# Transfer reaction studies at HIE-ISOLDE

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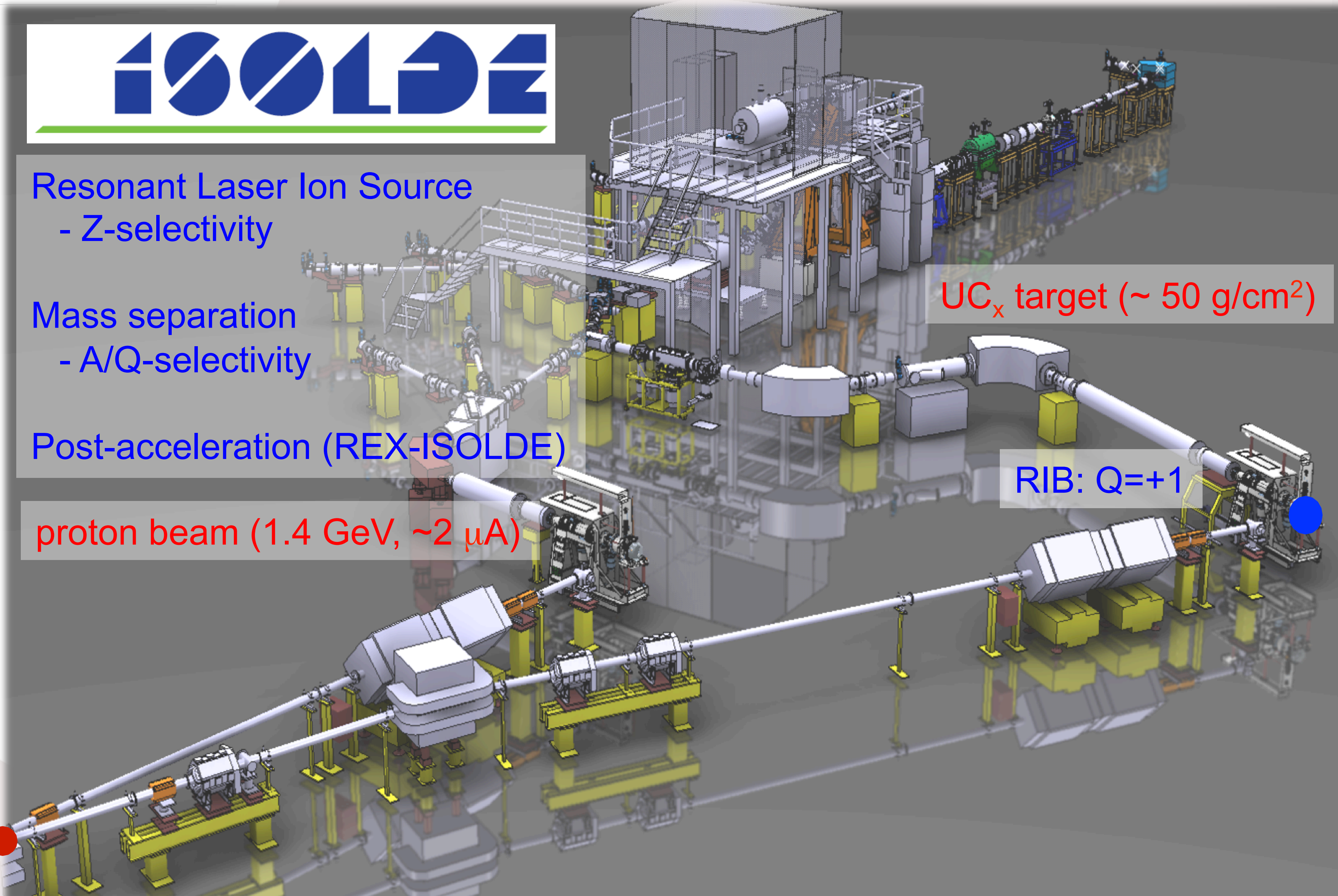
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

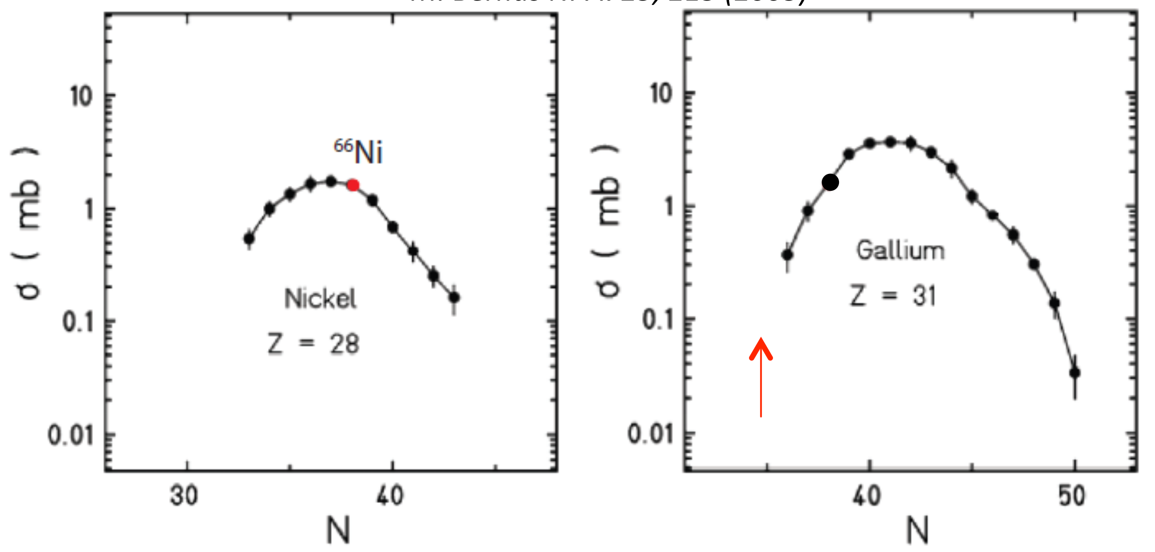
# Introduction: ISOLDE



# Introduction: ISOLDE

*Fission cross sections for p+$^{238}$U at 1GeV/A*

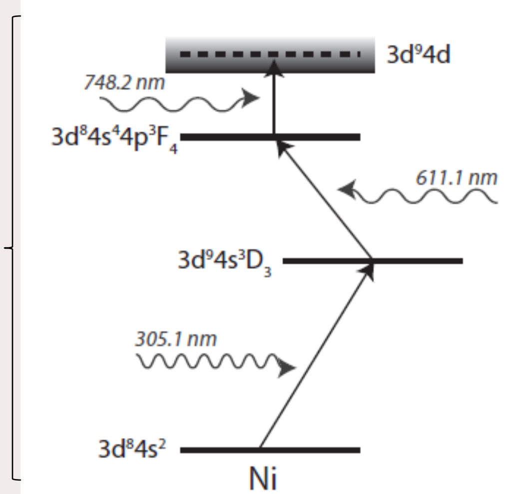
*M. Bernas NPA725, 213 (2003)*



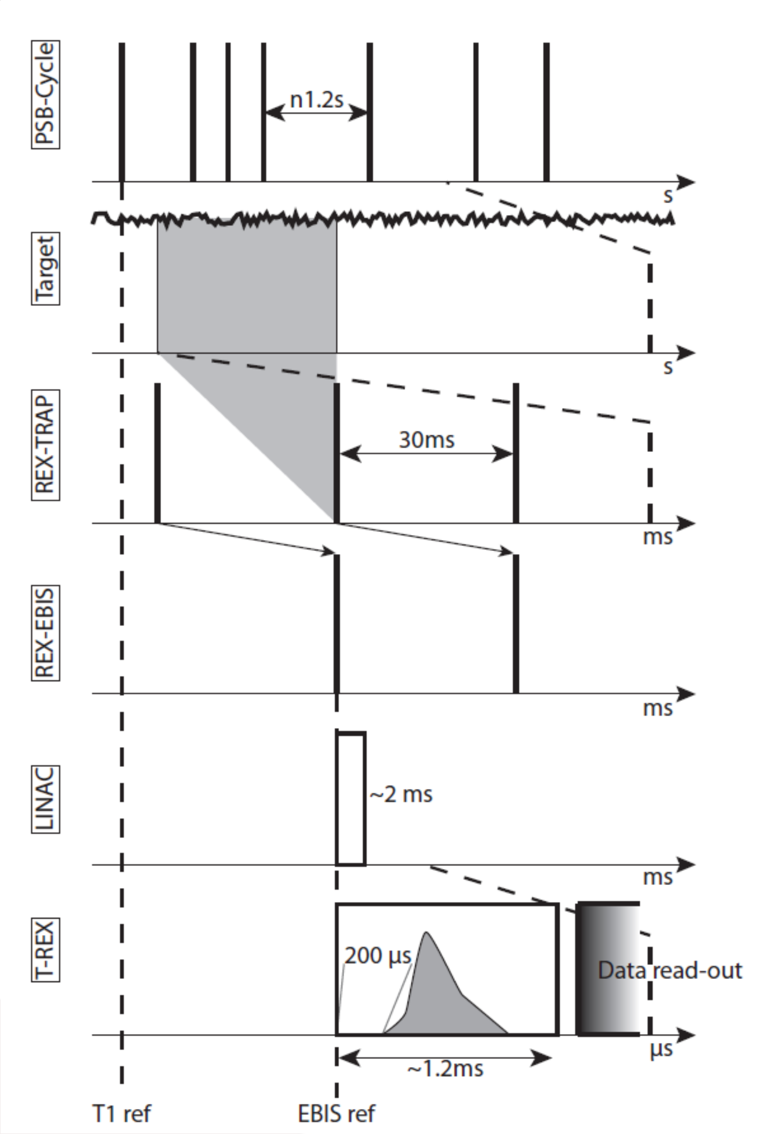

Averaged intensity($^{66}$Ni)=4.10$^{6}$ pps

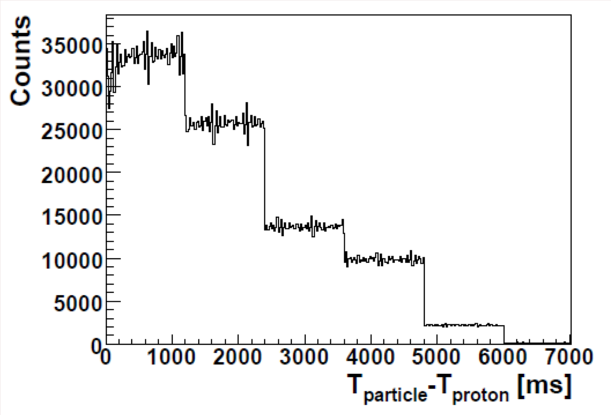
*Ionization scheme used by RILIS for Ni*

*Ion. Efficiency~6%*



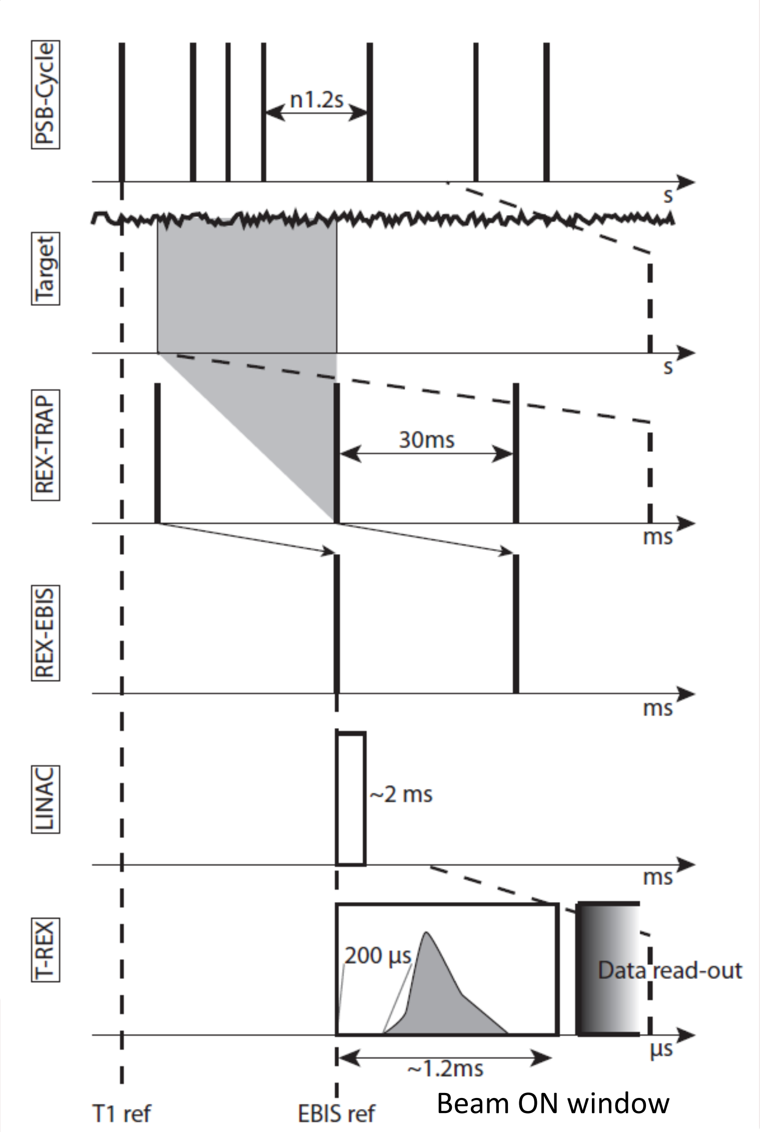
# Time structure (ex: $^{66}$Ni beam)



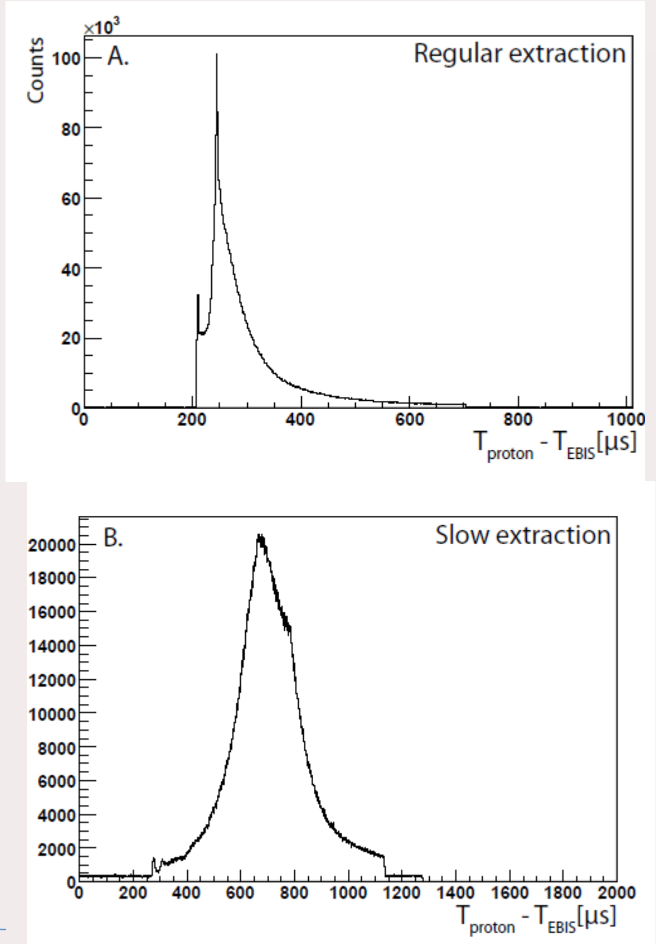

*Rate of scattered particle at secondary target with respect to Proton pulse*

# Time structure (ex: $^{66}$Ni beam)



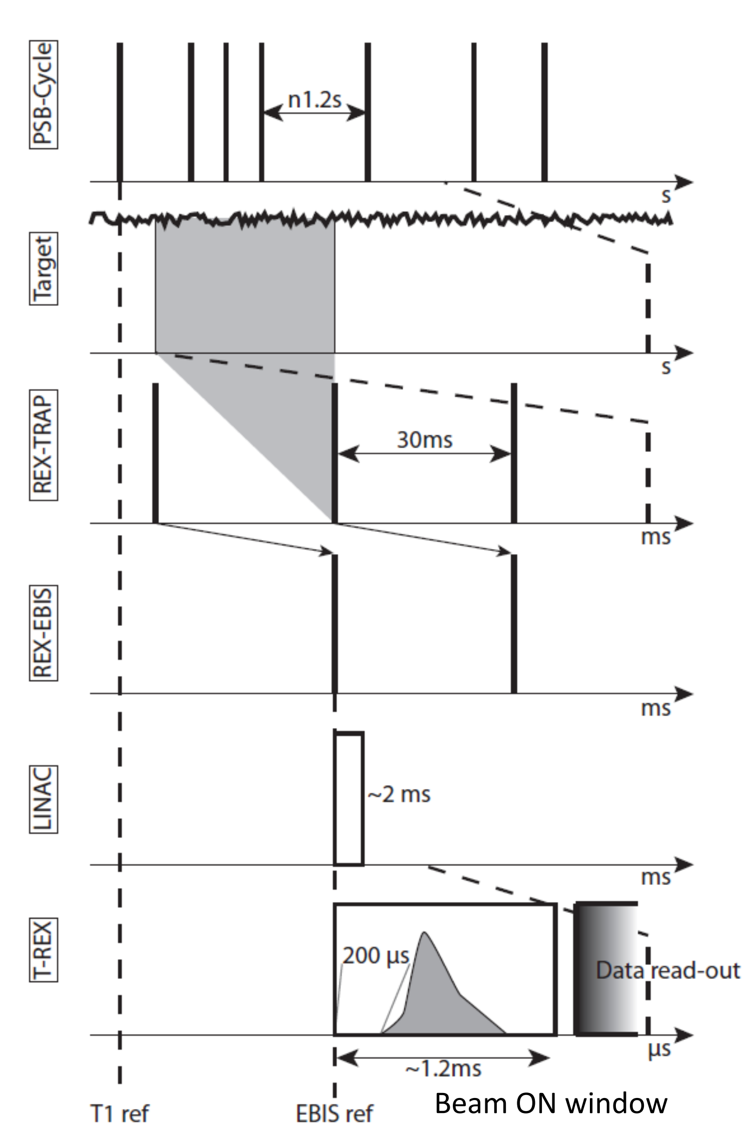

Trigger ACQ

*REX EBIS release profile*




*Rate of detected particle at secondary target with respect to EBIS release time*

# Time structure (ex: $^{66}$Ni beam)




Trigger ACQ

<u>Example for $^{66}$Ni beam:</u>

BeamON width = 1.2 ms
REX-cycle = 33 Hz (Max 50Hz)

**=>39.6 ms of beam /s (4%)**

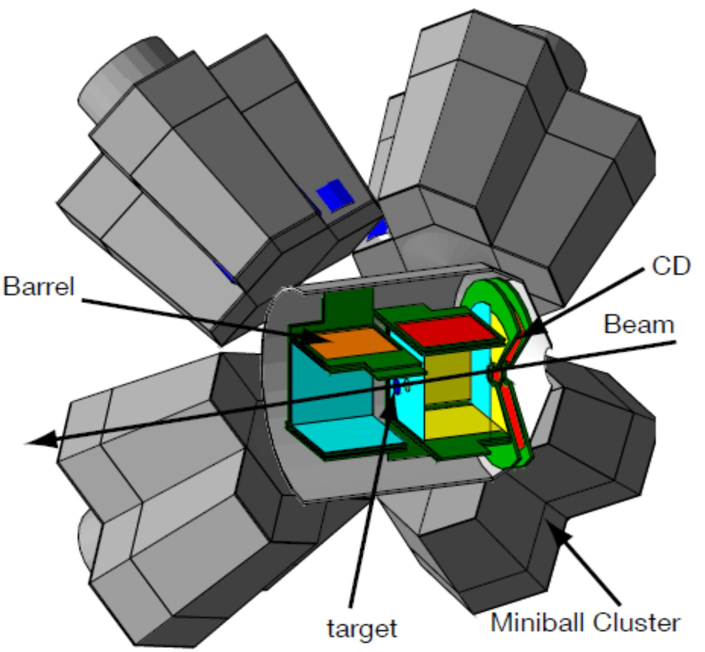
If integrated rate is $10^6$ pps:

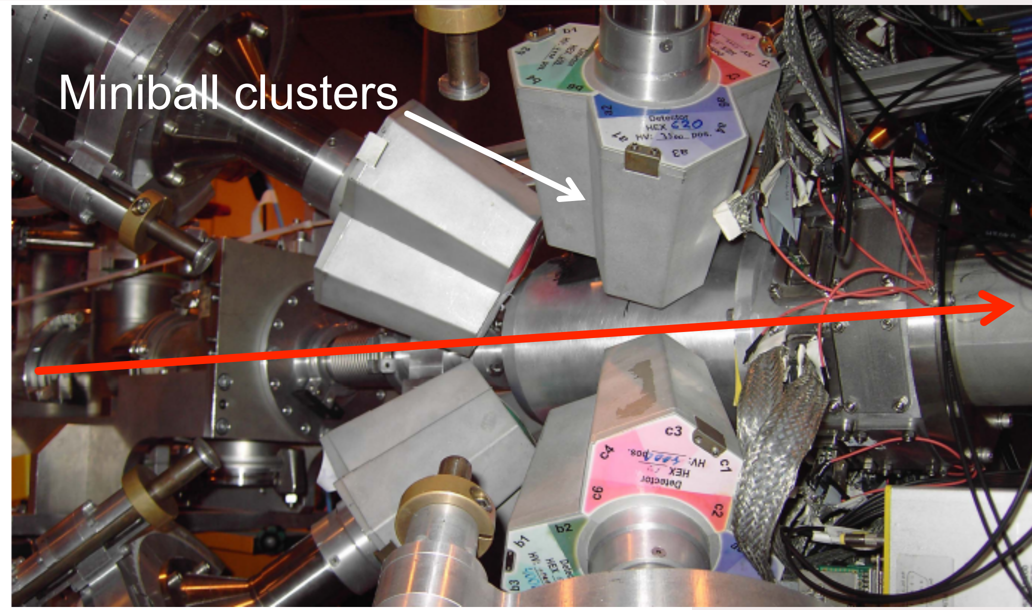
**=> Instantaneous rate = 2.5*$10^7$ pps**

# Setup for Transfer: TREX + Miniball

- T-REX:
  - identification
  - energy
  - angular distribution

- gamma detection in Miniball:
  - energy
  - angular distribution (Doppler correction)




- 8 $\Delta E$-$E_{rest}$ barrel detectors
- 1 $\Delta E$-$E_{rest}$ CD detectors
- Covered $\theta_{lab}$ range:

  28° to 78° and 102 to 152° (Barrel)
  and 152 to 172° (Bw CD)

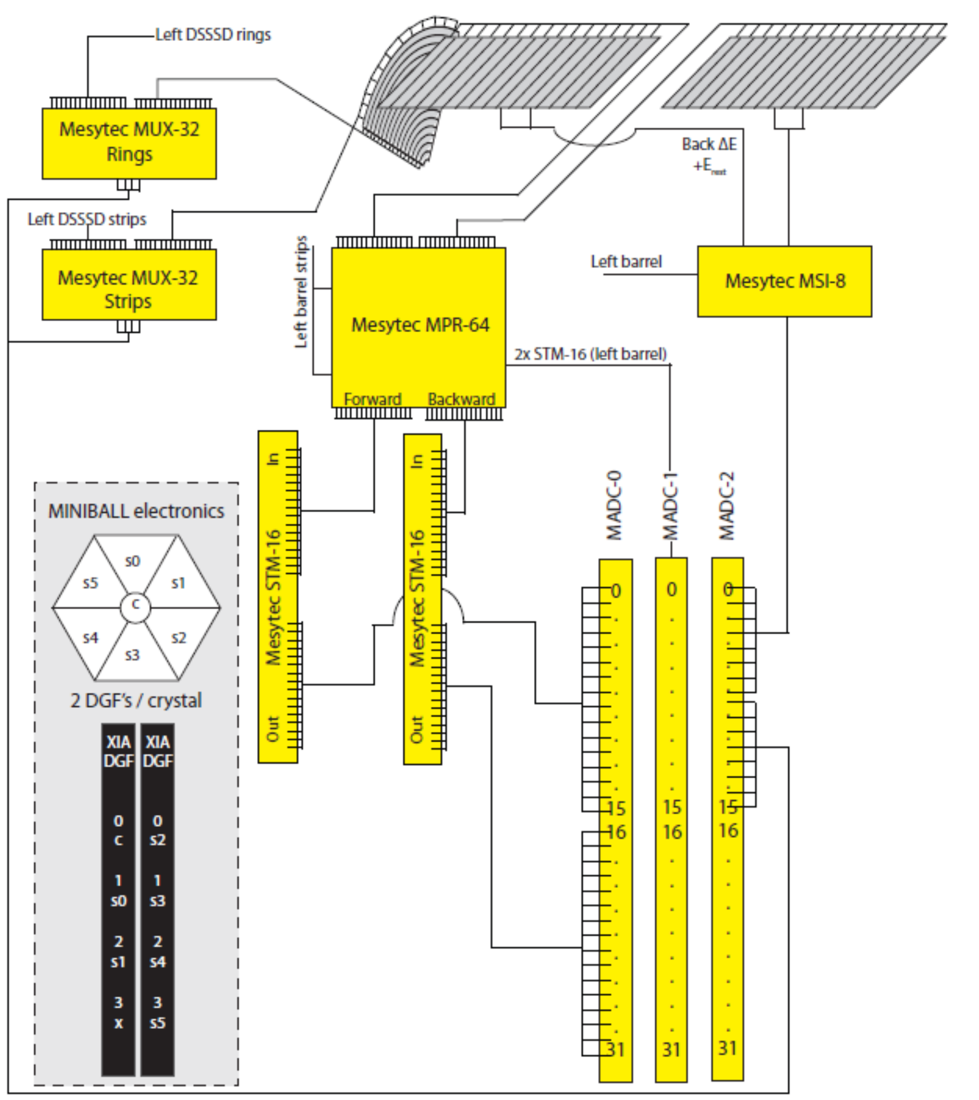
- 8 Miniball triple (HPGe) clusters
- Each crystal: 6-fold segmented

- Reaction chamber:

  Diameter: 140 mm
  Thickness:2mm Al

Miniball: Warr EPJ49 (2013) T-REX: Bildstein EPJ48 (2012)

# Electronics + DAQ




## MiniBall: Digital electronic (DGFs )

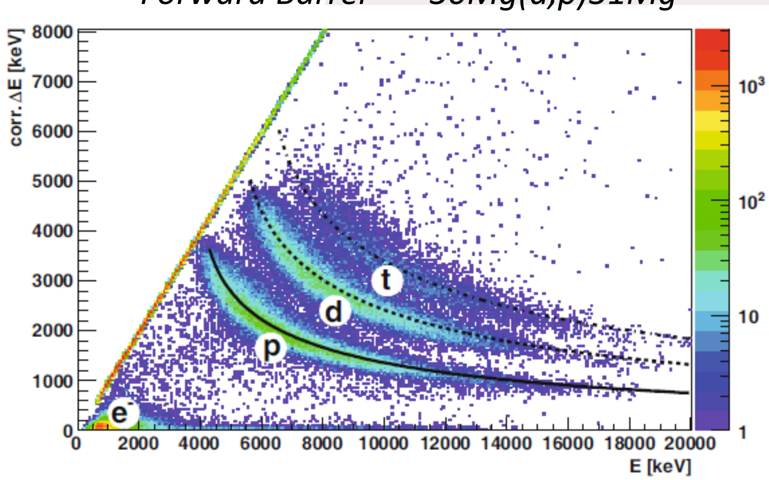
- DGF: Digital Gamma finder (CAMAC stdrd)
  - Amplifier (gain+offset)
  - 2 DGFs per crystal – 48 DGFs -168 ch.
- ADC : 40 MHz – 16 bit sampling
- Timestamp + Buffer until read out

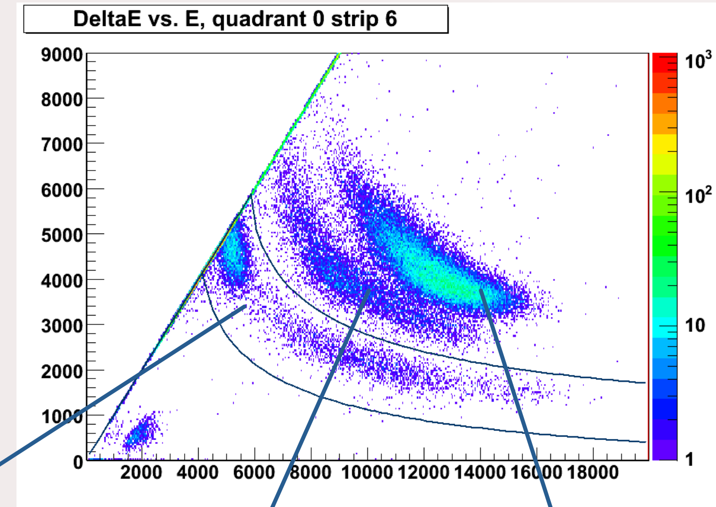
## TREX: Analog electronic (Mesytec)

- CD signals multiplexed (MUX32)
  - From 32 to 4= 2*(Energy+Position) signals
  - 2 events over thresh. max per 30ns
- 2 Trigger groups (Top-Left, Bottom-Right)
- MADCs + buffer + read-out
- Timestamp sync. with DGF master clock

# TREX: Particle identification (examples)

*Forward Barrel - 30Mg(d,p)31Mg*




ΔE [keV]

$E_{tot}$ [keV]

Protons: Elastic + (t,p)
$^{3}H(^{66}Ni,^{68}Ni)^{1}H$

Deuterons: (t,d)
$^{3}H(^{66}Ni,^{67}Ni)^{2}H$

Tritons: Elastic scattering

# TREX: Resolutions

*Angular resolution*

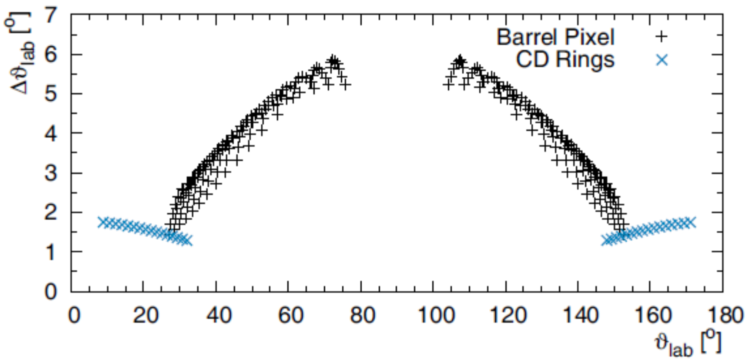
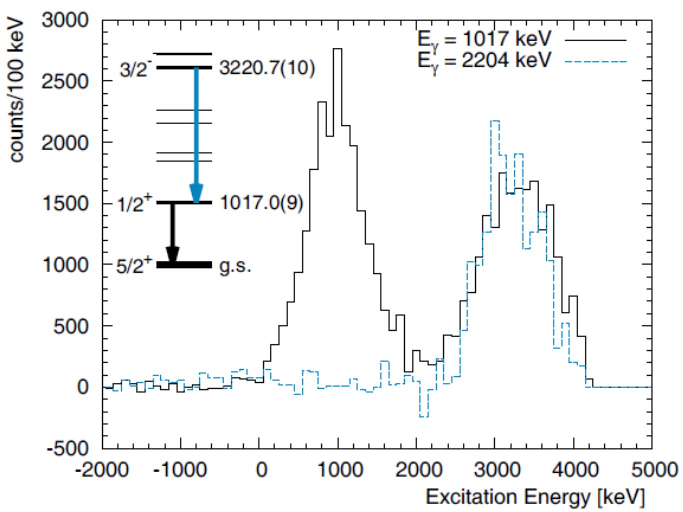



**Fig. 6.** Polar resolution achievable with T-REX if the strips are divided in the analysis into 16 bins along their length.

*Excitation Energy*




*Geant4 Simulations*

*$^{22}Ne(d,p)^{23}Ne$ @ 2.85 MeV/u*

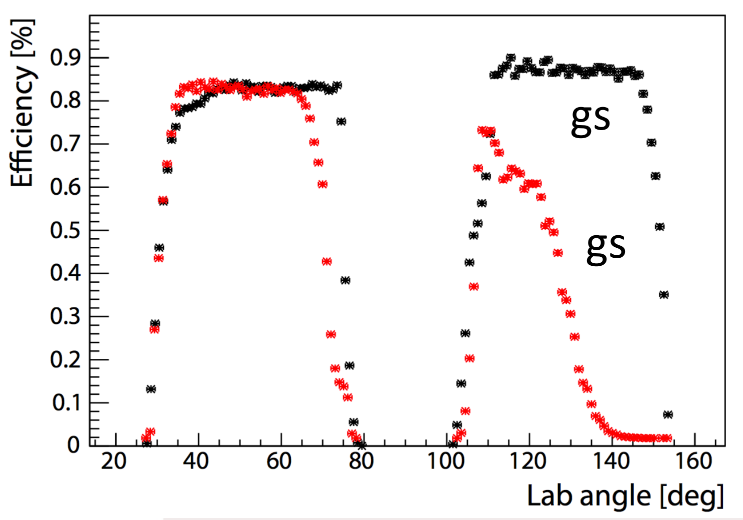
**Table 2.** Contributions from different features to the excitation energy resolution determined by Geant4 simulations. The contributions depend on the beam used, the values reported are for the d($^{22}$Ne, p)$^{23}$Ne/d($^{30}$Mg, p)$^{31}$Mg reaction, both at 2.85 MeV $u^{-1}$. The 12 $\mu$m thick Mylar™ foils in front of the forward barrel detectors contribute only on the order of 1 keV to the final resolution.

| Feature | Amount | Excitation energy resolution (FWHM) [keV] Forward | Backward |
|---|---|---|---|
| Detector res. | 100 keV | 93 / 76 | 130 / – |
| Beam spot size | 5 mm | 120 / 81 | 40 / – |
| Target thickness | 1 mg cm$^{-2}$ | 597 / 497 | 489 / – |
| | 100 $\mu$g cm$^{-2}$ | 86 / 29 | 28 / – |
| $\vartheta_{lab}$ res. | 2° to 6° | 357 / 315 | 129 / – |
| Total res. | 1 mg cm$^{-2}$ | 680 / 619 | 399 / – |
| | 100 $\mu$g cm$^{-2}$ | 137 / 111 | 150 / – |

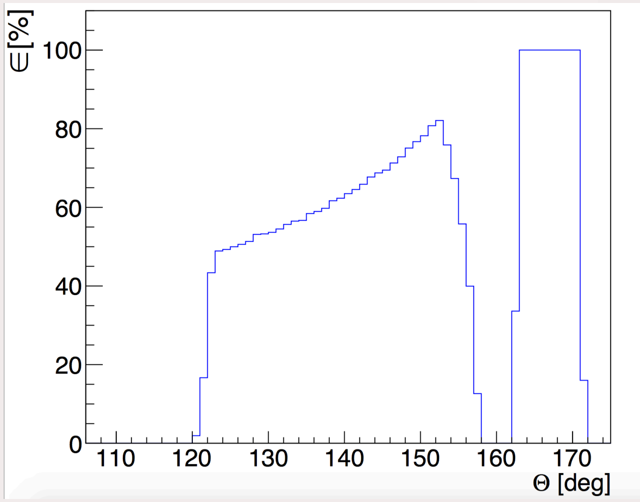
Exp(1mg.cm$^{-2}$) : FWHM =1 MeV

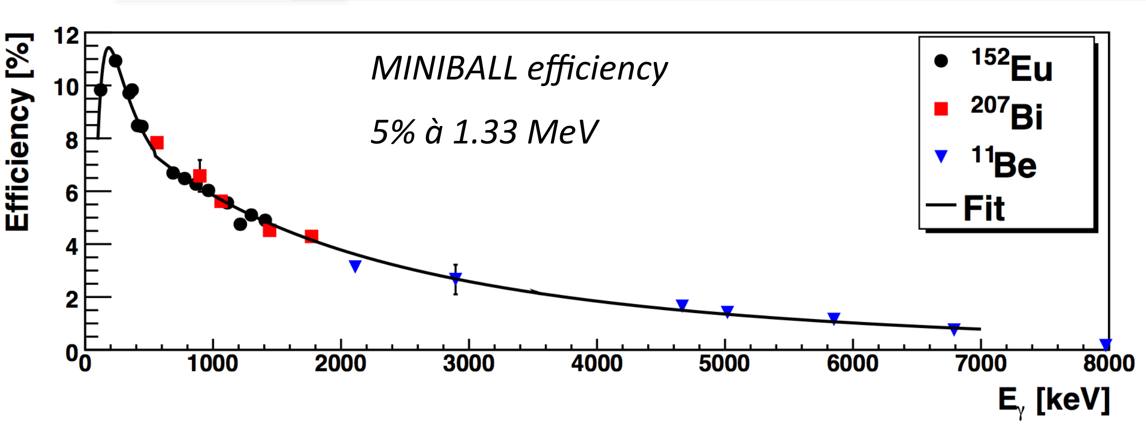
# TREX+MINIBALL: Efficiencies

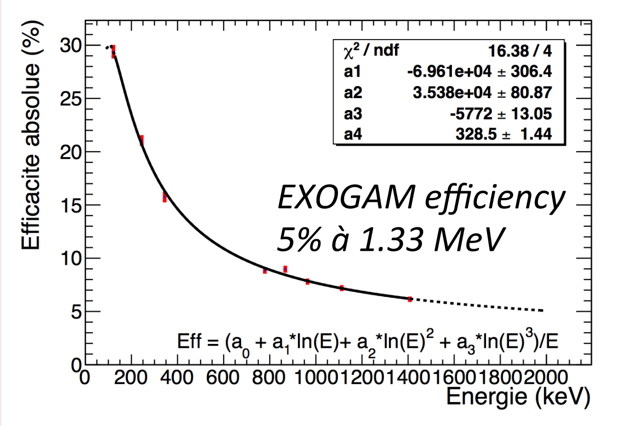
*TREX Barrel efficiency for $^{66}Ni(d,p)^{67}Ni$*



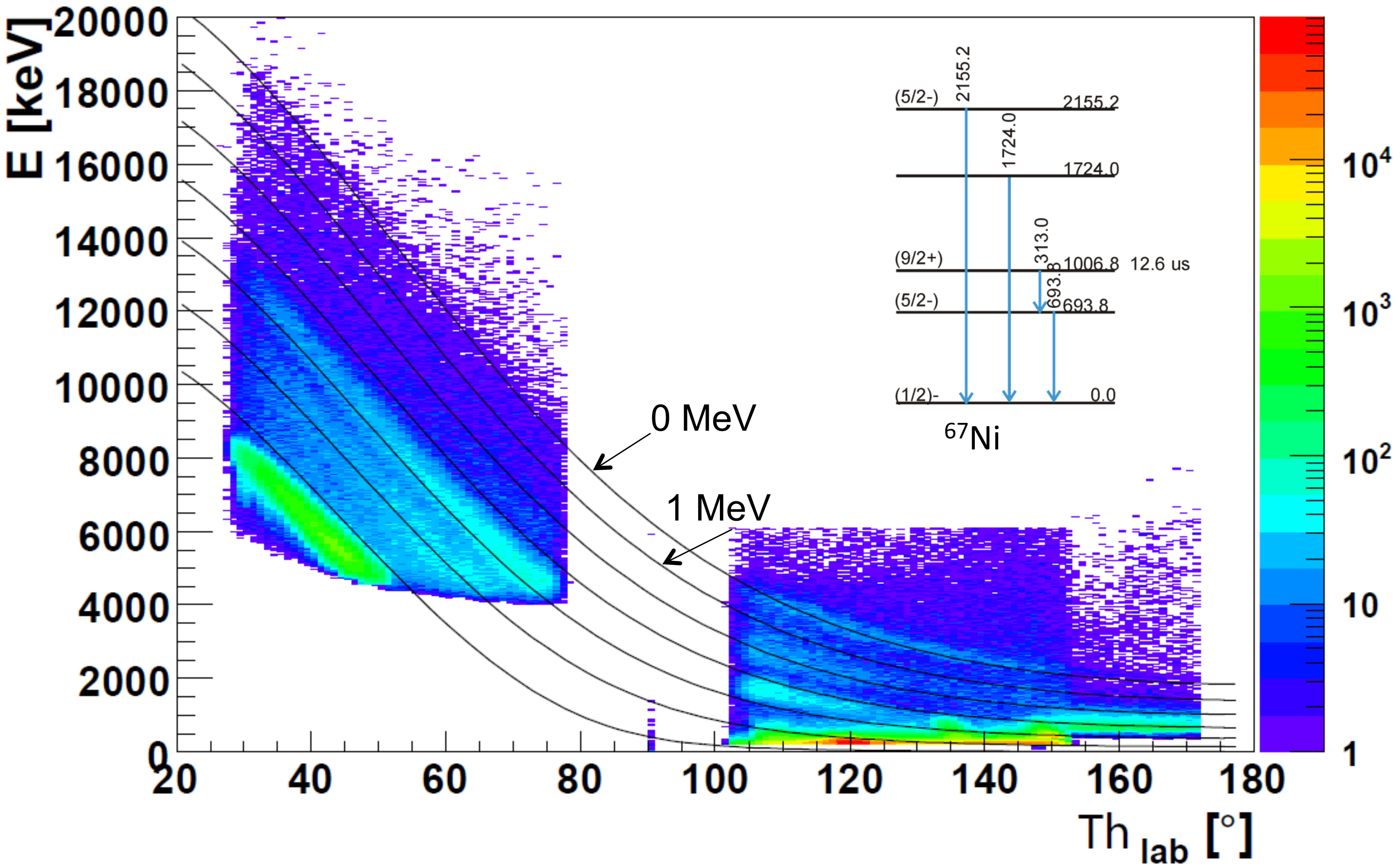

*M2+ Annular efficiency (diabolo configuration)*



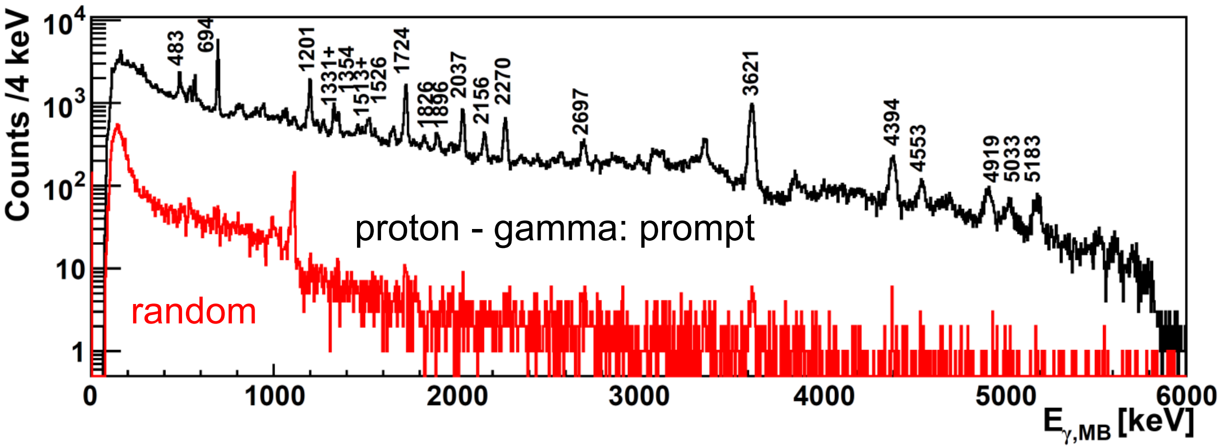



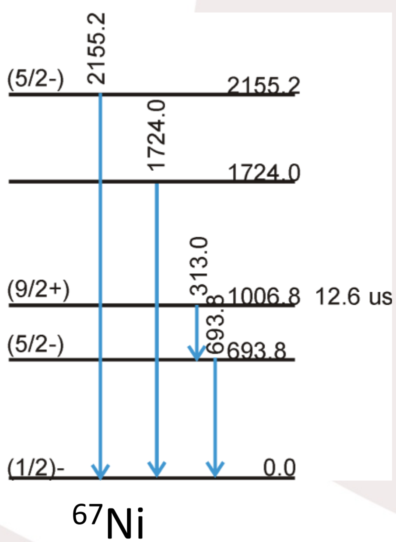
# Kinematics for $^{66}Ni(d,p)^{67}Ni$

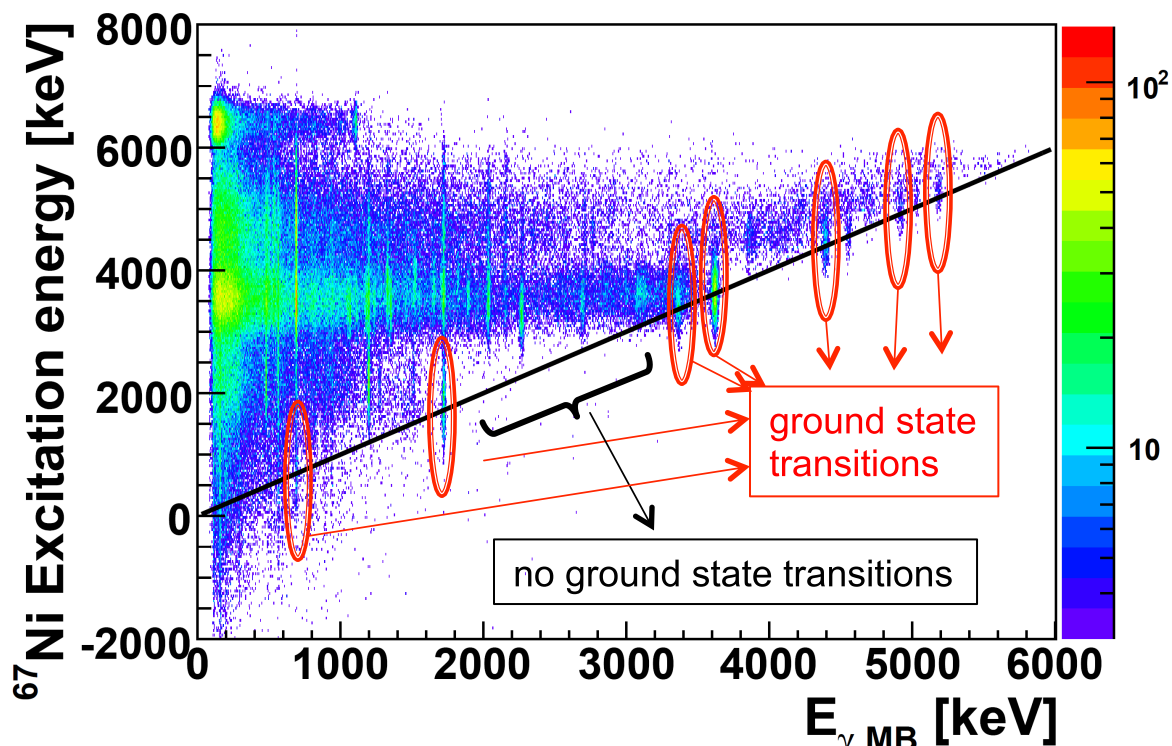


# Particle-gamma coincidences

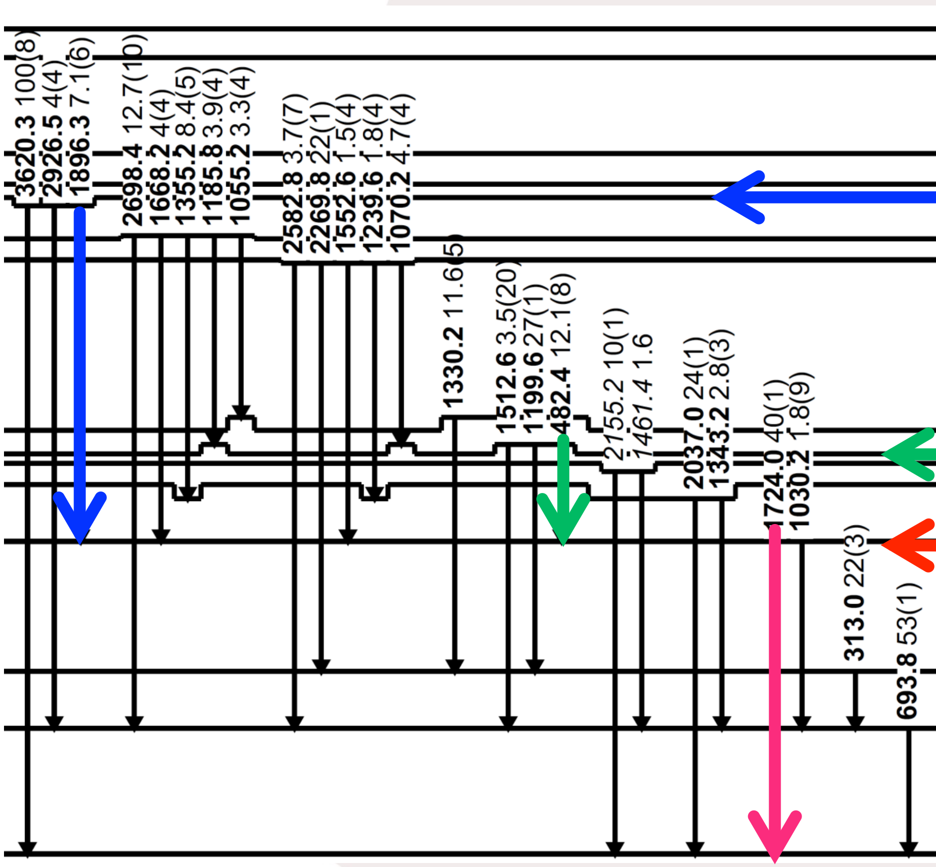



$^{2}H(^{66}Ni,p)^{67}Ni$
(Q=+3.58 MeV)

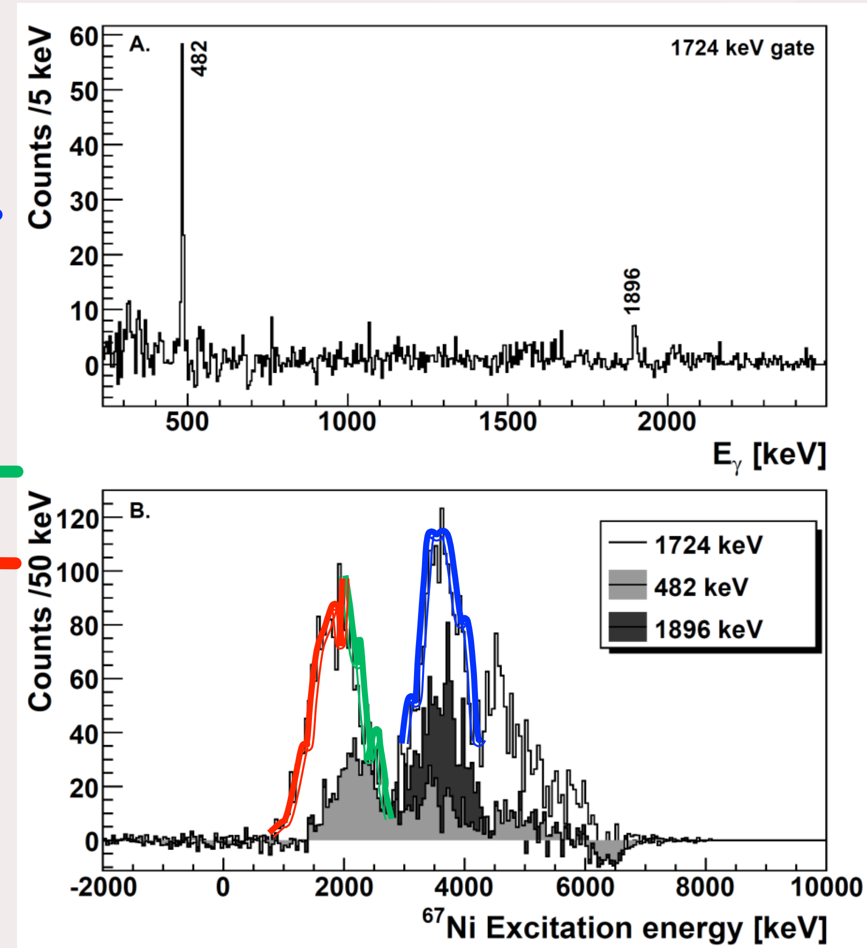


# Building the level scheme – gamma gates



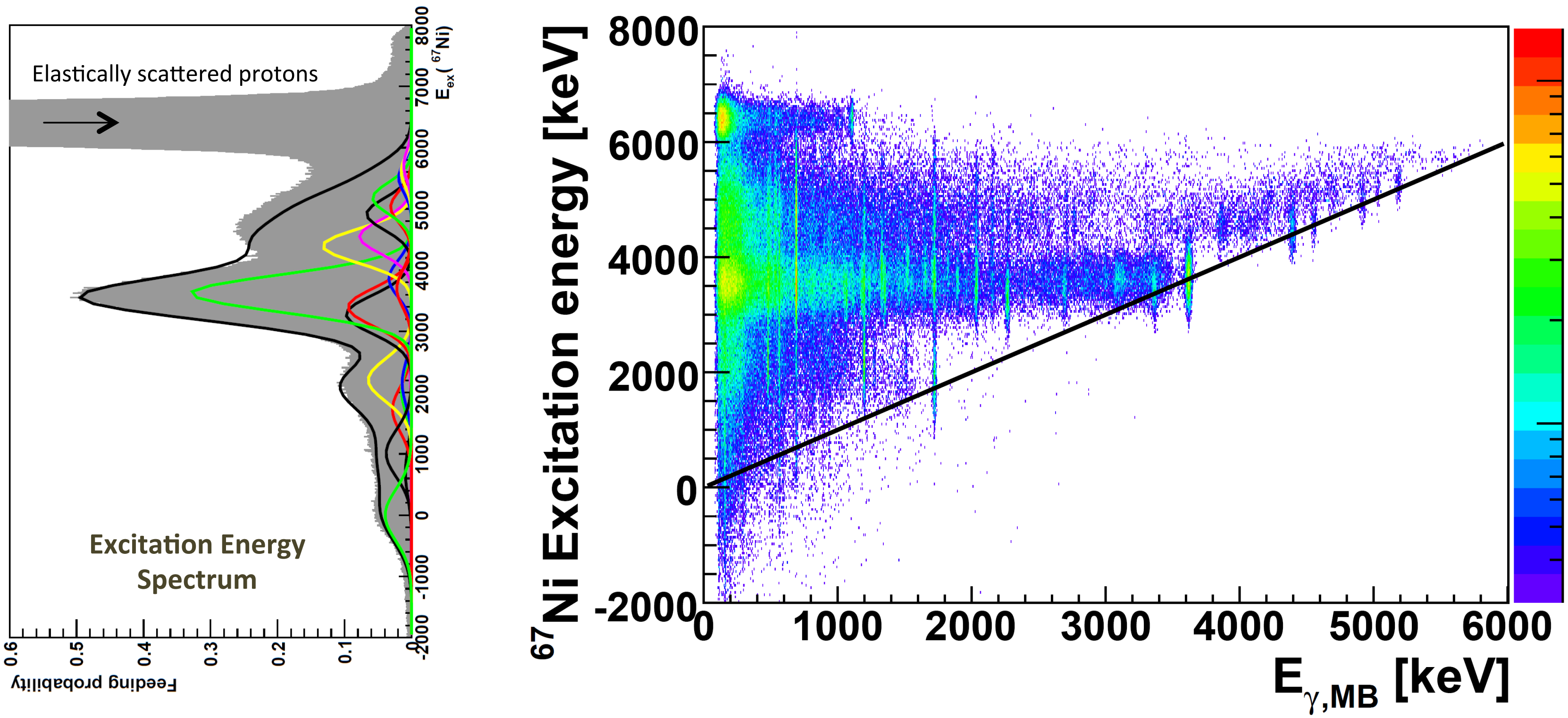

$^{67}$Ni




**Condition:** prompt proton-$\gamma_{MB}$ coincidence

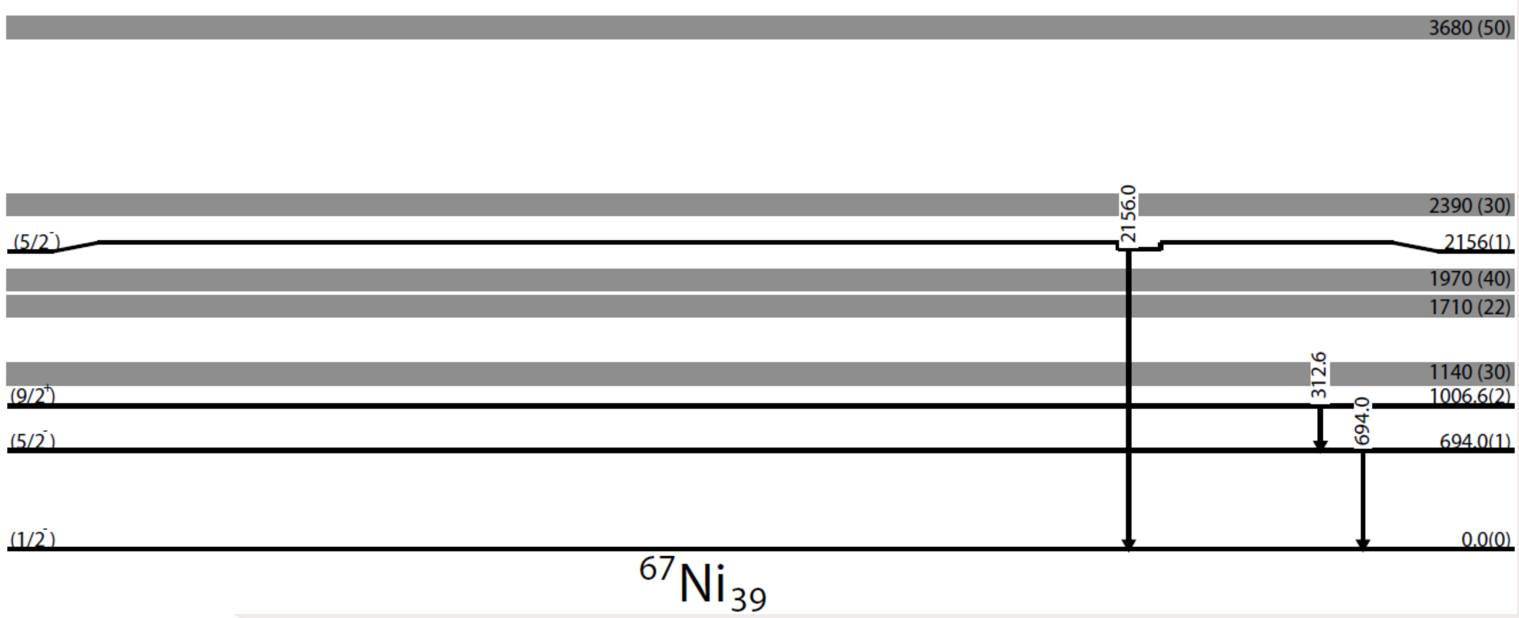
**Resulting information:** $^{67}$Ni excitation energy from proton kinematics

# Particle-gamma coincidences




Colors: feeding to all different levels populated in $^{67}$Ni

# Improved level scheme



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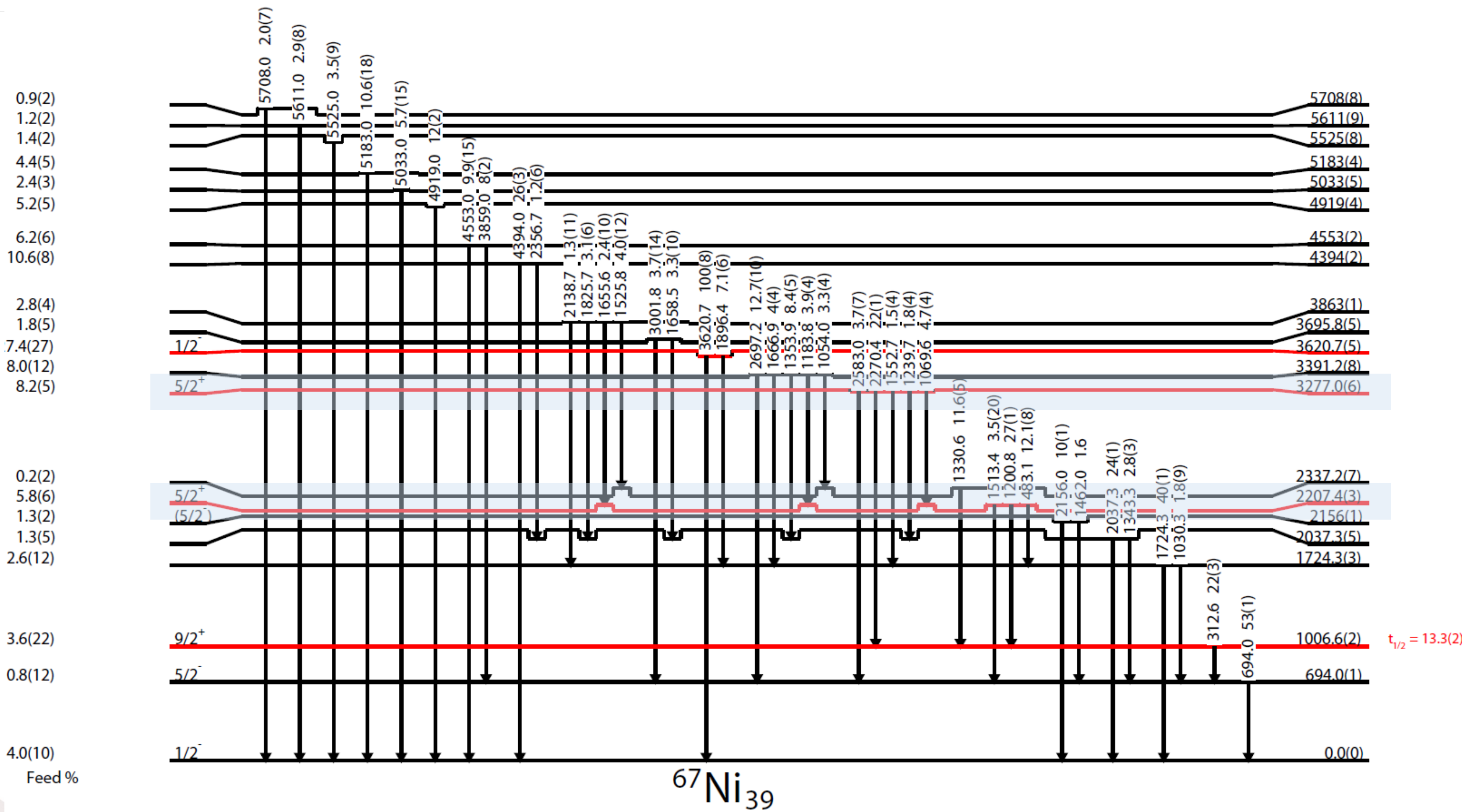
# Improved level scheme



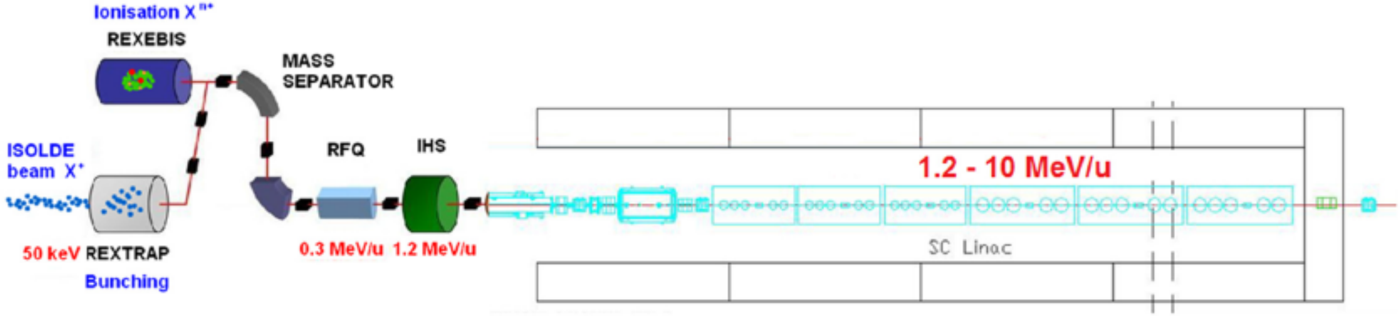

**Identification of 5/2+ states (neutron excitations above the N=50 shell gap, d5/2 )**

# Completed transfer experiments

| Reaction | |
|---|---|
| $^{30}Mg(d,p)$ | V. Bildstein |
| $^{66}Ni(d,p)$ | J. Diriken |
| $^{66}Ni(t,p)$ | J. Eleseviers |
| $^{30}Mg(t,p)$ | K. Wimmer |
| $^{44}Ar(t,p)$ | K. Nowak |
| $^{78}Zn(d,p)$ | R. Orlandi |
| $^{72}Zn(t,p)$? | S. Hellgartner |
| $^{11}Be(d,p)$ | J. Joanssen |
| $^{8}Li(d,p)$ | Tengborn |
| $^{28}Na(d,p)$ | ??? |

# HIE-ISOLDE project

✓ **ENERGY:**
Energy upgrade and lower energy capacity
- Wider range of radioactive beams
- Variable energy range from 1.2 up to 10 MeV/u




✓ **INTENSITY:**
ISOLDE proton driver beam intensity upgrade (LINAC4 +PSB)
Increase in Intensity expected of a factor of 3
Increase in proton energy to 2 GeV → Increase in production cross sections
- Target and frontend upgrade

✓ **QUALITY:**
Improvement of secondary beam quality: Reduction of phase space
- Purity, emittance: Selectivity
- Time structure: bunching

| **Timelines** : Physics at 4.3 MeV/u | Autum 2015 |
|---|---|
| 5.5 MeV/u | Spring 2016 |
| 10 MeV/u | 2017 |

From M.Borge

# Accepted experiments (26) + LOIs

Accepted for 4-5.5 MeV/u:

| Reaction | SpokePersons | I(pps) | Contaminant |
|---|---|---|---|
| $^{17}$N(d,p) | A. Matta | $1*10^4$ | |
| $^{68}$Ni(d,p) | F. Flavigny, L. Gaffney | $2*10^5$ | $^{68}$Ga |
| $^{9}$Li(t,p)$^{11}$Li | K. Riisager, D. Mucher | $1*10^6$ | |
| $^{80}$Zn(d,p) | R. Orlandi, R. Raabe | $2\text{-}8*10^3$ | $^{80}$Ga |
| $^{70}$Ni(d,p) | J. Valiente Dobon | $1*10^4$ | $^{70}$Ga |
| $^{7}$Be(d,p) | D. Gupta | $1*10^7$ | |
| $^{20}$Mg+p->$^{21}$Al | B. Fernandez | 50 | $^{20}$Na |

+ 11 Coulomb Excitation experiments

Letters of Intent (2010)

| Reaction | SpokePersons |
|---|---|
| $^{100}$Sn region | J. Cederkall |
| $^{184}$Hg region | P. Van Duppen |
| $^{132}$Sn region | Th. Kroll |
| $^{50\text{-}52}$Ca region | S. Freeman |
| GASPARD | W. Catford, D. Beaumel |

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# MUST2 at ISOLDE ?

- **Competitivity**
  - Forward reactions
  - dE-T identification of stopped particles
  - Better Angular + Excitation Energy resolutions ?
    - → To simulate case by case (low energy, beam spot effect)

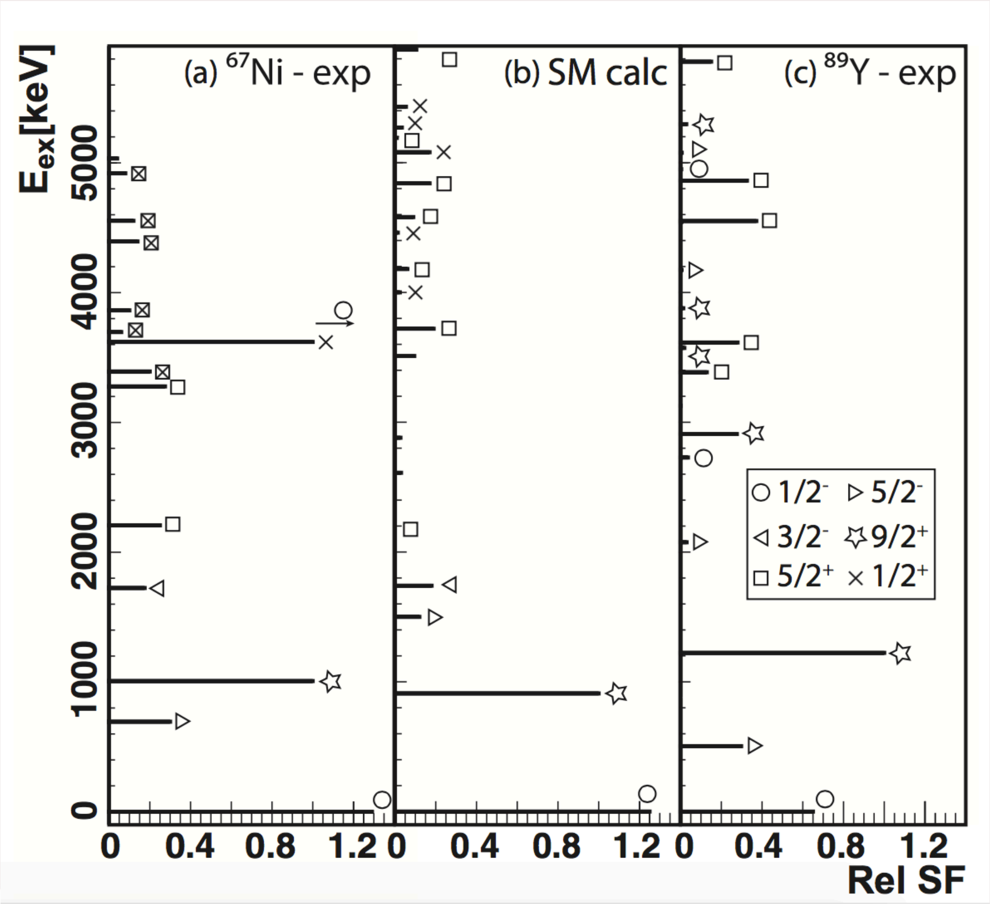
- Acquisition completely different from Miniball+TREX
  - → No easy coupling with Miniball possible (mechanics, electronics)

- Can MUST2 handle the instantaneous rate ?
  - →Yes
  - → BUT not beam trackers like CATS/BTD

- dE-T : Time reference (what to use instead of CATS?)
  - → Plastic at 0 degrees, PPAC?

- Normalization
  - →Use of elastic scattering like TREX
  - → But better elastic coverage if M2 Telescopes at 90°

Backup



(a) 67Ni - exp
(b) SM calc
(c) 89Y - exp
Eex[keV]
0
1000
2000
3000
4000
5000
0 0.4 0.8 1.2
Rel SF
1/2- 5/2-
3/2- 9/2+
5/2+ 1/2+

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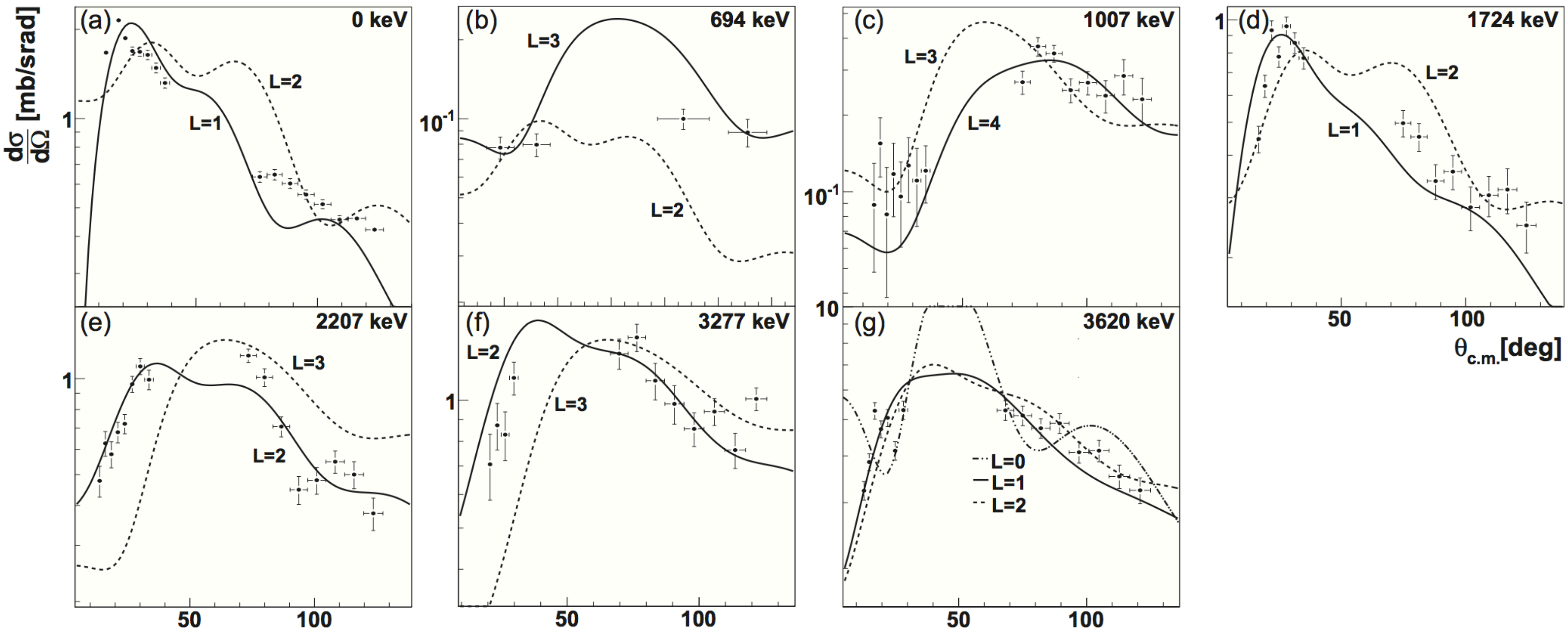
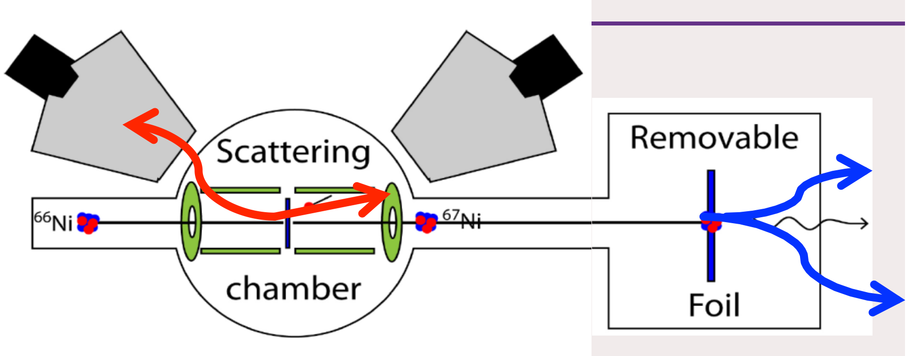
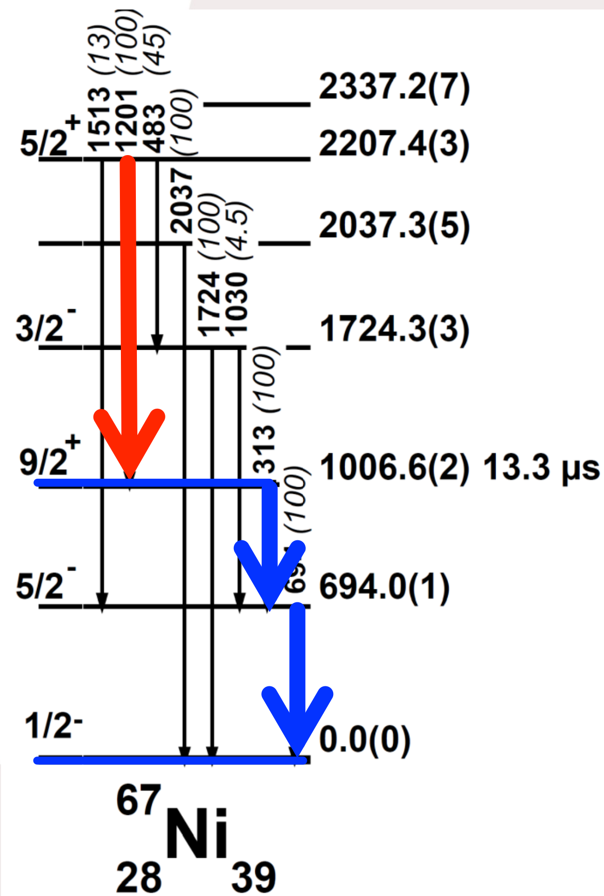
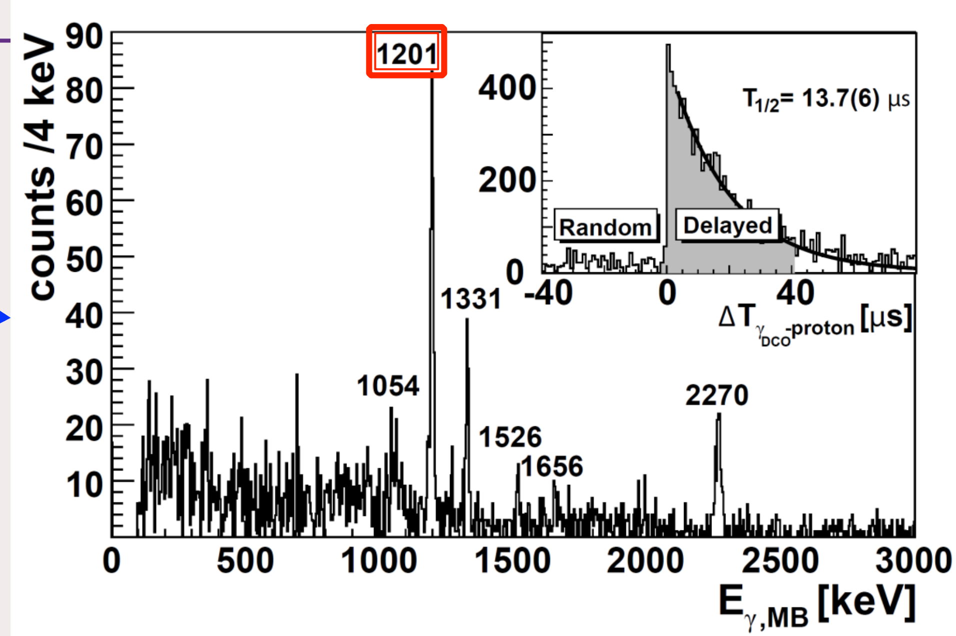
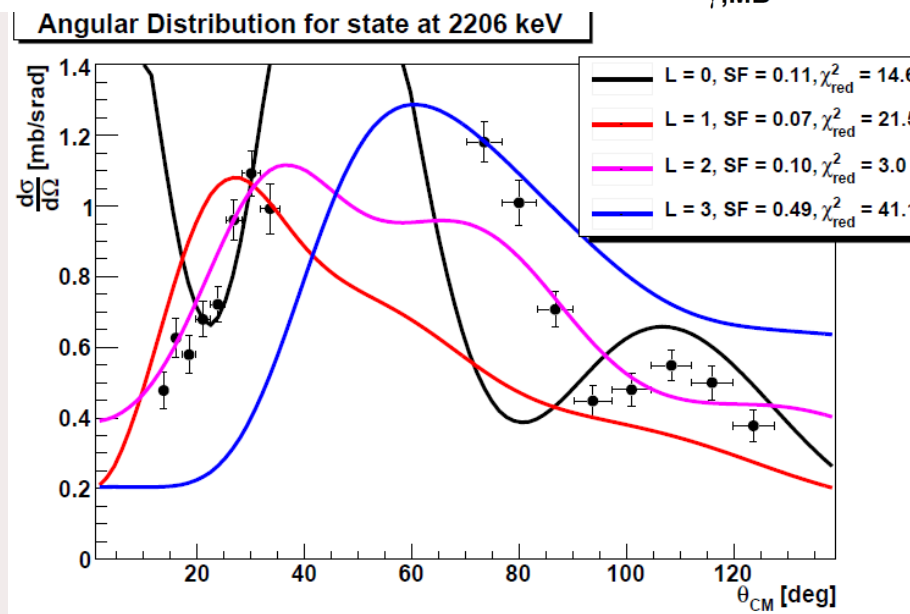


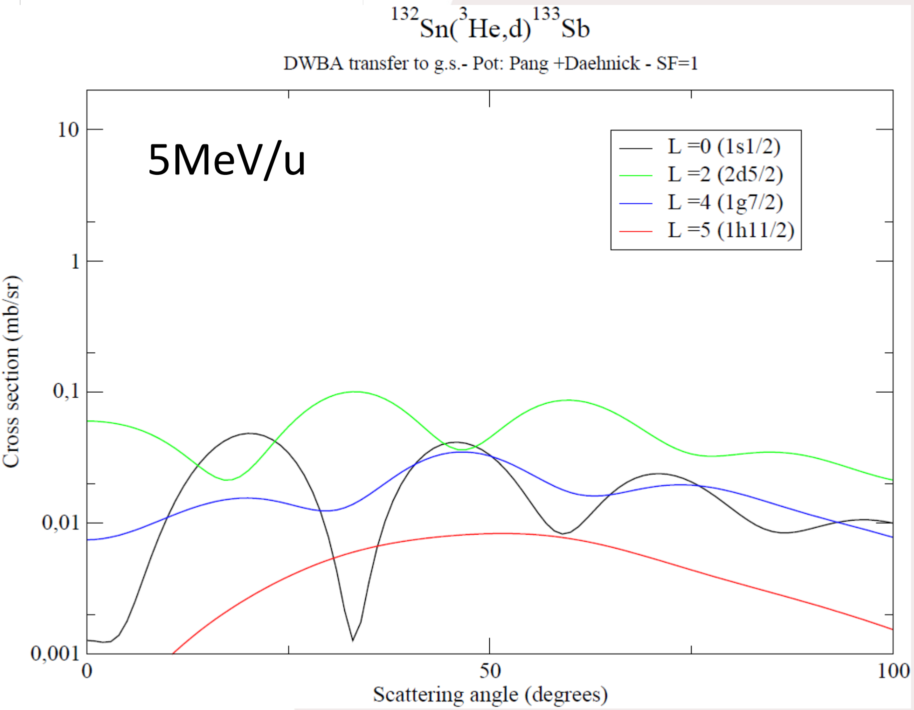
# Building the level scheme – spin/parity

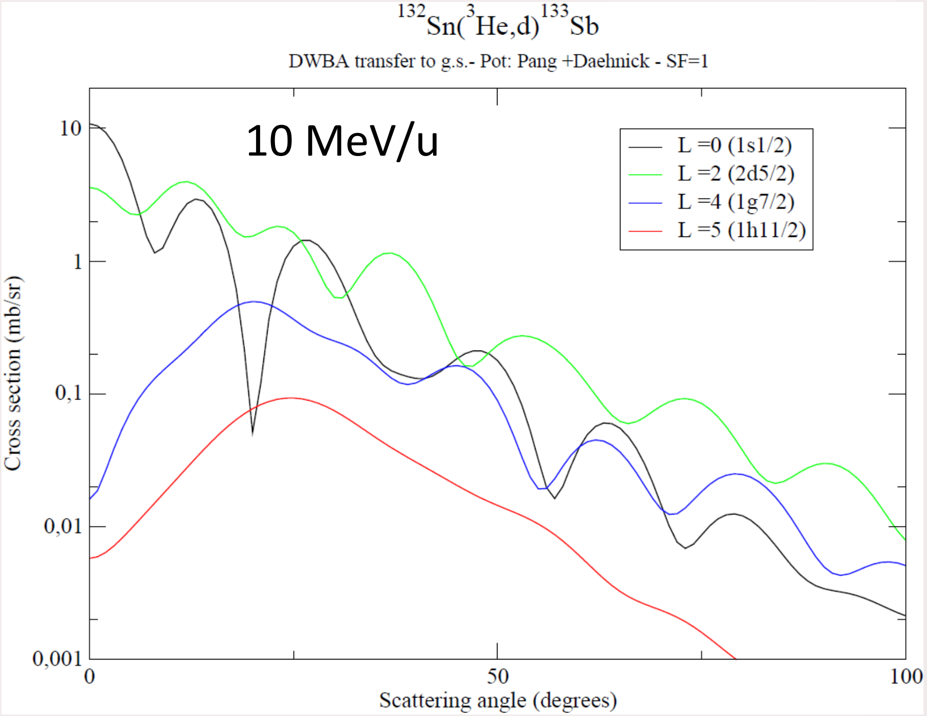


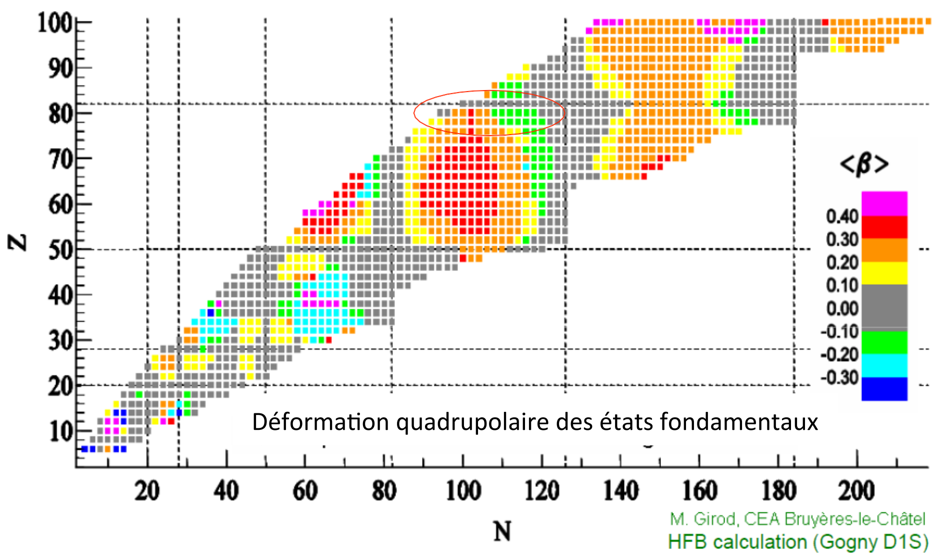



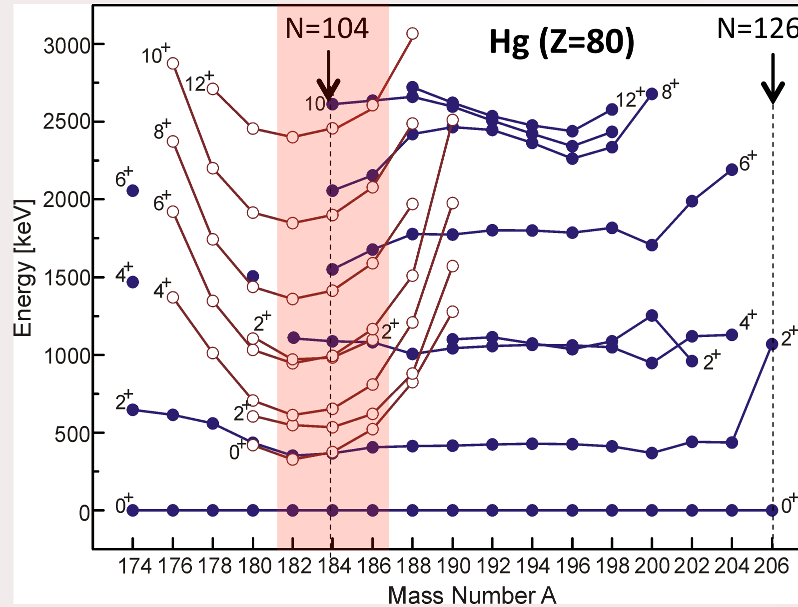




$^{132}Sn(^3He,d)^{133}Sb$
DWBA transfer to g.s.- Pot: Pang +Daehnick - SF=1
5MeV/u
L =0 (1s1/2)
L =2 (2d5/2)
L =4 (1g7/2)
L =5 (1h11/2)
Cross section (mb/sr)
10
1
0,1
0,01
0,001
0
50
100
Scattering angle (degrees)


$^{132}Sn(^3He,d)^{133}Sb$
DWBA transfer to g.s.- Pot: Pang +Daehnick - SF=1
10 MeV/u
L =0 (1s1/2)
L =2 (2d5/2)
L =4 (1g7/2)
L =5 (1h11/2)
Cross section (mb/sr)
10
1
0,1
0,01
0,001
0
50
100
Scattering angle (degrees)

# Shape coexistence below Z=82



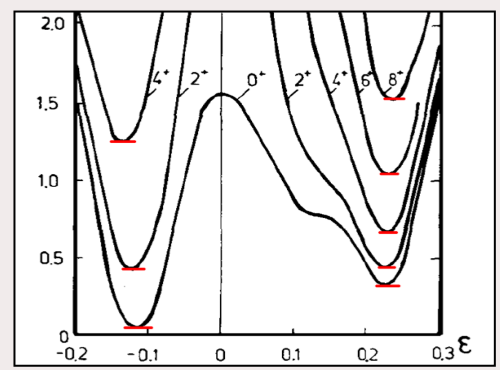




*Measured intensity at MB in 2008*

| Isotope | Int. (pps) |
|---|---|
| $^{182}$Hg | $5*10^{3}$ |
| $^{184}$Hg | $1*10^{5}$ |
| $^{186}$Hg | $2.5*10^{5}$ |
| $^{188}$Hg | $3*10^{5}$ |

‘spherical-weak oblate’ ‘deformed (prolate)’

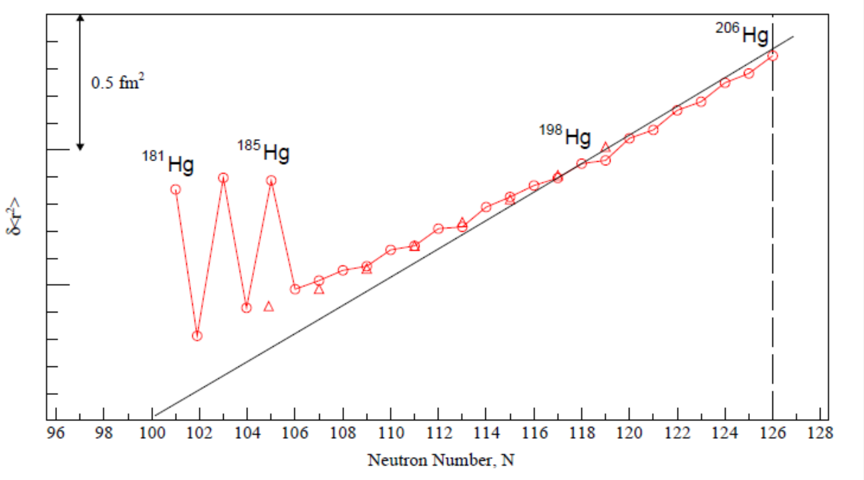
$\beta_2 \approx -0.15$
(2h)



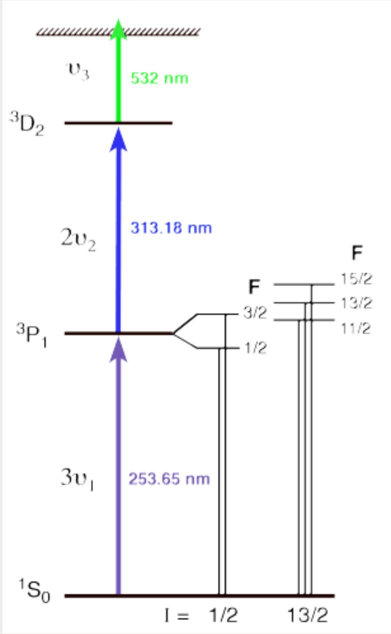

$\beta_2 \approx +0.25$
(4p-6h)

**→ Interplay between collective properties and single particle structure**

# $^{185}$Hg Laser Ionization

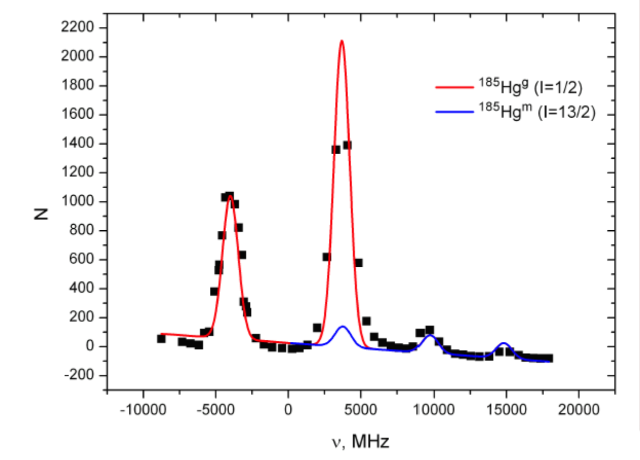



*NEW RILIS Ionization scheme for Hg*




$^{185}$Hg:

gs: 1/2- (49.1s) ½[521] from p3/2
iso: 13/2+ (21.6 s) (i13/2) hole



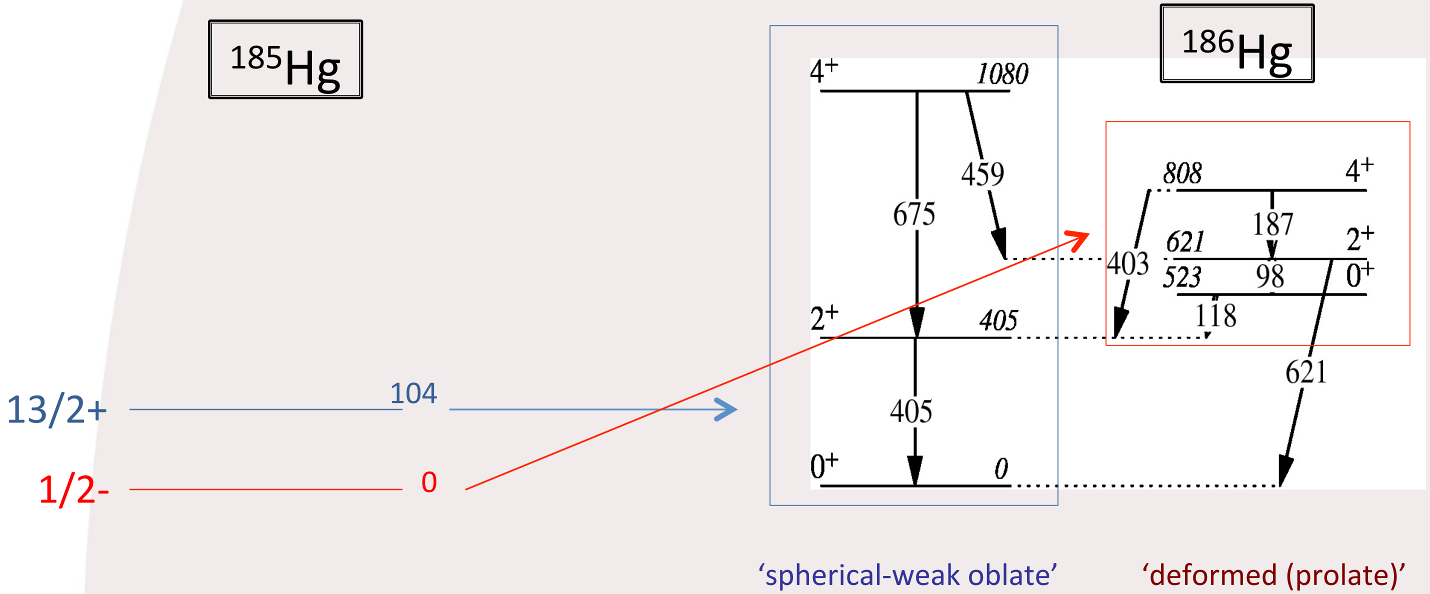

Long history of Hg production and study at ISOLDE

Aug. 2014:
-> First demonstration of isomer selective ionization in $^{185}$Hg with RILIS

**Unique:**

- Transfer on shape-isomers
- Transfer on Z=80 nucleus in inverse kinematics

# Hg (d,p) reaction possibilities



Accepted (HIE-ISOLDE)

18N: a challenge to the shell model and a part of the to r-process element production in Type II supernovae, A. Matta.
Characterising 68Ni using Coulomb excitation and one-neutron transfer, F. Flavigny/ L. Gaffney
Study of the unbound p-rich nucleus 21Al with resonant-elastic and inelastic scattering using an active Target, B. Fernandez
Transfer Reactions and Multiple Coulomb Excitation in the 100Sn Region, J. Cederkall
Transfer reactions at the neutron dripline with triton target, K. Riisager, D Mucher
Spectroscopy of low-lying single-particle states in 81Zn populated in the 80Zn(d,p) reaction, R. Orlandi, R. Raabe
Study of shell evolution in the Ni isotopes via one-neutron transfer reaction in 70Ni, J. Valiente, Orlandi, Mengoni
Search for higher excited states of 8Be* to study the cosmological 7Li problem, D. Gupta

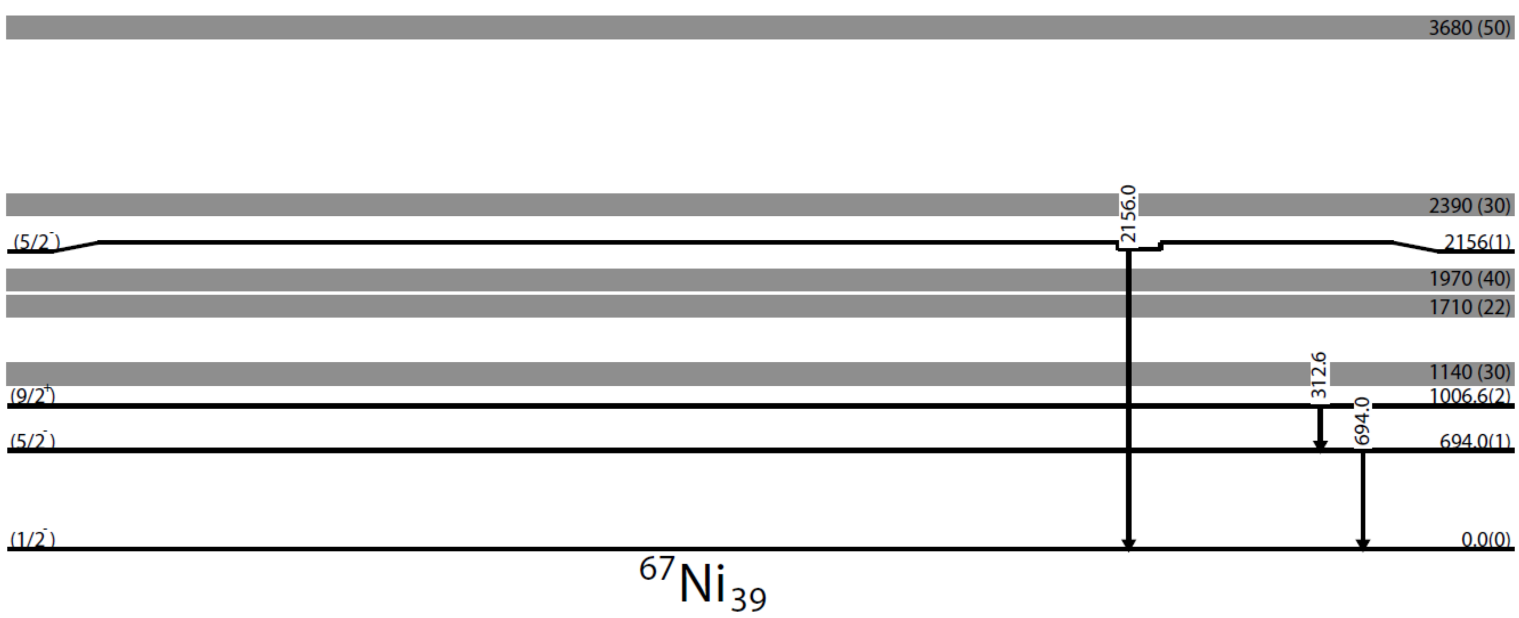
HIE ISOLDE LOIs

Elastic resonance scattering study with a 20Mg beam: p(20Mg,p)21Al, M Borge.
Single-Particle Evolution and Test of Shell Models, S.Freeman
Shape coexistence in the neutron-deficient region around Z=82 studied via Coulex and transfer, P Van Duppen
Coulomb excitation and nucleon transfer reactions in the 132Sn region, Th. Kroel
GASPARD at HIE-ISOLDE, W. Catford

| Reaction | |
|---|---|
| $^{30}$Mg(d,p) | V. Bildstein |
| $^{66}$Ni(d,p) | J. Diriken |
| $^{66}$Ni(t,p) | J. Eleseviers |
| $^{30}$Mg(t,p) | K. Wimmer |
| $^{44}$Ar(t,p) | K. Nowak |
| $^{78}$Zn(d,p) | R. Orlandi |
| $^{72}$Zn(t,p)? | S. Hellgartner |
| $^{11}$Be(d,p) | J. Joanssen |
| $^{8}$Li(d,p) | Tengborn |
| $^{28}$Na(d,p) | ??? |

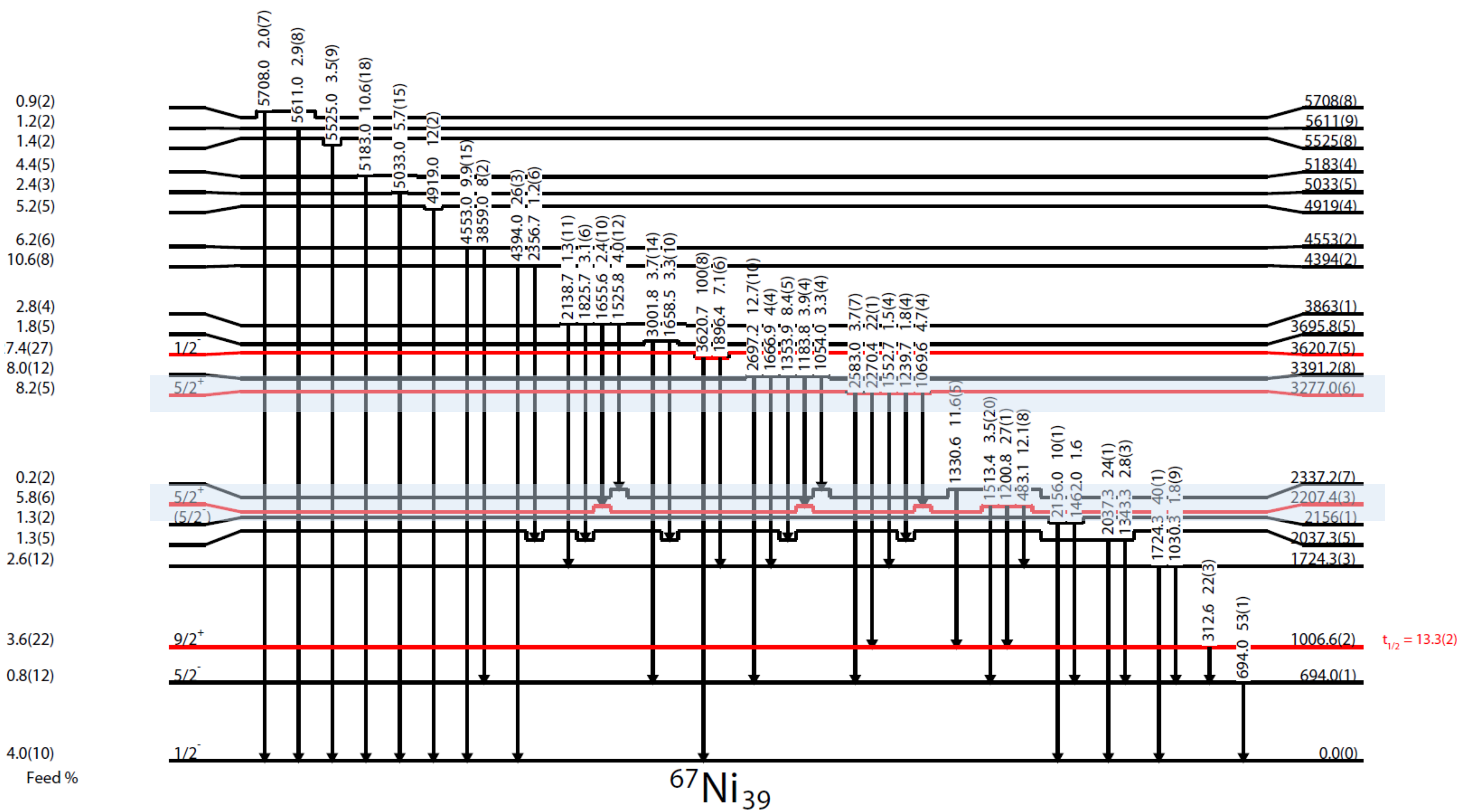
# Improved Level scheme for $^{67}Ni$





KU LEUVEN

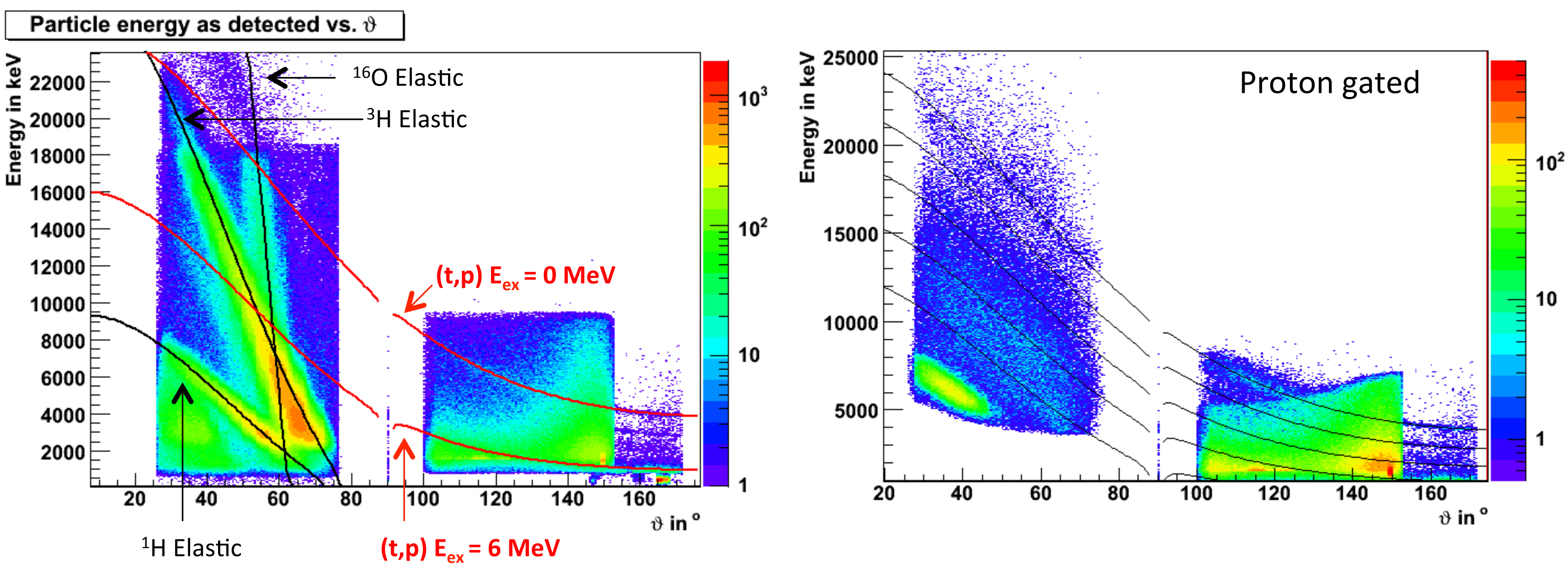
# Improved Level scheme for $^{67}Ni$




**Identification of 5/2+ states (neutron excitations above the N=50 shell gap, d5/2 )**

# $^{3}H(^{66}Ni,p)^{68}Ni$ : Results

## Kinematical plots (Q = 5.12 MeV)




- **Population of states up to 9 MeV, strong feeding around 5-8 MeV and the ground state**