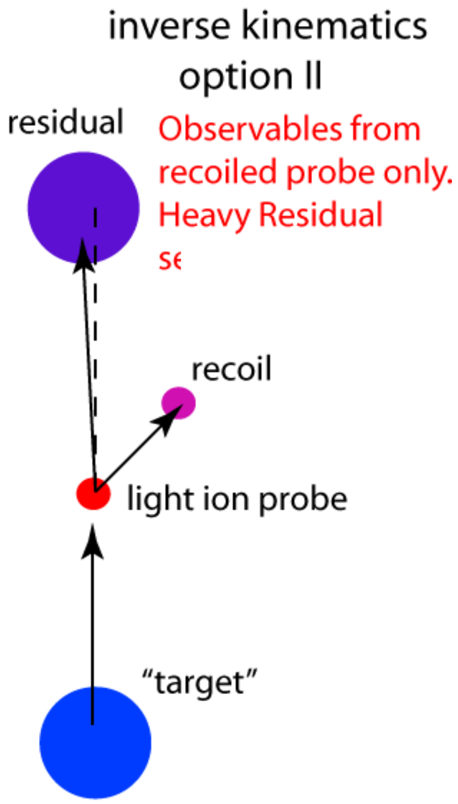
(Meharchand et al., to be published)

^{1}H(^{14}Be,^{13}B+**n**)n

(Satou et al., Phys. Lett. B 697 (2011) 459-462.

→ Only several low-lying states and light nuclei

(For high Ex/heavier nuclei, to analyze the residue decays becomes difficult)



Our method

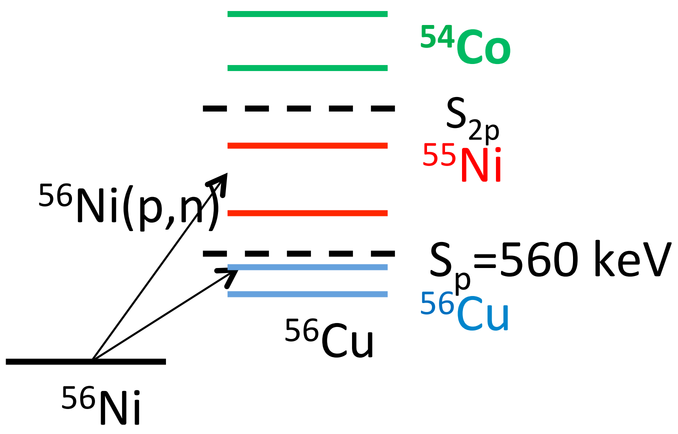
Missing mass spectroscopy by the detection of the recoil neutron

Advantages

- target can be thick (neutron recoil)
  → high luminosity
  even with unstable beams
  with low intensities

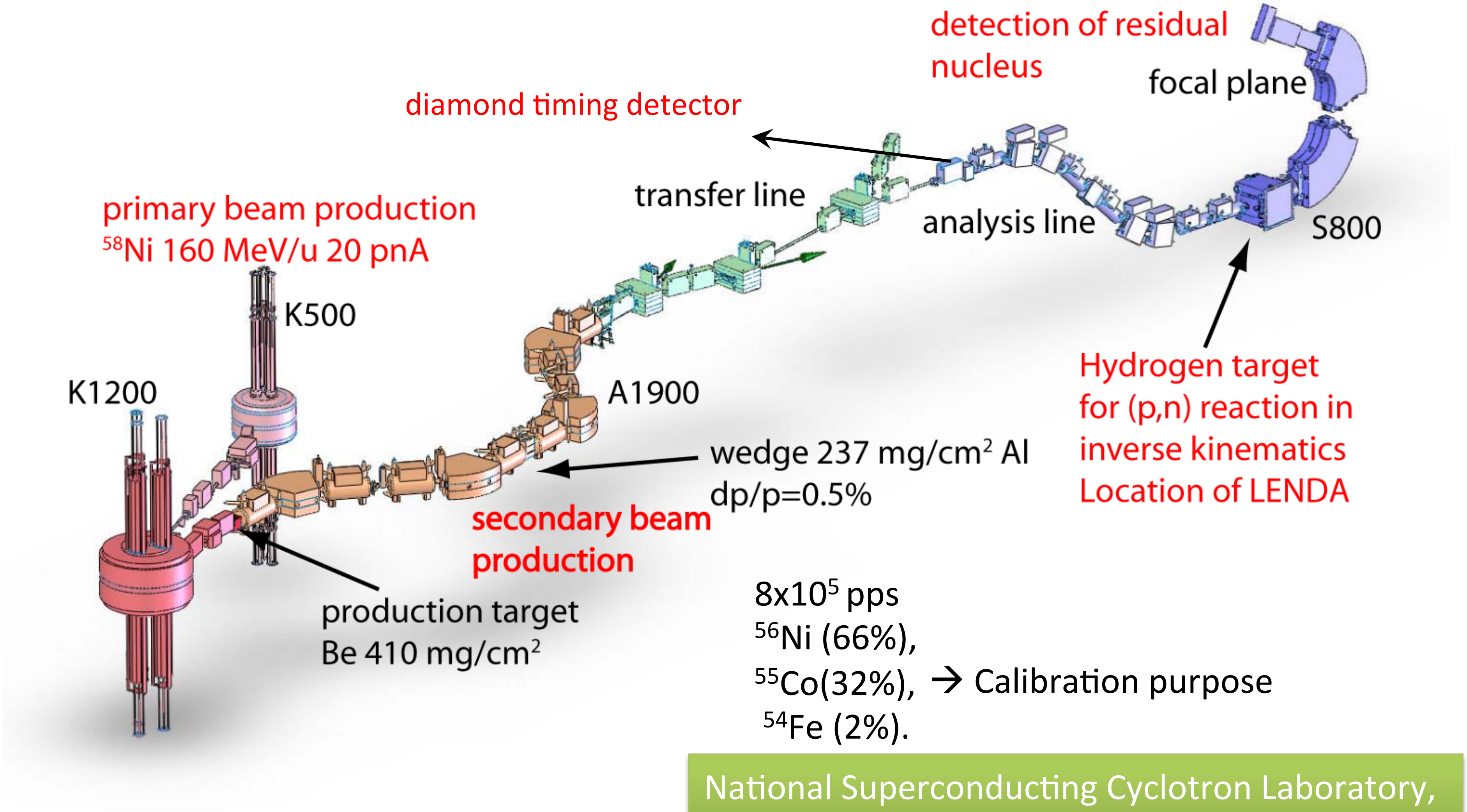
- All kinematic information from measurement of the neutron (two-body kinematics)
  → simple measurement and analysis,
  compared to invariant mass method

- Heavy fragment serves as tag for CE reaction
  → branching ratio of the particle decay



Can be applied to any mass region and to any excitation energy

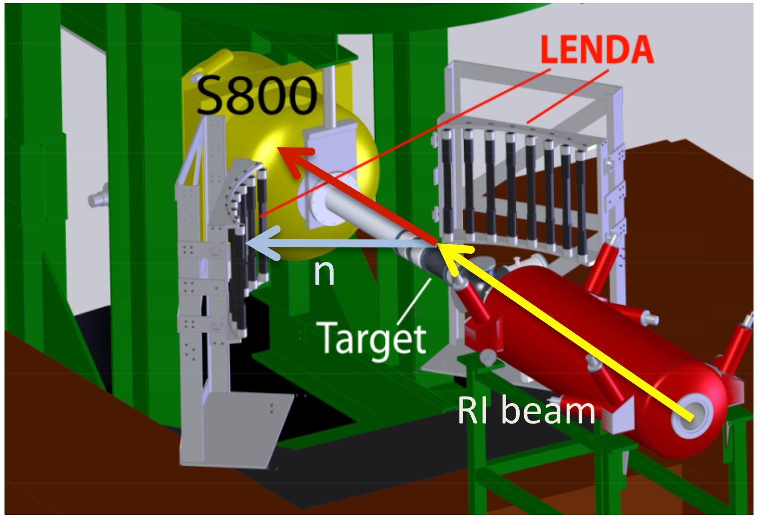
^{56}Ni beam production and experiment overview



8x10^5 pps
^{56}Ni (66%),
^{55}Co(32%), → Calibration purpose
^{54}Fe (2%).

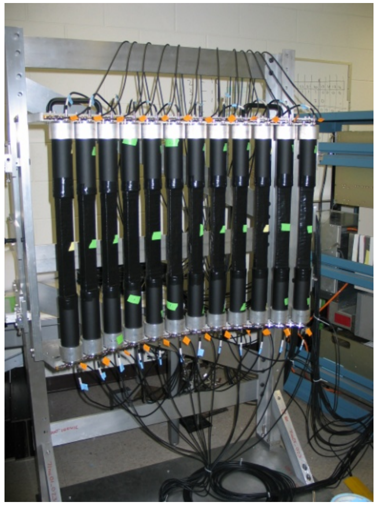
National Superconducting Cyclotron Laboratory,
Michigan State University

Set up of LENDA



Neutron energy & angles

Excitation energy
& reaction scattering angles



Low Energy Neutron Detector Array (LENDA)

neutron detection

Plastic scintillator

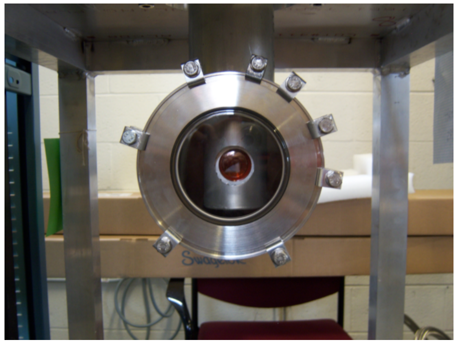
24 bars 2.5x4.5x30cm

150 keV < E_n < 10 MeV

ΔE_n ~ 5% $\Delta\theta_n < 2^o$

efficiency 15-40%

Flight path : 1 m



Liquid Hydrogen target

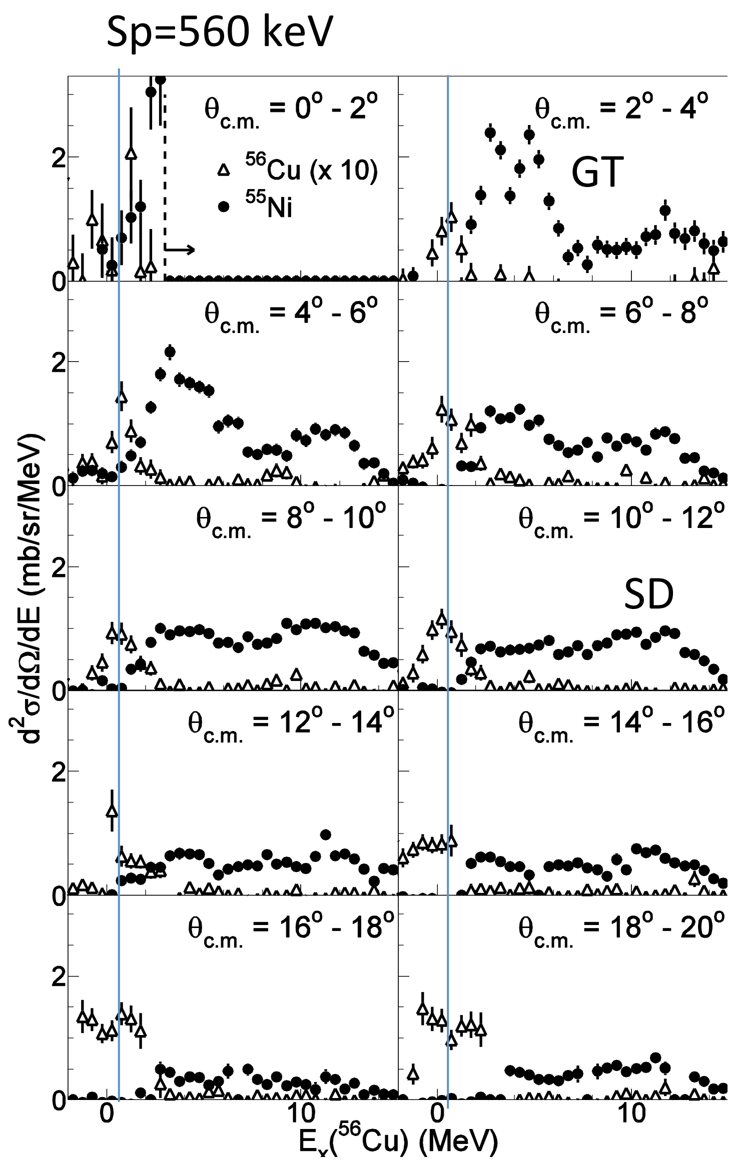
"proton " target

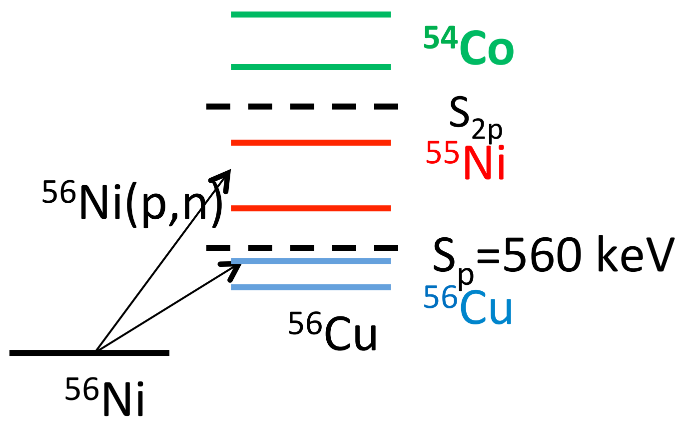
65 mg/cm² (~7 mm)

~3.5 cm diameter

T=20 K ~1 atm

Double differential cross sections





Two bumps at 3 and 5 MeV
with forward angle peaks (GT:ΔL=0)

A bump around 12 MeV
→ Peak around 10-12 degrees
→ Spin dipole (ΔL=1)

States without proton emission
→ Peak at most backward angle
→ Higher multipoles (ΔL>1)

To extract GT component quantitatively
→ Multipole decomposition

Multipole decomposition analysis

Experimental angular distribution for each energy bin

Fit with linear combination of calculated angular distribution

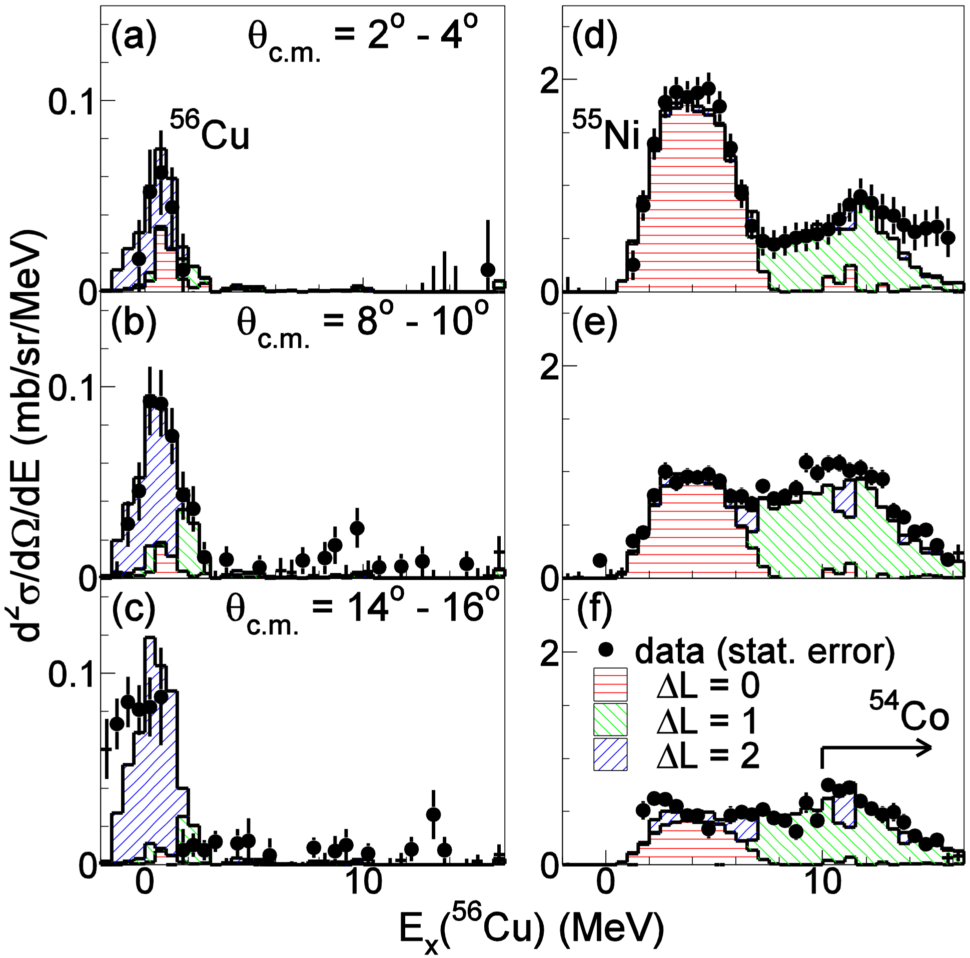
$\sigma_{exp}(\theta_{cm}) \approx \sum_{\Delta L=0}^{2} a_{\Delta L}\, \sigma_{\Delta L;\,calc}(\theta_{cm})$

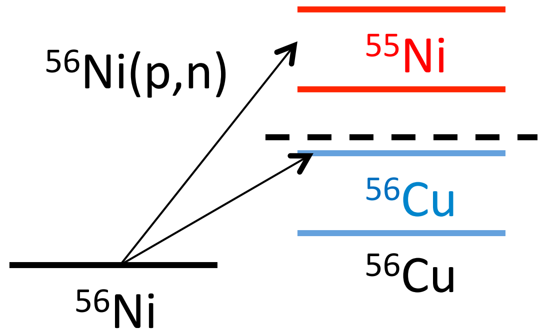
Cross sections of each multipole (ΔL)

A distorted wave impulse approximation (DWIA)

- Code : DW81
- Optical potential by Nadasen et al., Phys. ReV. C 23, 1023 (1981).
- Normal modes for transition density calculation
- NN interaction by Franey and Love, Phys. ReV. C 31, 488 (1985).

Results of MDA

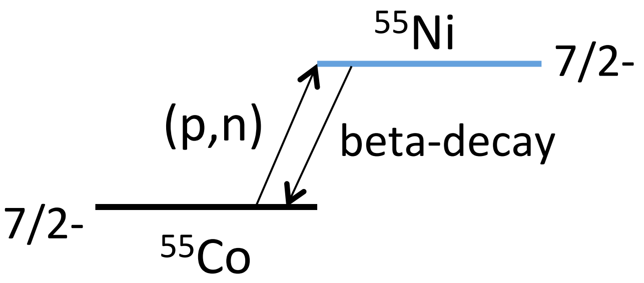


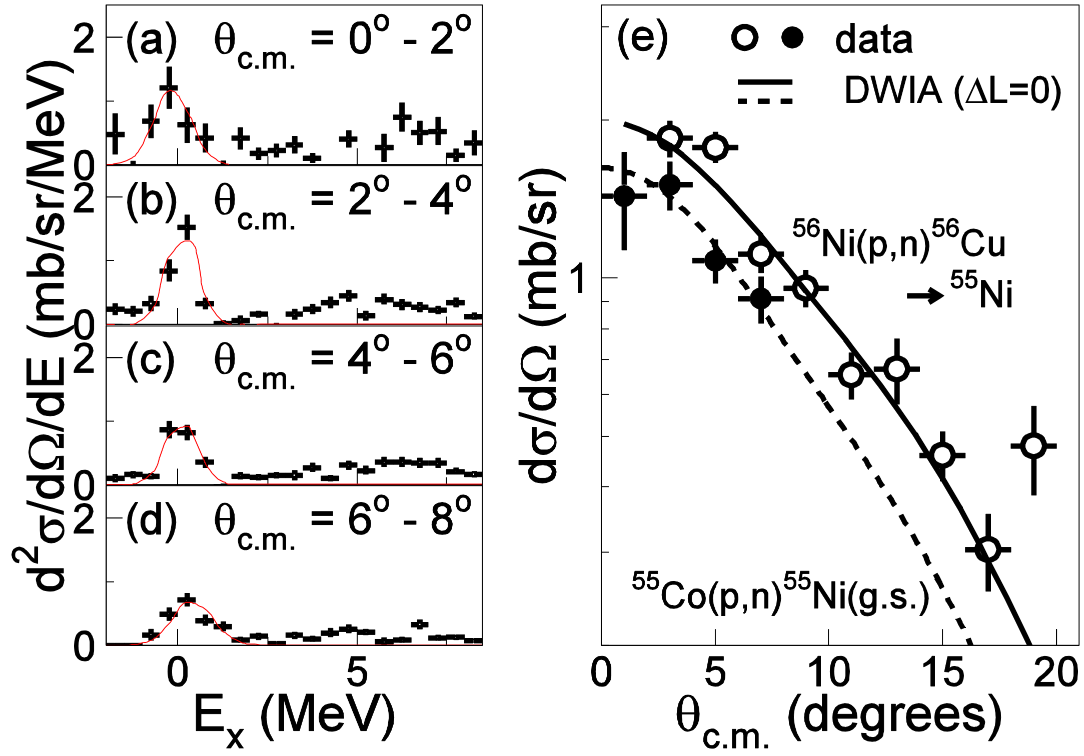


GTR and SDR are extracted!

Calibration of the proportionality

$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(p,n)} = \hat{\sigma}\, B(GT)$$





Mixed :

GT of B(GT)=0.267

(Aysto et al., Phys. Lett. B138, 369 (1984))

Fermi of B(F)=1

Fraction of GT cross section : 0.51+-0.03

using $\hat{\sigma}_{GT} / \hat{\sigma}_F = 4.0 \pm 0.2$

Taddeucci et al., Nucl. Phys. A469, 125 (1987).

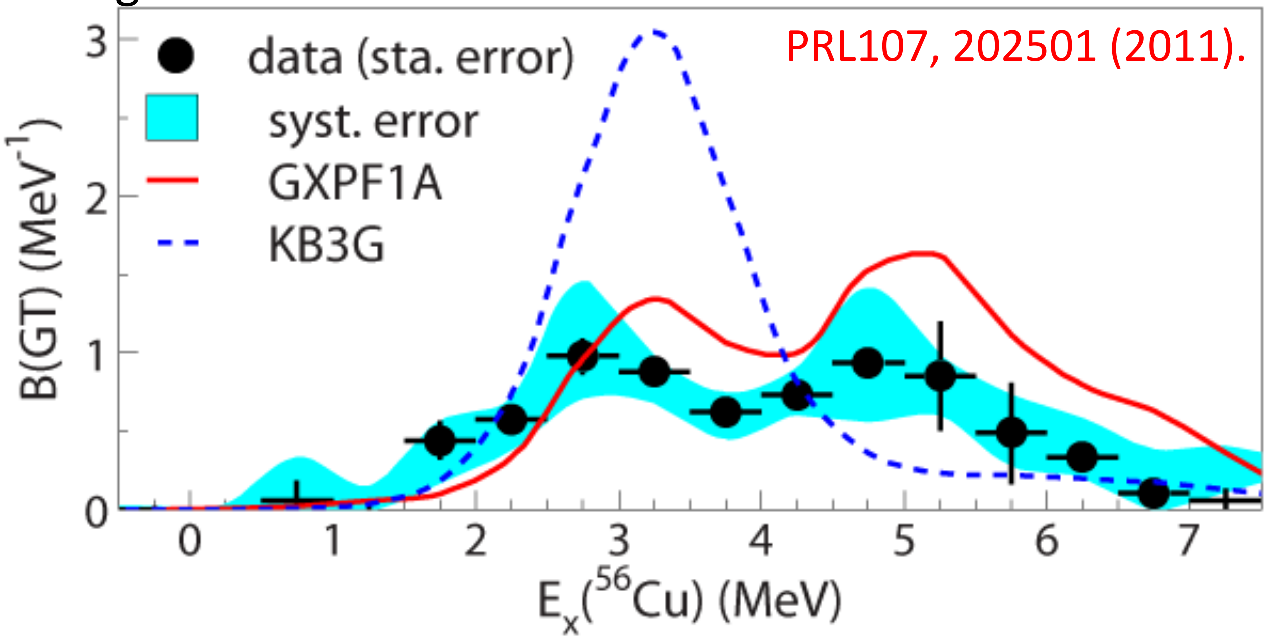
GT unit cross section of ^{55}Co(p,n) at 110 MeV/u

→ 3.2 +- 0.5 mb/sr

→ Consistent with 3.5+-0.2 mb/sr for ^{58}Ni(p,n) at 120 MeV

GT strengths from ^{56}Ni(p,n) at 110 MeV/u

- Use the extracted $\Delta L=0$ component in combination with unit cross section to extract Gamow-Teller strength [B(GT)].
- Compare with large-scale shell-model calculations



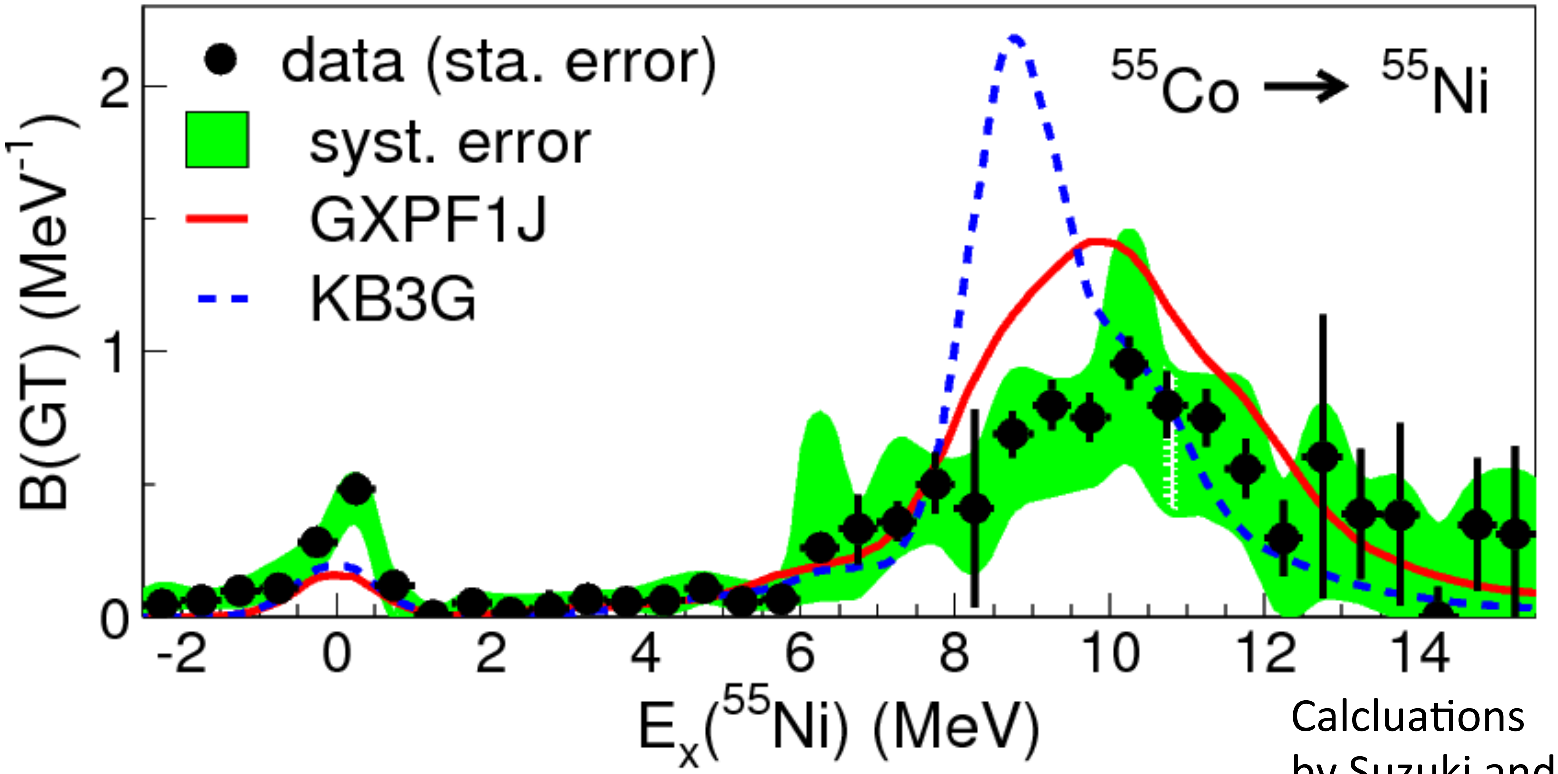
GXPF1A: Honma et al. : constrained by data in full pf-shell

KB3G: Poves et al. : less constraints – used in database for weak rates for astrophysical purposes.

Difference between KB3G and GXPF1A:

- KB3G weaker spin-orbit and pn-residual interactions
- KB3G lower level density

A preliminary result of ^{55}Co



Calcluations
by Suzuki and Honma

KB3G : X

GXPF1"J" : O

Consistent with the comparison in ^{56}Ni

Astrophysical applications in RIKEN

The developed technique
+ RIKEN RIBF (intense RI beam)
+ SAMURAI spectrometer (efficient PID)
+ Neutron wall (WINDS)

probe any Ex on any A/Z
(beam intensity 10^{4-5} pps)

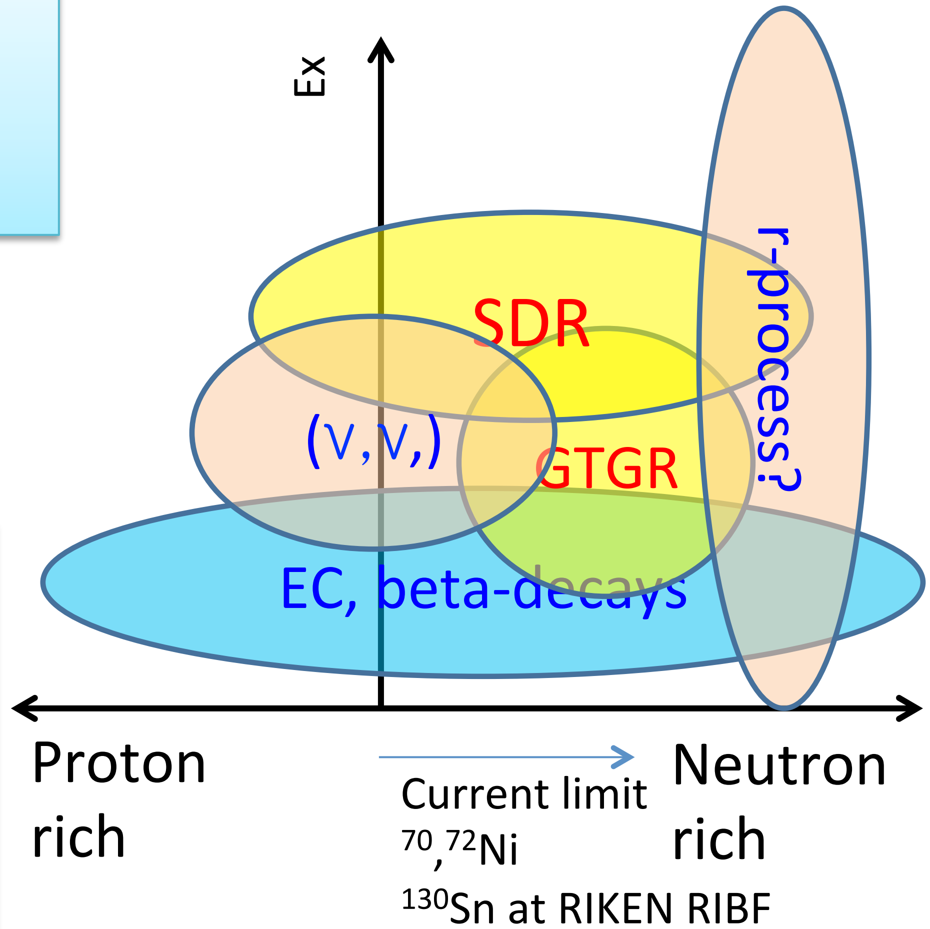
Better understanding of weak response →

EC/beta-decays

Neutral weak currents

e.g., Synthesis of Mn
$^{56}Ni(\nu,\nu p)^{55}Co \rightarrow {}^{55}Fe \rightarrow {}^{55}Mn$
GXPF1 >> KB3G (a factor of 3)
T. Suzuki et al., Phys. Rev. C79, 061603(R) (2009).

R-process (GT + first forbidden)
T. Suzuki et al., arXiv:1110.3886



Questions :
Which nucleus is the key?
How reliable is the calculation during the extra/interpolation?

Summary and conclusion

- A new experimental technique to measure GT strengths (any Ex & (A,Z))
- The first case: ^{56}Ni (nuclear structure/astrophysics)

  → KB3G (used in astrophysical data base) : x

  GXPF1A : O
- Preliminary results for ^{55}Co(p,n)^{55}Ni
- A lot of applications;

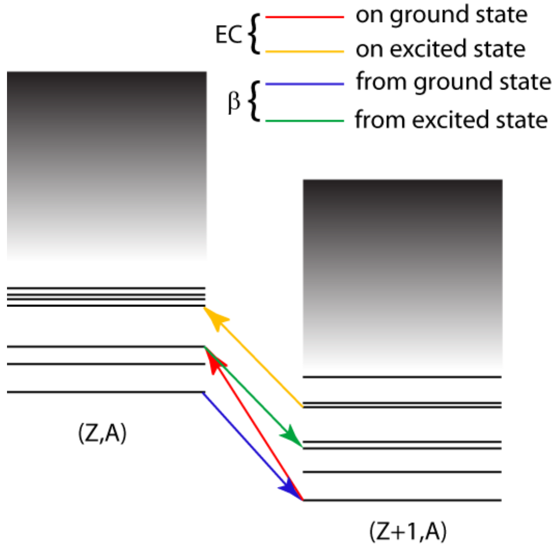
  EC/beta-decays, Neutral weak currents, R-process

  (GT + first forbidden)

Backups

Weak reactions (electron capture) in supernovae

- Key ingredient: **Gamow-Teller strengths**
- Many nuclei play a role (A-40-120)
- Majority are unstable
- excitation can take place from excited nuclear states



Impossible to measure even a sizeable fraction of cases

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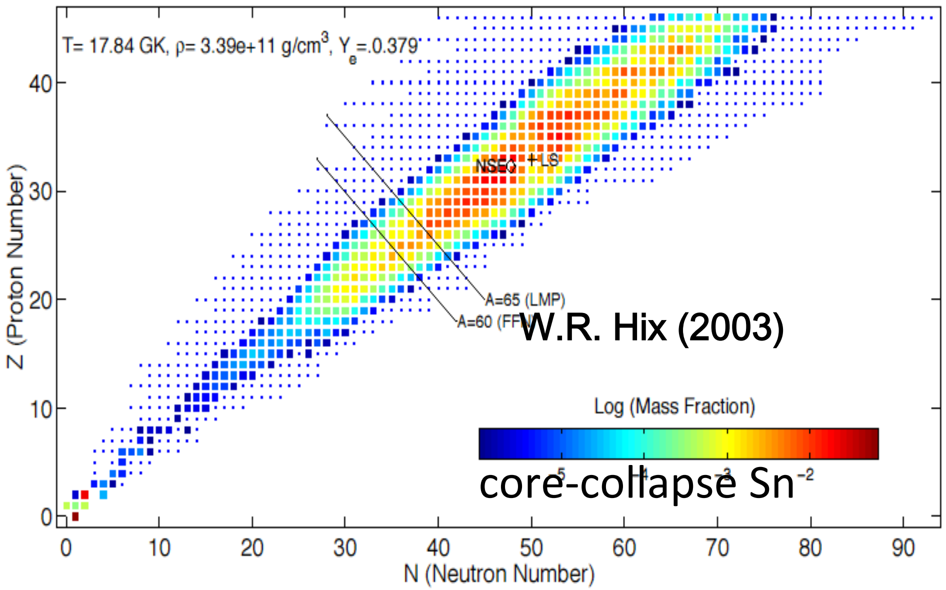
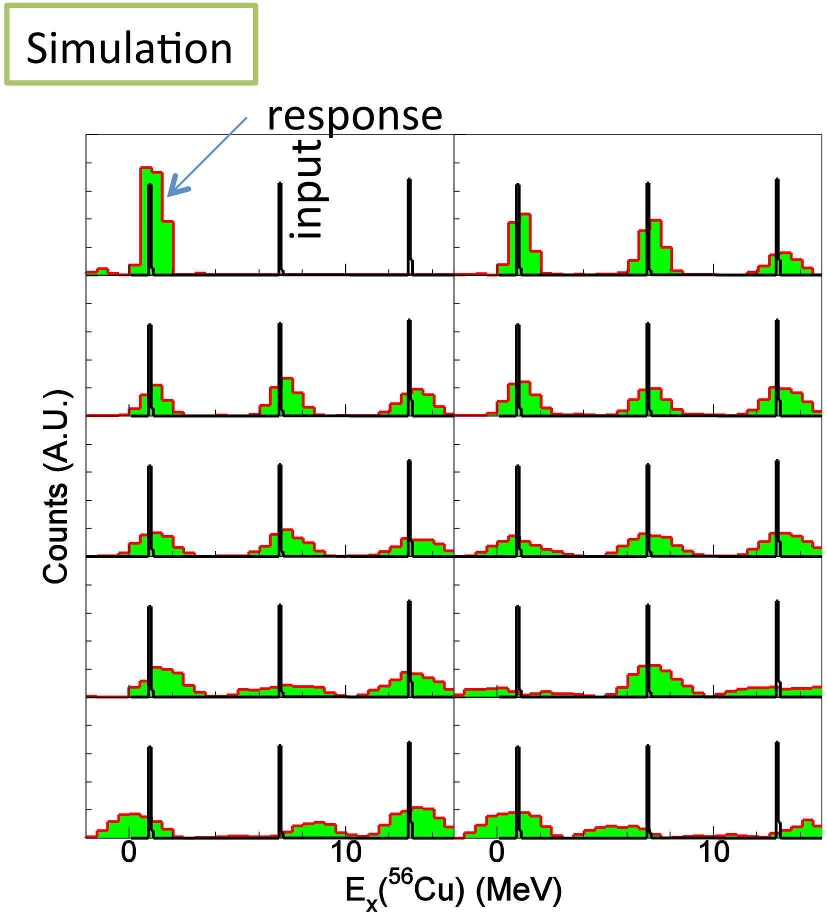
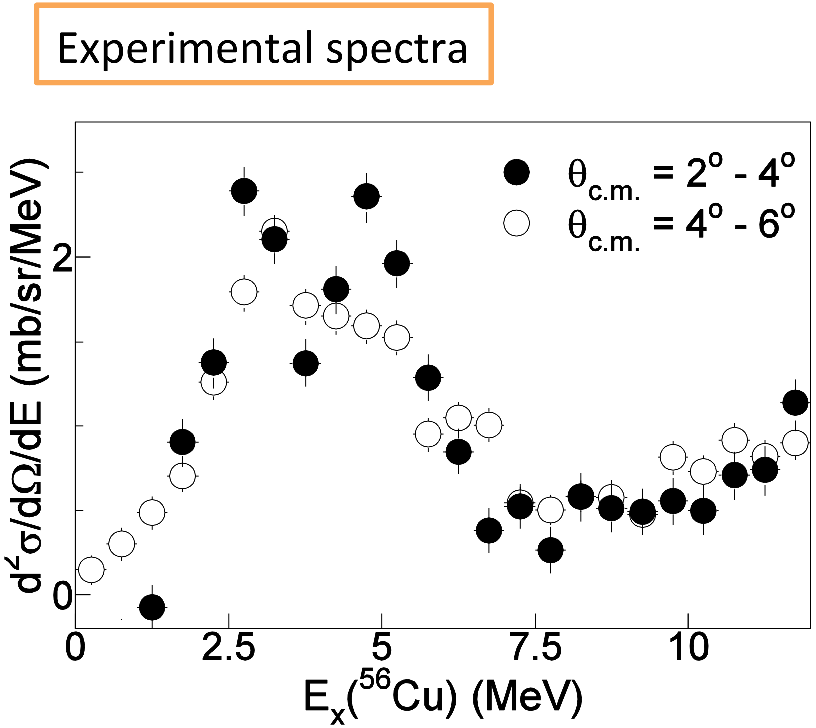


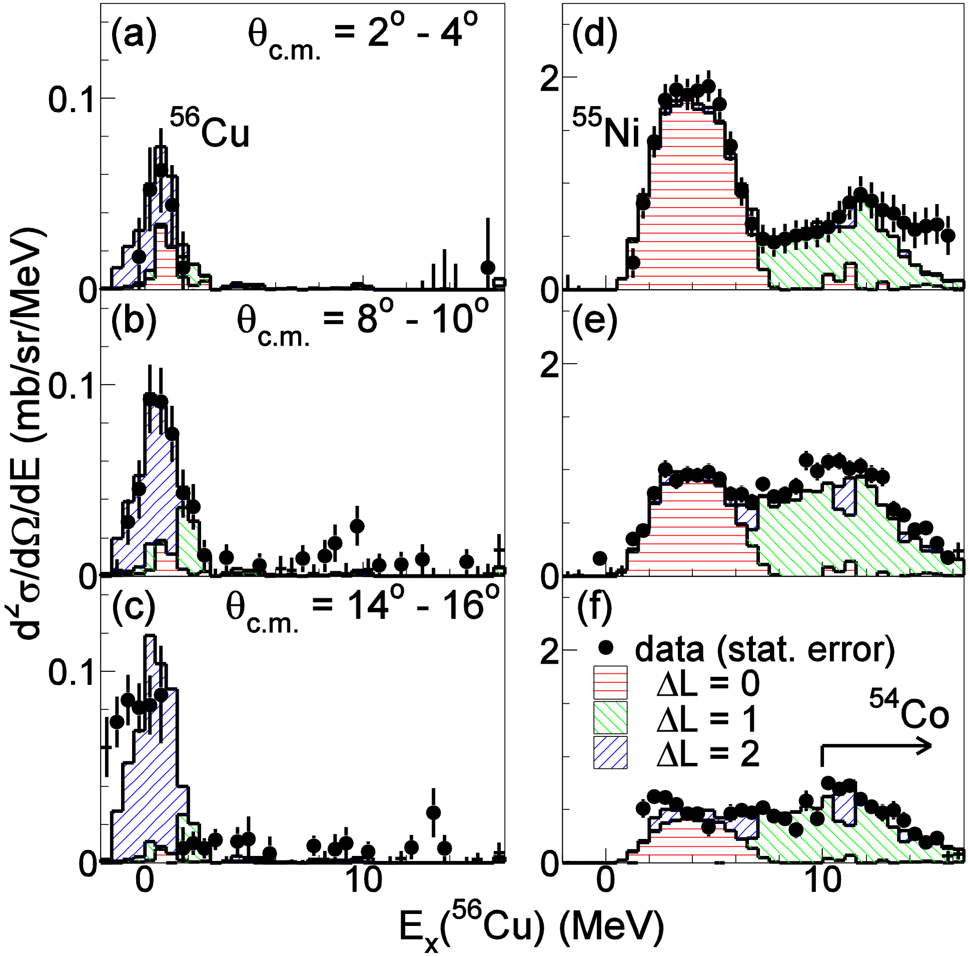
Resolution effect

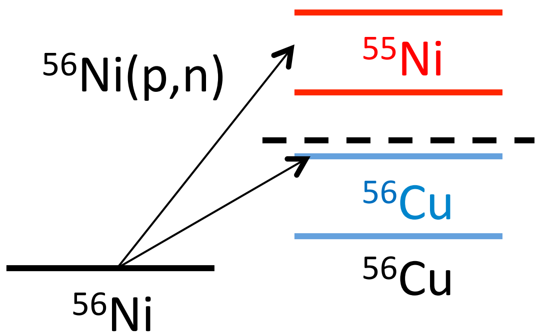




Spectra at forward angles are smeared by using simulated energy resolution.

Results of MDA

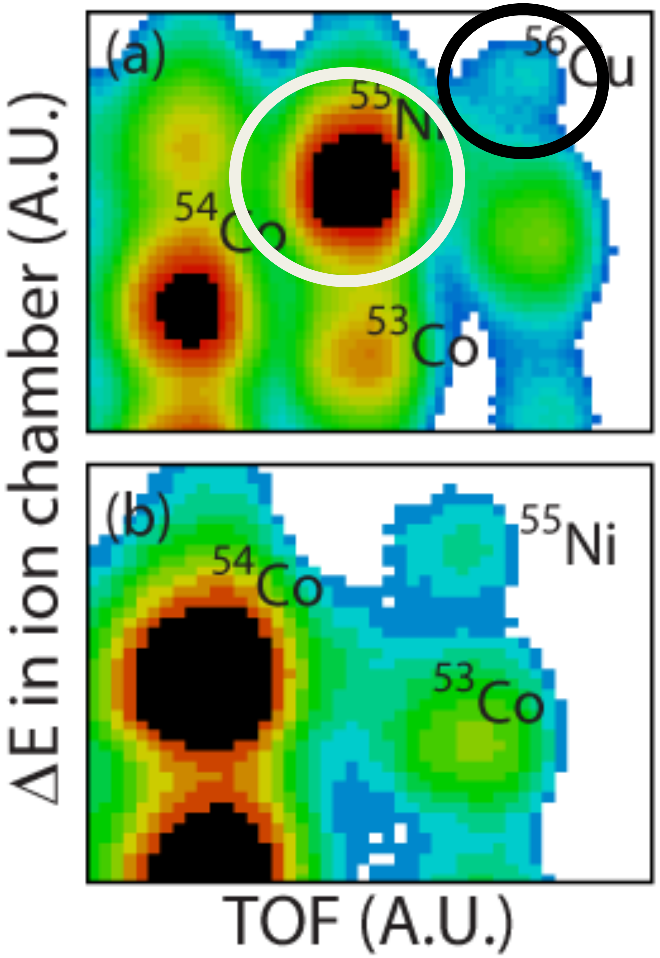




GT component dominates the region below 8 MeV.
→ Scale the spectrum before smearing

Event selection in S800

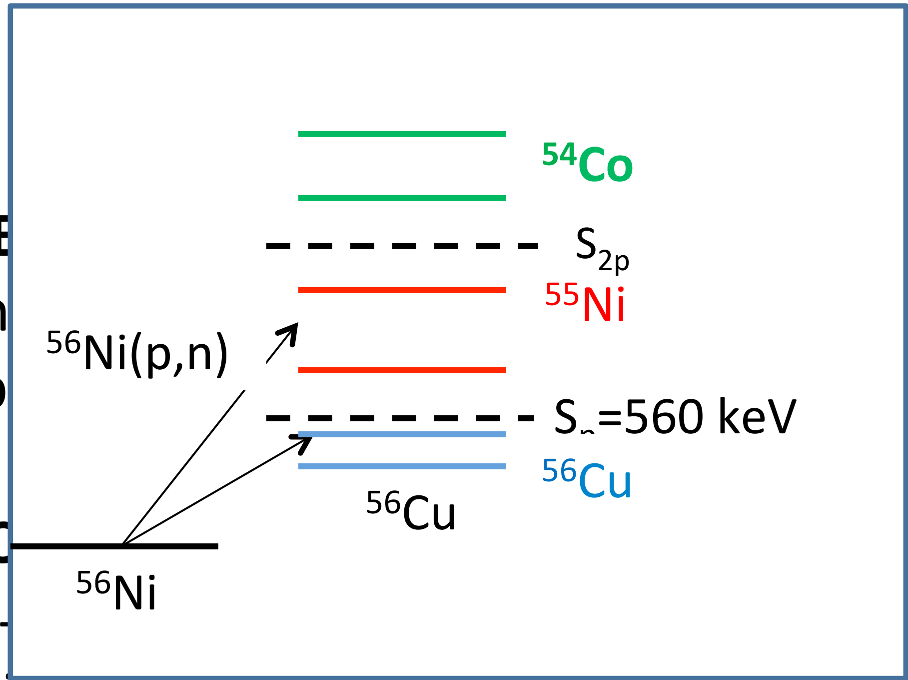
^{56}Ni beam component



^{55}Co beam component

ΔE
ch
sp

TO en
in-
scintillator in focal plane of S800.



Applications of CE reactions

Nuclear Astrophysics

- weak rates for late stellar evolution
- neutrino processes
- specific weak interactions for novae

Nuclear structure

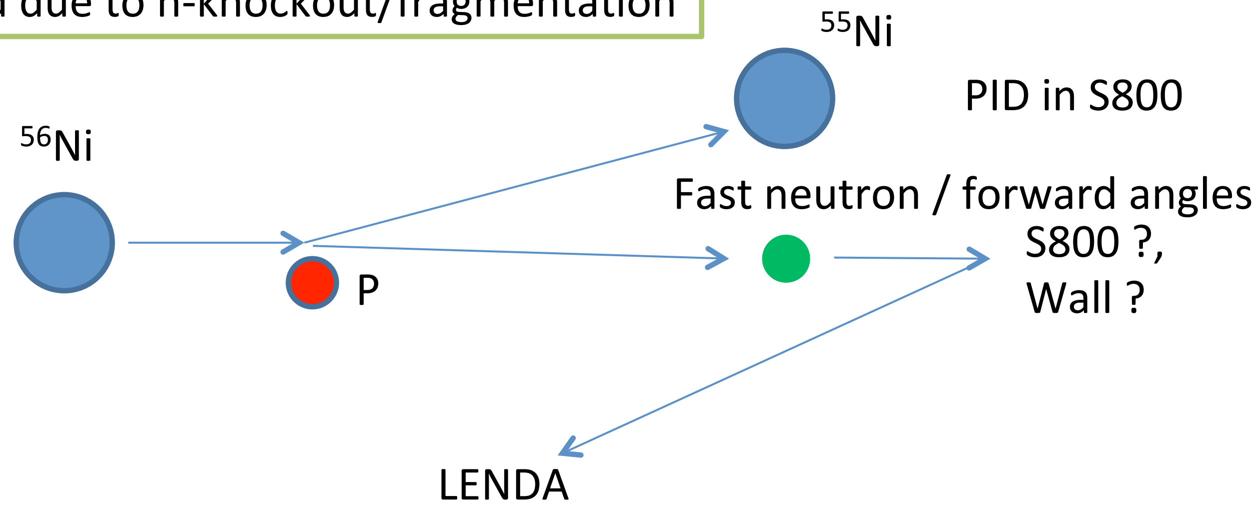
- Spin-isospin response
- test of structure models up to high excitation energies
- **Shell evolution**
- Double beta decay

Isovector giant resonances

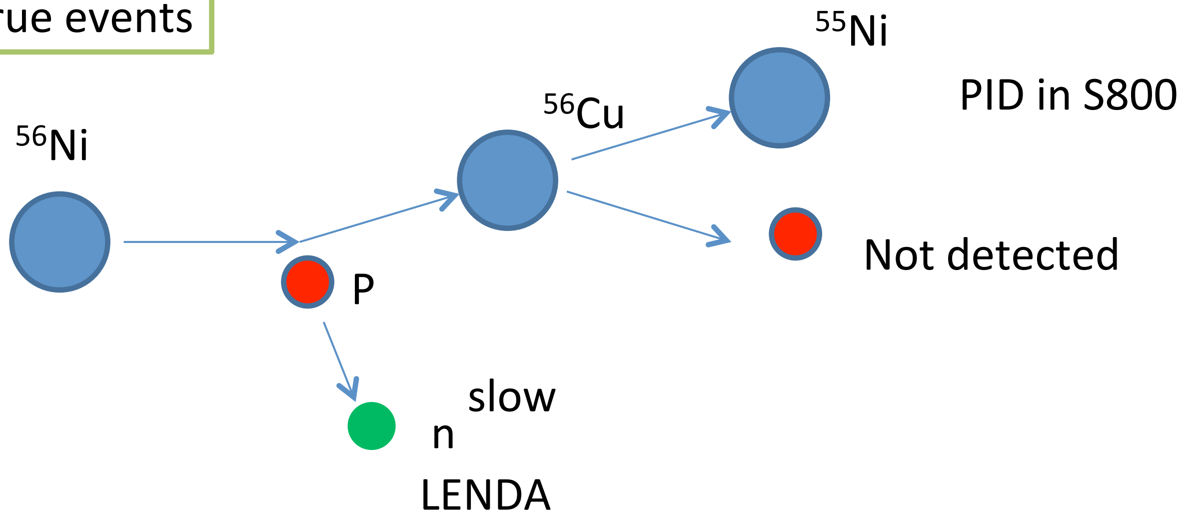
- macroscopic properties of nuclear matter (neutron-skin, EOS)
- microscopic descriptions high in the continuum

Background
due to n-knockout/frag. reactions

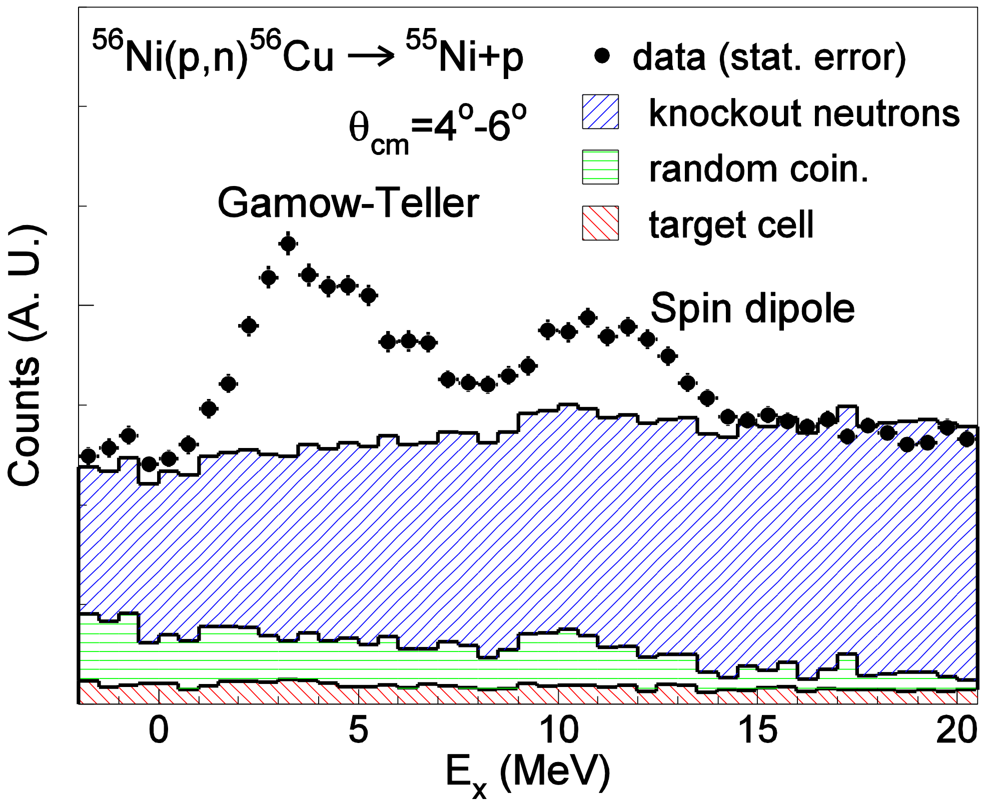
Background due to n-knockout/fragmentation



True events



Background subtraction

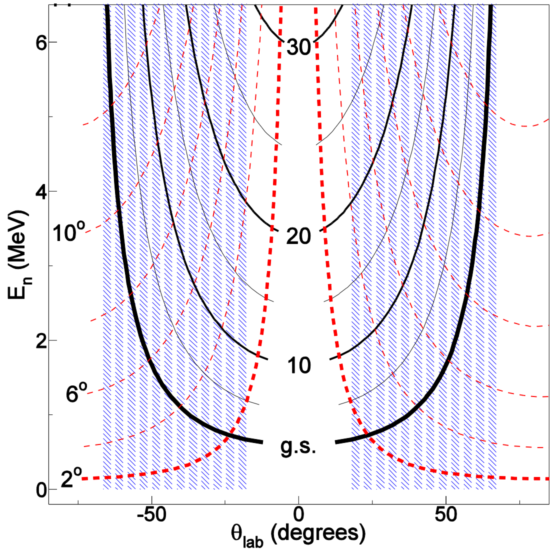


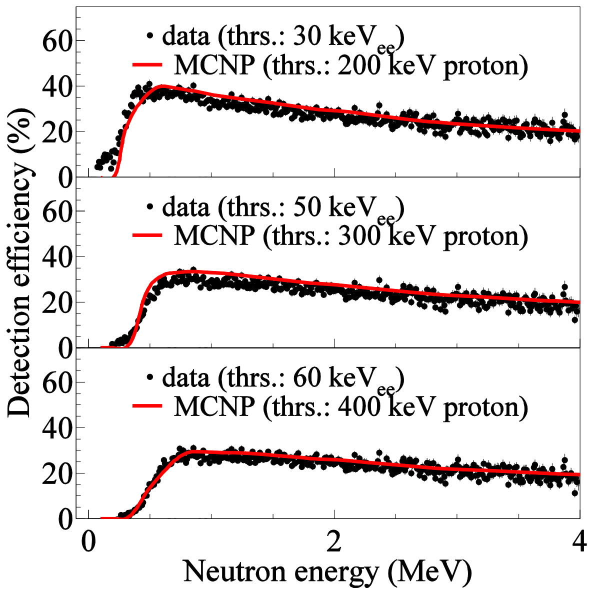
Largest source of background :
N-knockout/frag. background
Modeled by using
^{56}Ni+p → ^{53}Co + 2p + n
(scaled)

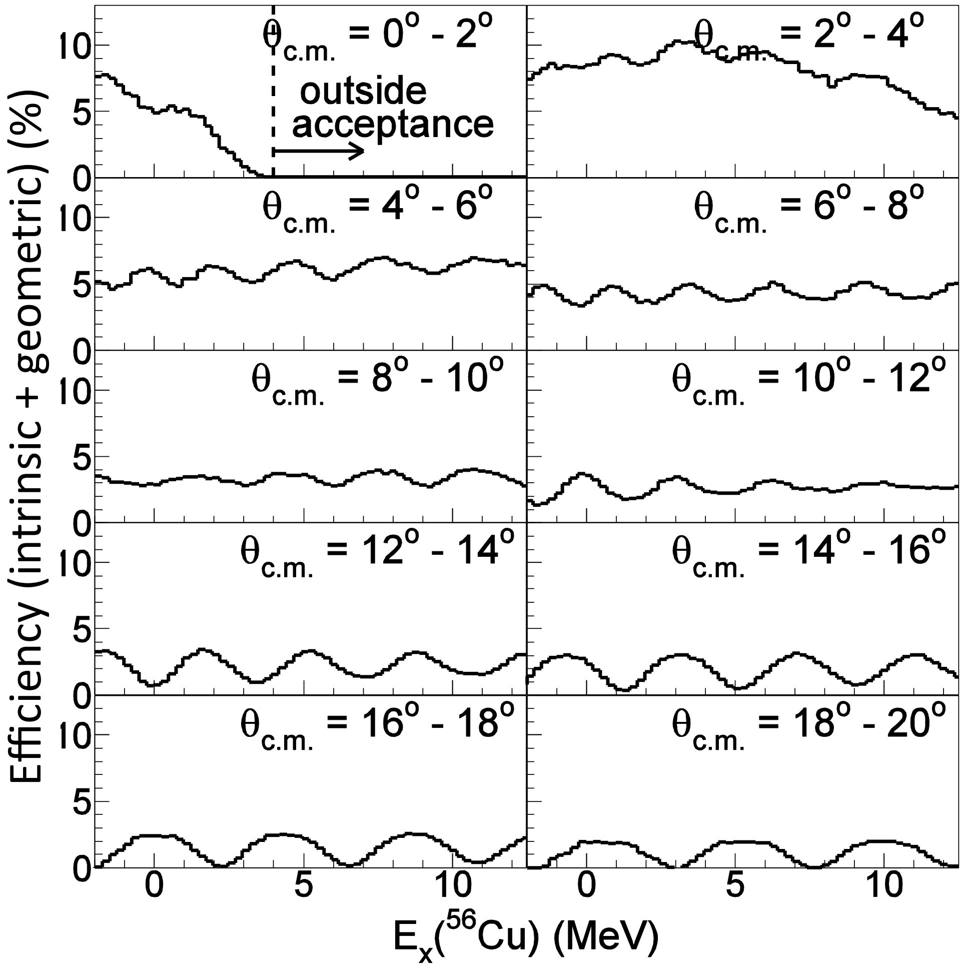
Second one :
Random background
caused by coincidence with
preceding beam pulse

Smallest one :
Background due to the cell of the target is small
→ liquid hydrogen target system is important!

Efficiency



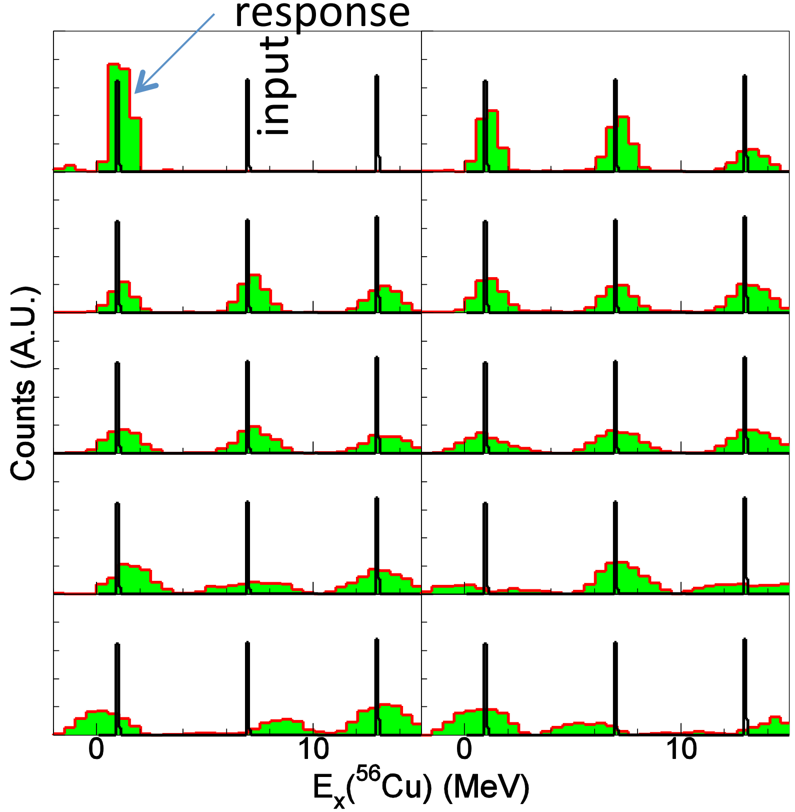




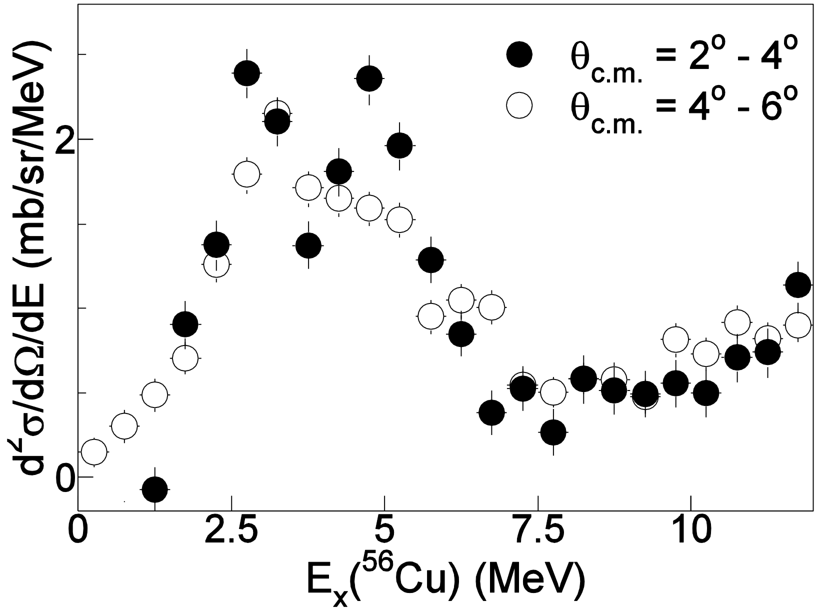
GEANT3

Resolution effect

Simulation



Experimental spectra



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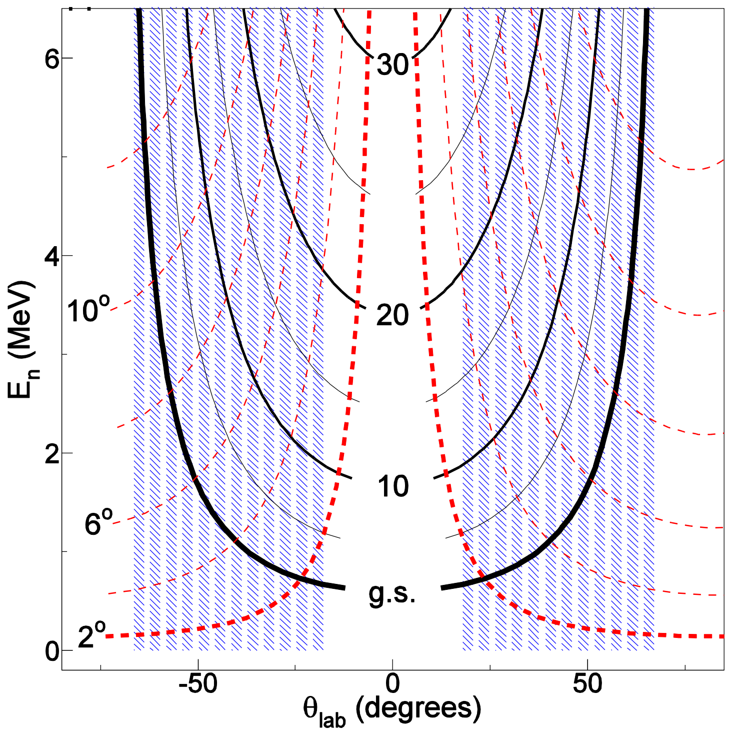
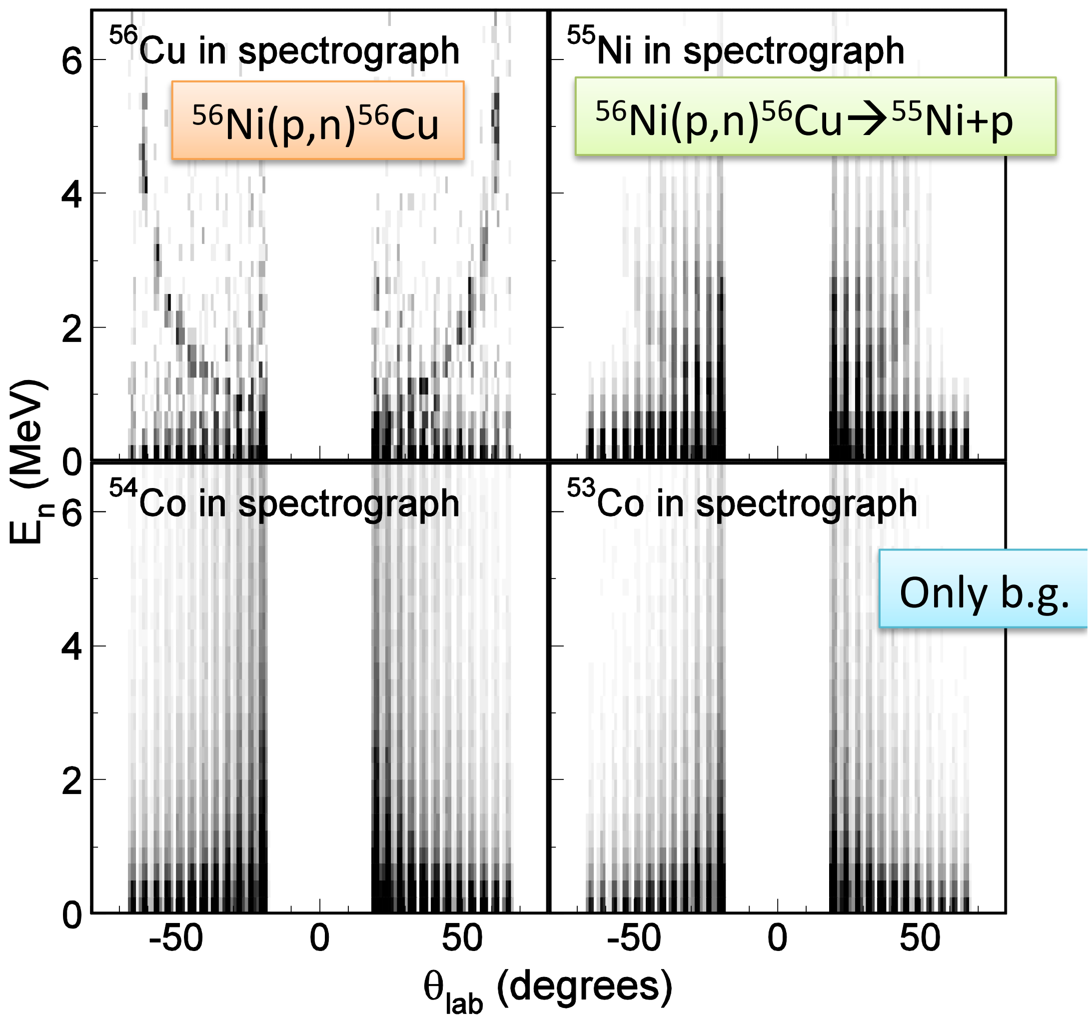
Neutron energy spectra





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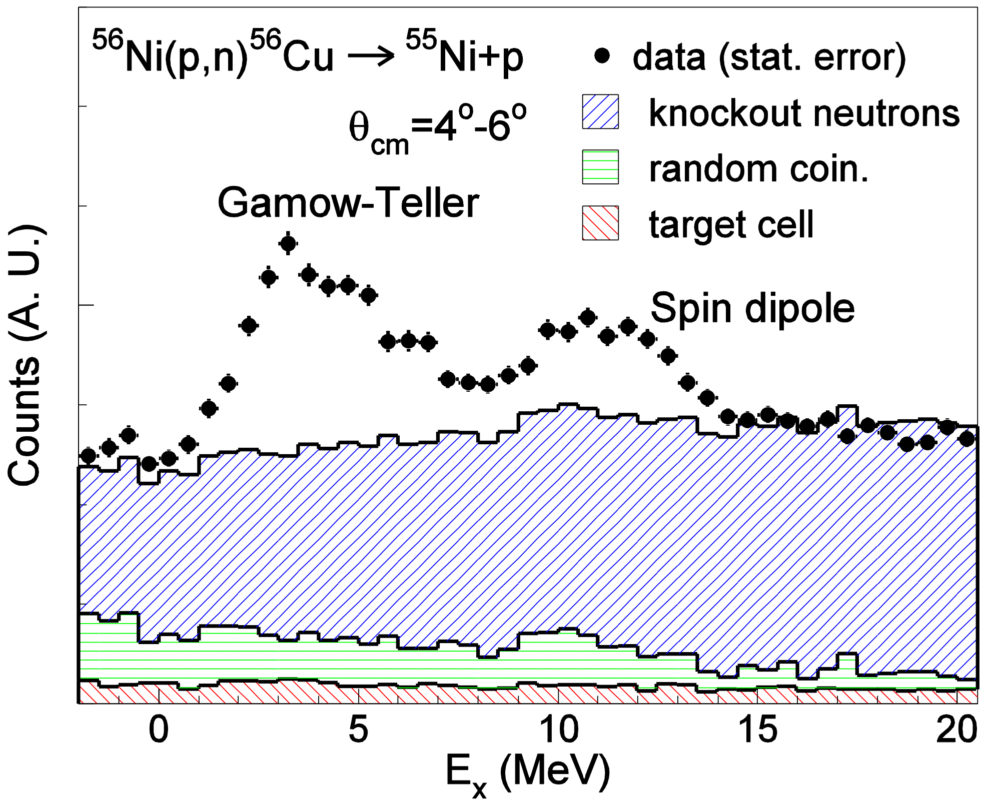

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