

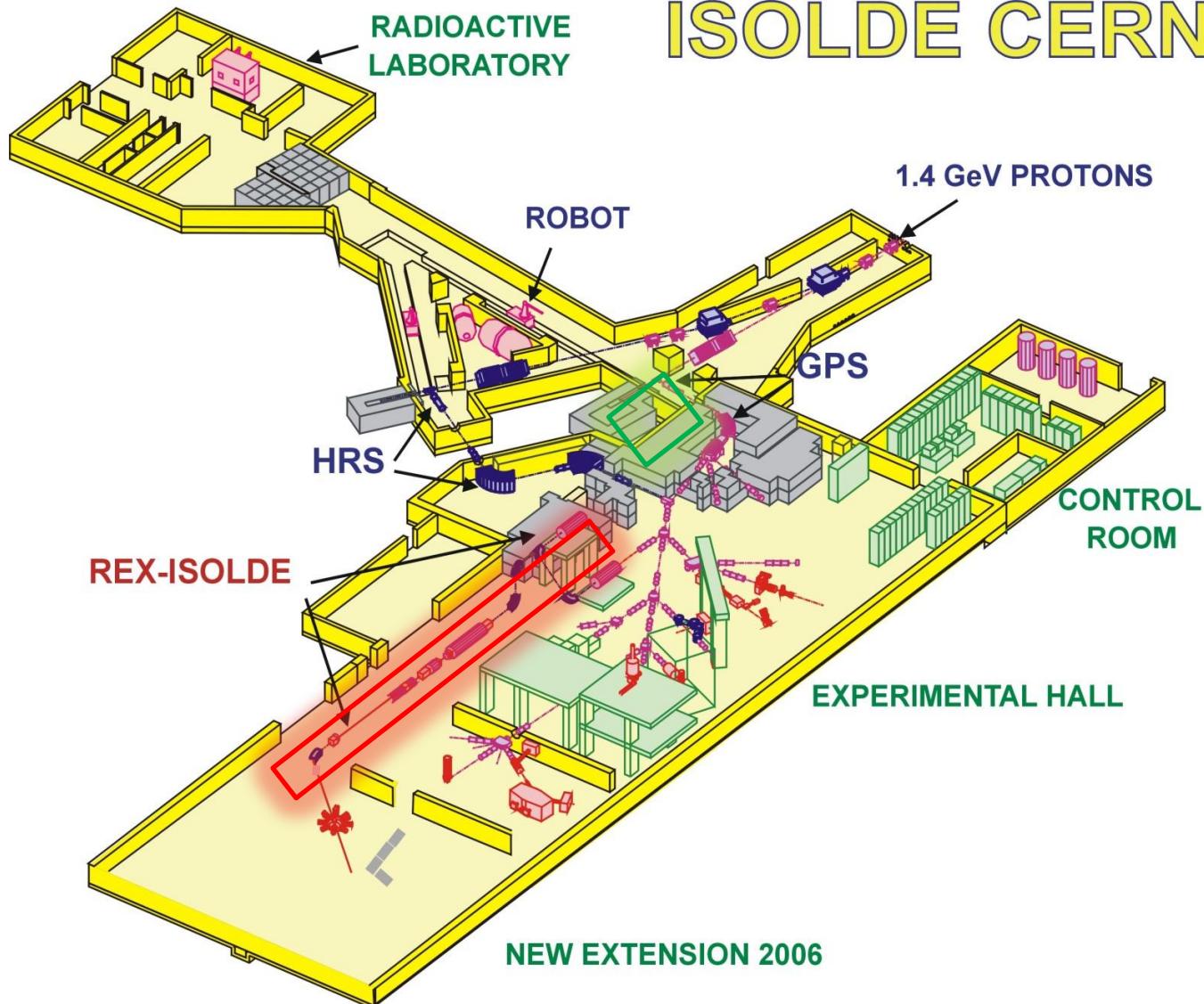
# Overview of MINIBALL results combined with decay spectroscopy studies for middle-mass nuclei

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Elisa Rapisarda, CERN, PH Division  
on behalf of the MINIBALL collaboration

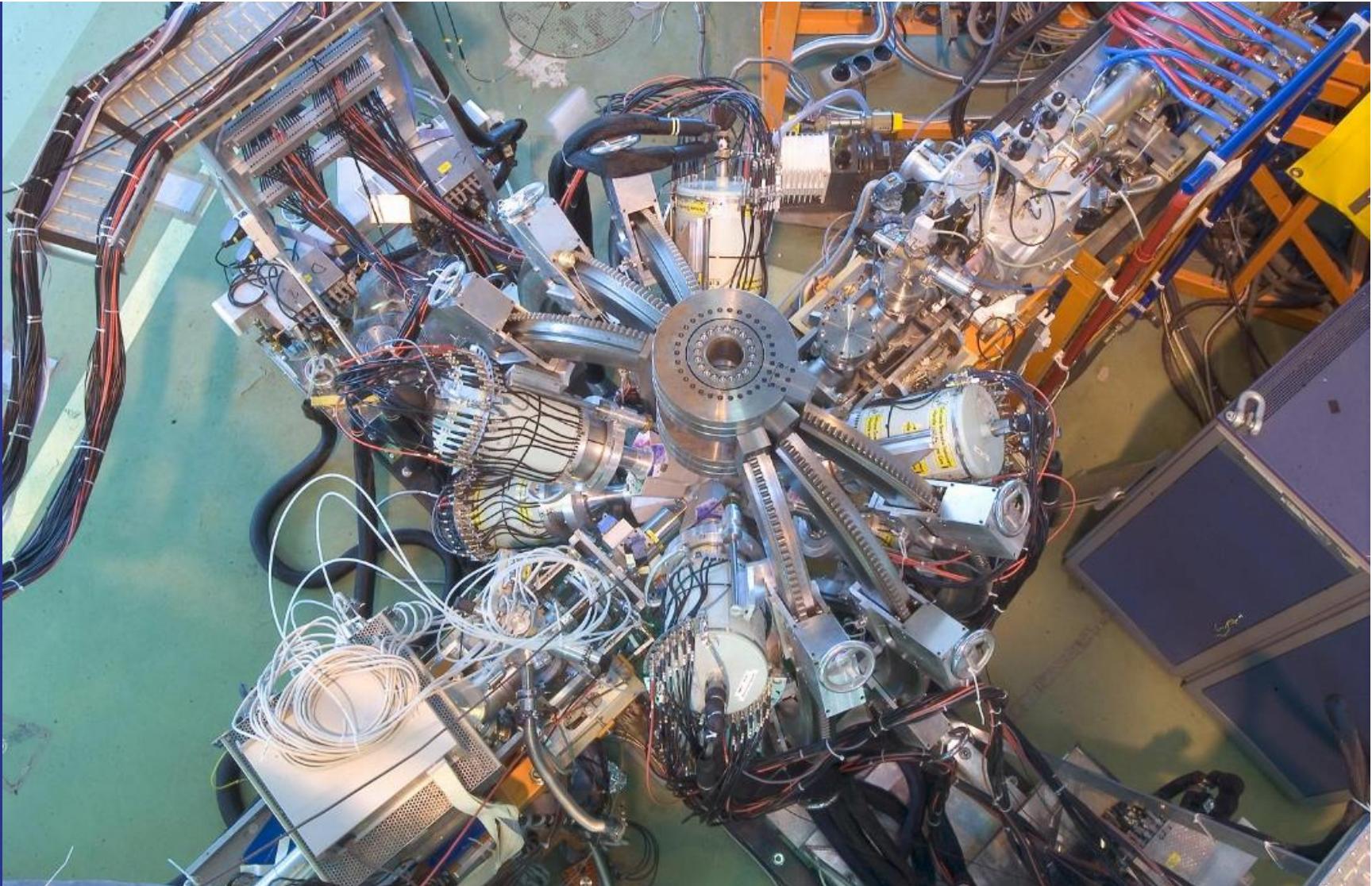


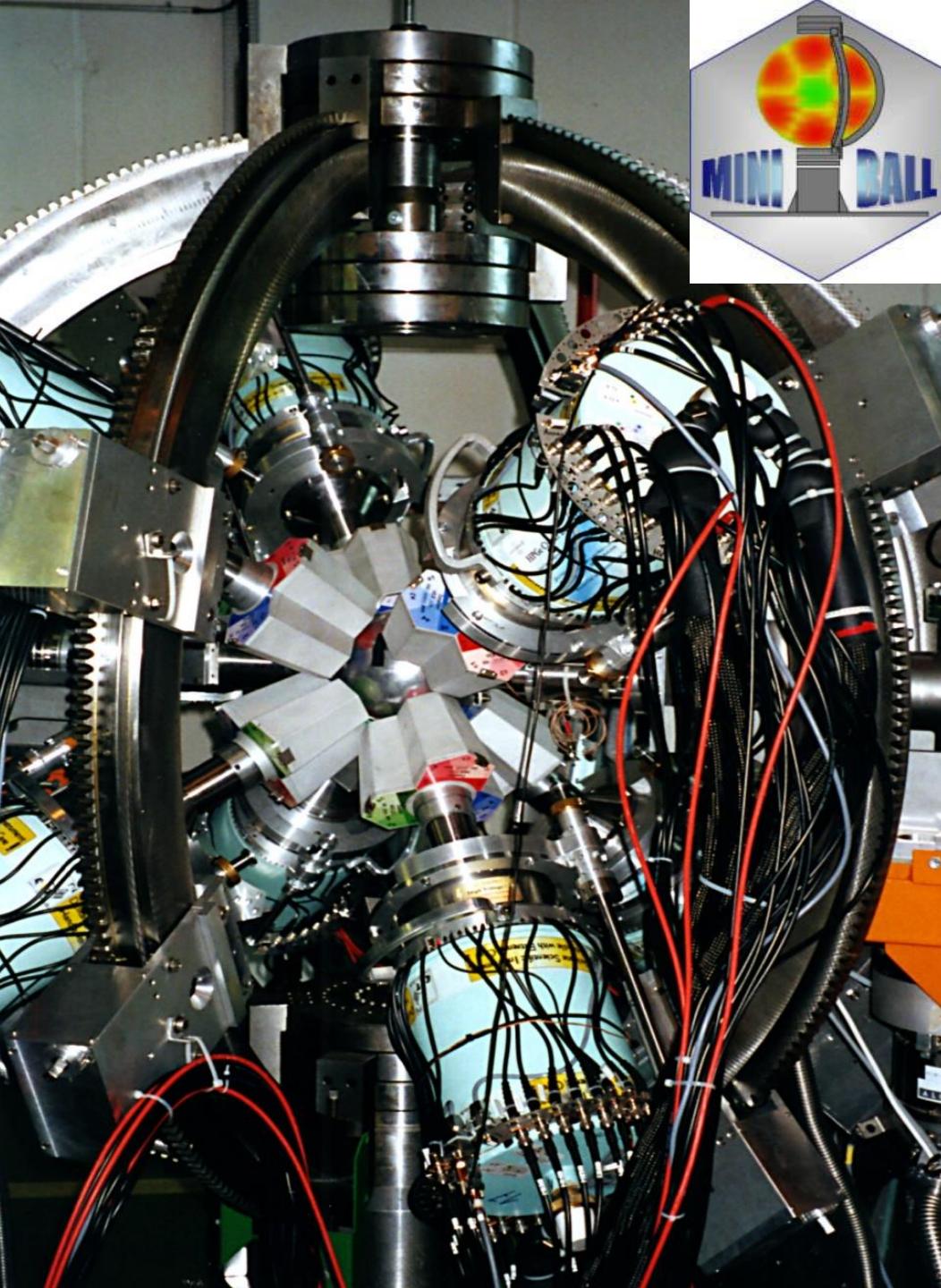
# ISOLDE CERN



1<sup>st</sup> post-accelerated beam and Coulomb excitation in 2001

# Miniball





# The MINIBALL detector array

## MAIN CHARACTERISTIC

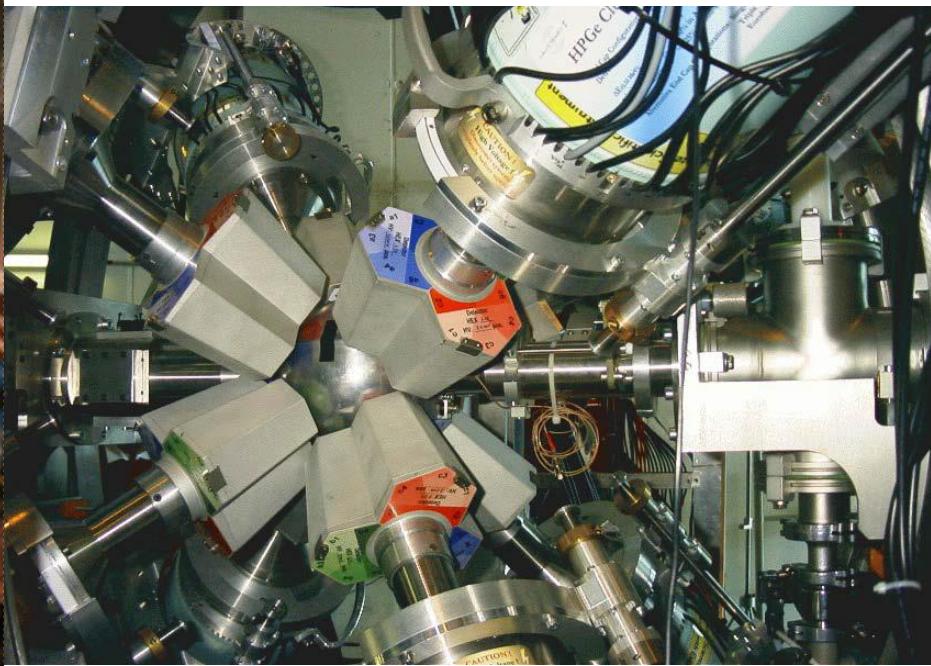
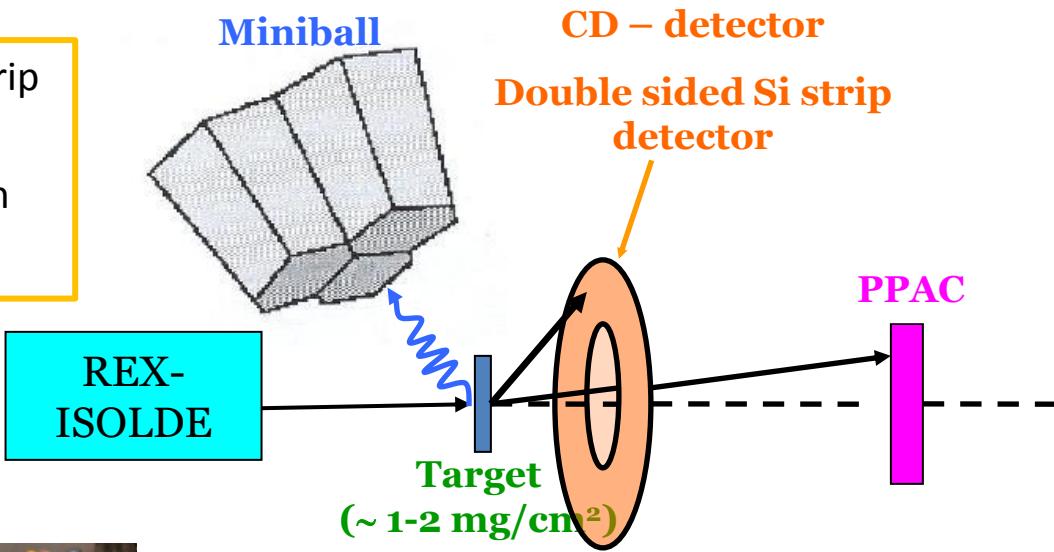
- 8 Miniball clusters
- Each cluster: 3 HPGe crystals
- Each crystal: 6-fold segmented
- 8% efficiency @ 1.3 MeV

München, Köln, Heidelberg,  
Darmstadt, Leuven, York, Liverpool,  
Daresbury, Strasbourg,...

# “Safe” Coulomb Excitation experiments

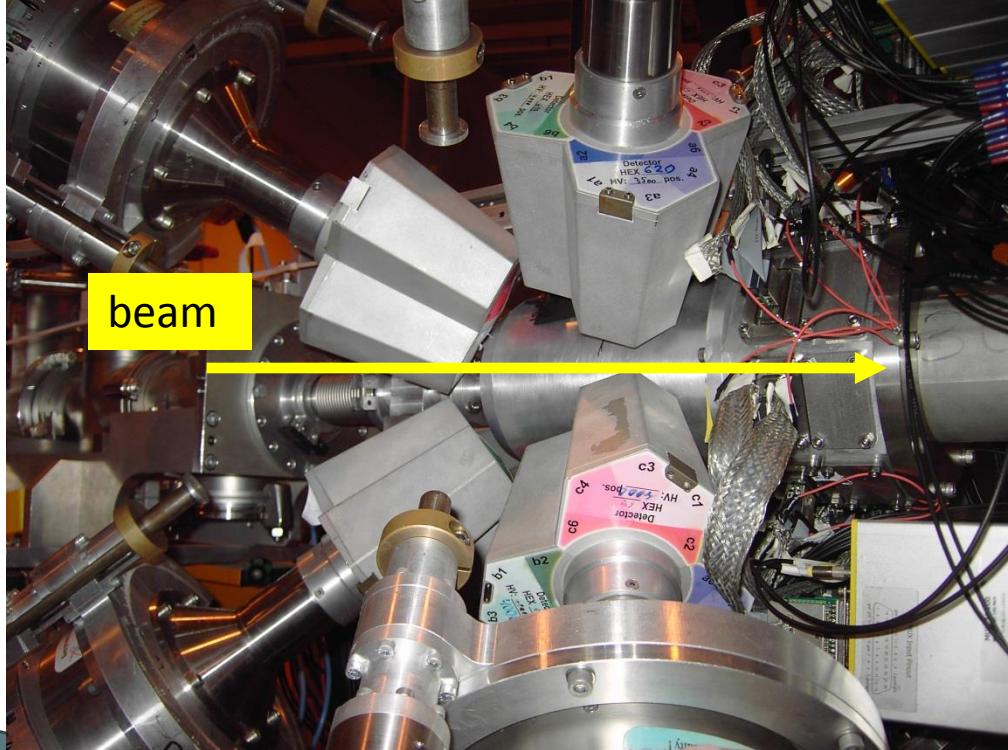
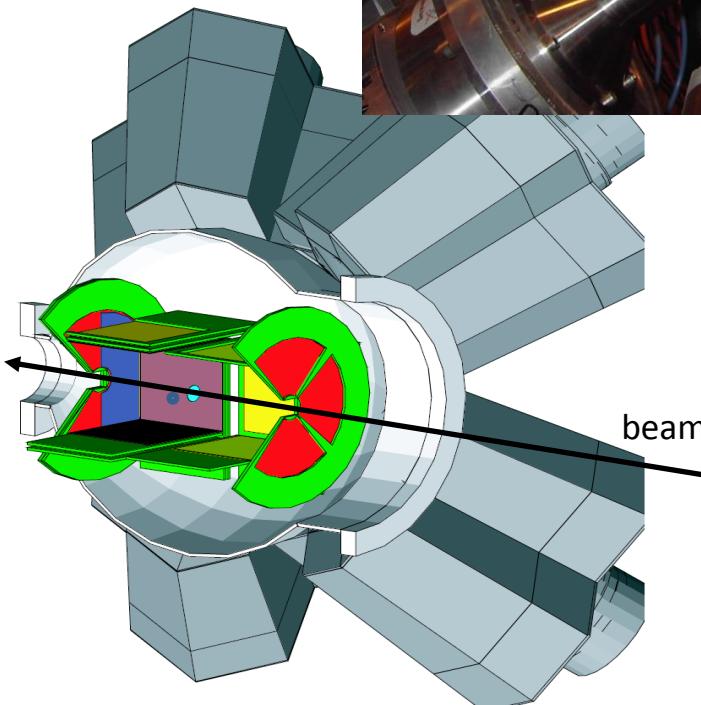
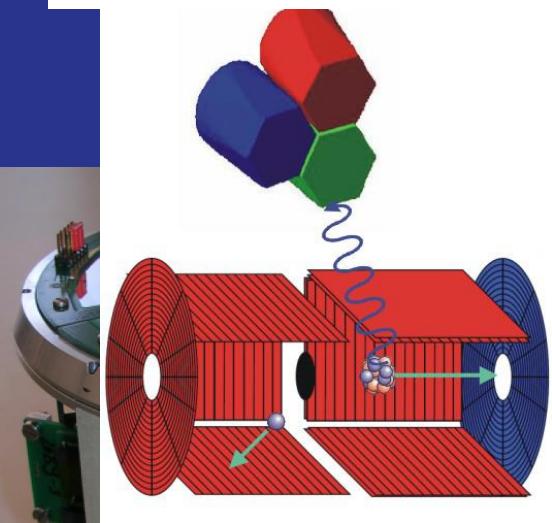
## ➤ Particle (CD) – $\gamma$ correlations

- Particle ID in a Double-Sided Si Strip Detector
- Event by event Doppler correction
- $17^\circ < \theta_{\text{lab}} < 54^\circ$



# T-REX

- ✓ Few-nucleon transfer: (d,p) and (t,p) reactions - E(single particle),  $\Delta\pi$ , (relative) spectroscopic factors
- ✓ Fusion evaporation reaction: cross sections
- ✓ Transient field: magnetic moments



## Some data

- large solid angle (58% of  $4\pi$ )
- position sensitive
- PID ( $\Delta E-E$ ): p, d, t,  $\alpha$ ,  
... and  $e^-$  from  $\beta$ -decay (!)

### Technical details:

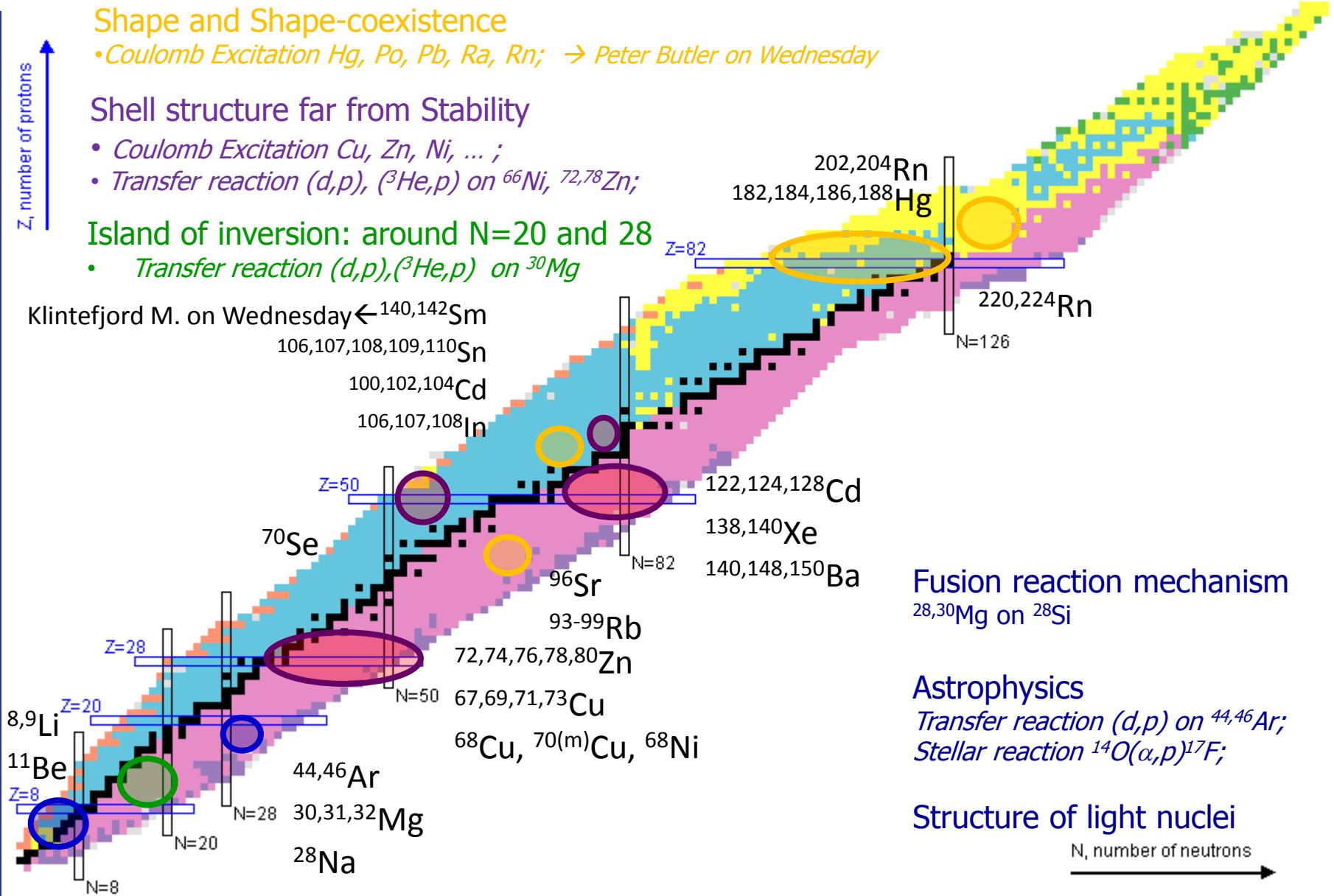
Barrel:  $140 \mu\text{m} \Delta E / 16$  resistive strips  
 $1000 \mu\text{m} E / \text{pad}$

Backward CD:  $500 \mu\text{m} \Delta E / \text{DSSSD}$   
 $500 \mu\text{m} E / \text{pad}$

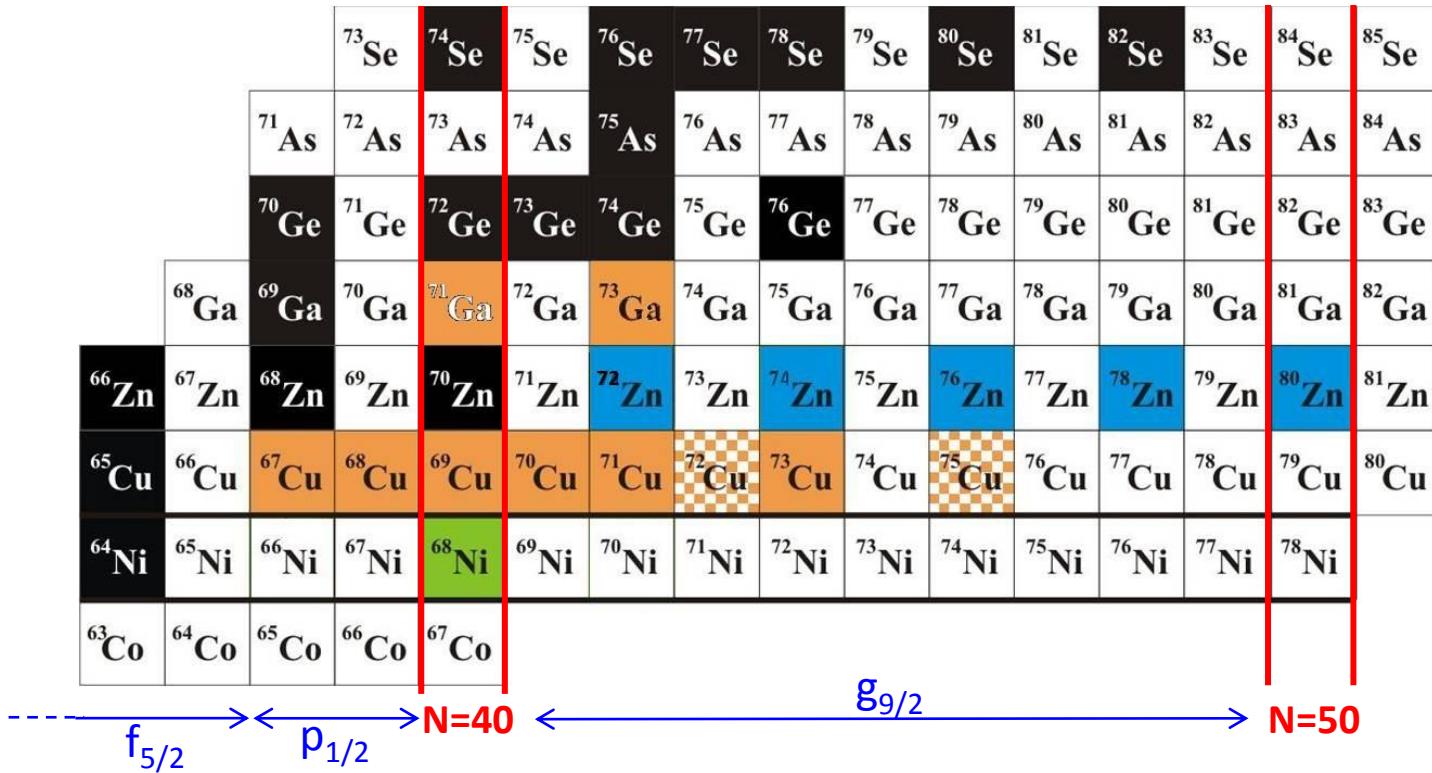


# The REX-ISOLDE-Miniball physics program:

Some physics cases “over the past years” ...



# Shell Evolution around Z=28 seen by MINIBALL



$^{72,74,76,78,80}\text{Zn}$

$^{68,70(\text{m})}\text{Cu}$ ,

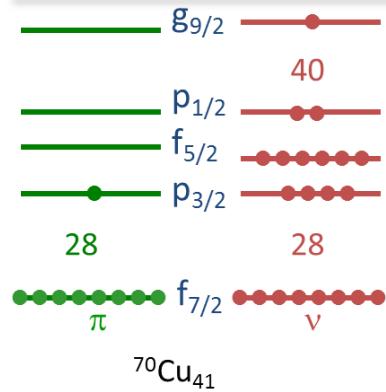
$^{67,69,71,73}\text{Cu}$

$^{66}\text{Ni(d,p)}\text{ }^{67}\text{Ni}$

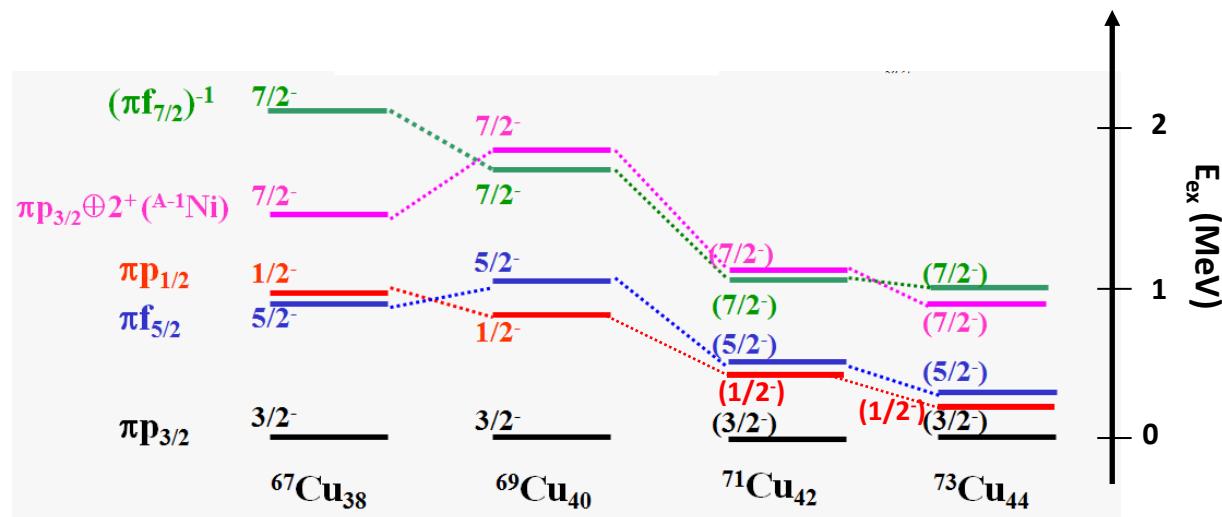
$^{66}\text{Zn(t,p)}\text{ }^{68}\text{Ni}$

Shell Model far from Stability  
from  $N=40$  to  $N=50$  around  $Z=28$

# Coulex of neutron-rich Cu isotopes - odd



Level schemes of odd-A Cu isotopes ( $Z=29$ ) expected to be dominated by single-particle excitations and core-coupled states.



$^{67,69}\text{Cu}$ , transfer reactions:  
B. Zeidman et al., PRC 18, 2122(1978).

$^{71}\text{Cu}$ , deep inelastic:  
R. Grzywacz et al., PRL 81, 766 (1998).

$^{69,71,73}\text{Cu}$ ,  $\beta$ -decay:

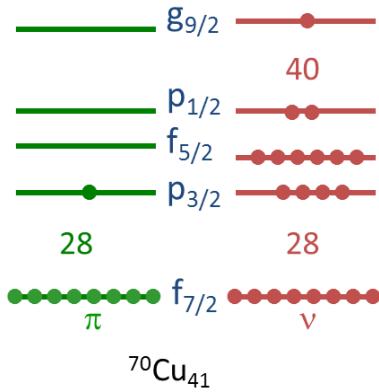
S. Franchoo et al., PRL 81, 3100(1998);  
S. Franchoo et al., PRC 64, 054308(2000);

$^{57-75}\text{Cu}$ , laser spectroscopy:

P. Vingerhoets et al., PRC 82, 064311 (2010)

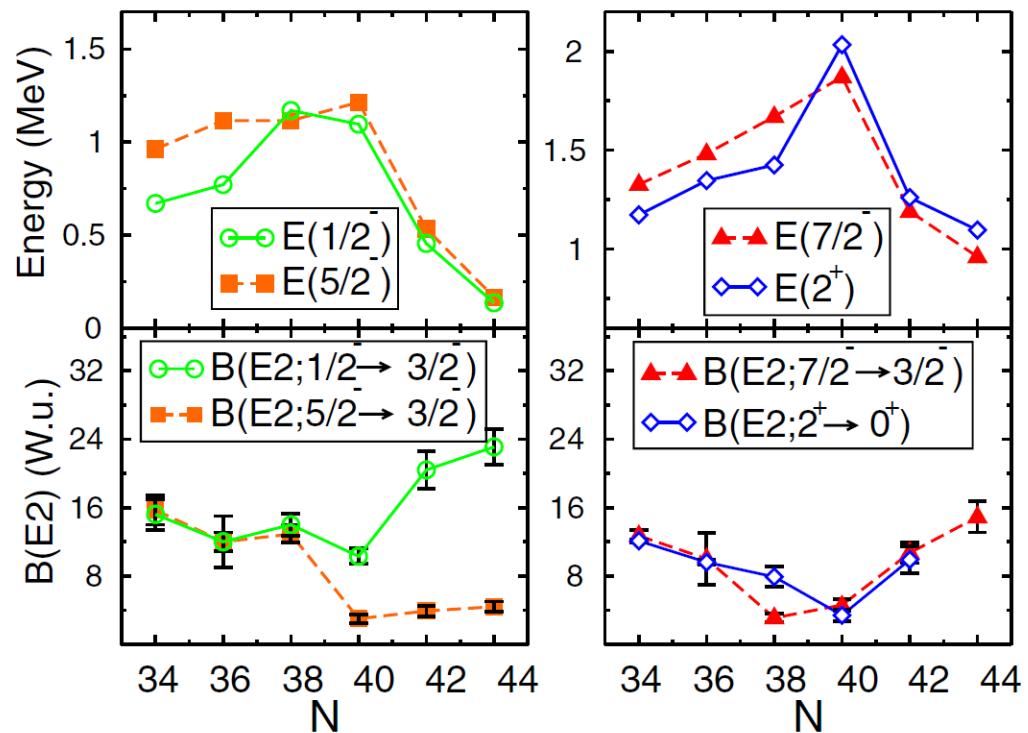
- Monopole migration of proton single particle states: collective states and proton intruder states in the n-rich Cu

# Coulex of neutron-rich Cu isotopes - odd



$B(E2; 7/2^- \rightarrow 3/2^-) \cong B(E2; 2^+ \rightarrow 0^+)$  in agreement with the proposed  $\pi p_{3/2} \oplus 2^+$  nature for the  $7/2^-$  states;

The observed  $1/2^-$  shows an important increase of collectivity beyond  $N=40$ . Whereas  $5/2^-$  behaves much more "single particle like ..."

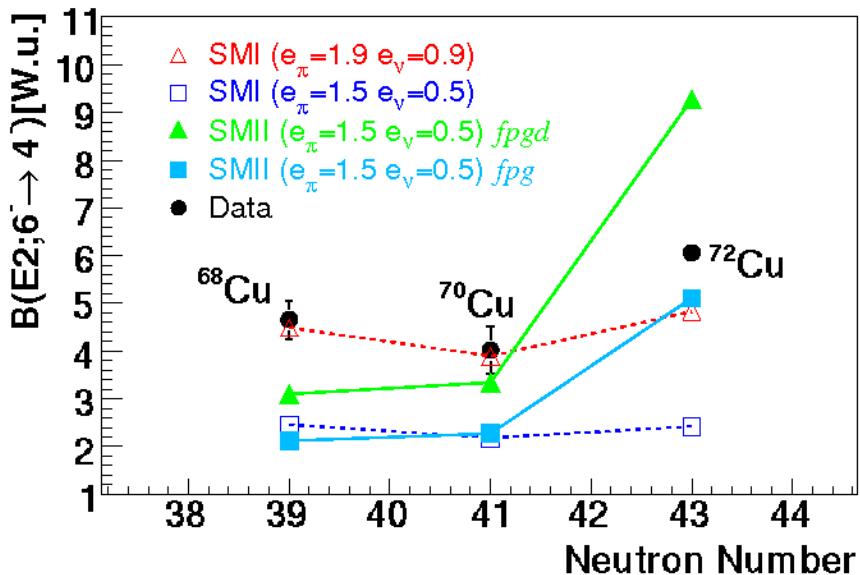


Coulomb excitation (I. Stefanescu, PRL100 (2008))

- Presence of both single-particle ( $\pi 2f_{5/2}$ ) and collective states ( $\nu g_{9/2}$  filling) at low excitation energy in the neutron-rich odd mass Cu

# Coulex of neutron-rich Cu isotopes - even

First use of post-accelerated Isomeric Beams



SMI Calculations by N. Smirnova

- NO proton-core excitations



- NO neutron-core excitations

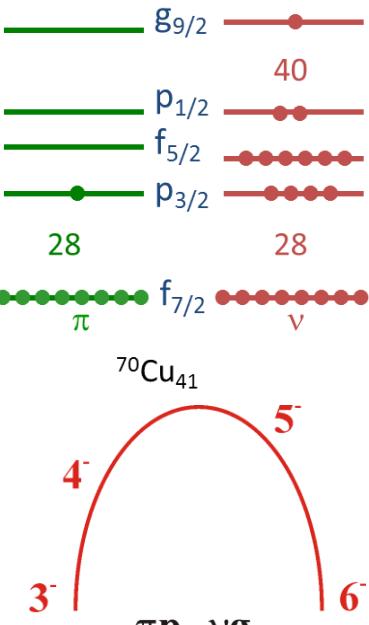
$^{58}\text{Ni}$  inert core

Z=28 N=28

SMII Calculations by K. Sieja



Z=20 N=28



$\pi p_{3/2} v g_{9/2}$

Neutrons excitations across N=50

Proton excitations across Z=28

$^{48}\text{Ca}$  inert core

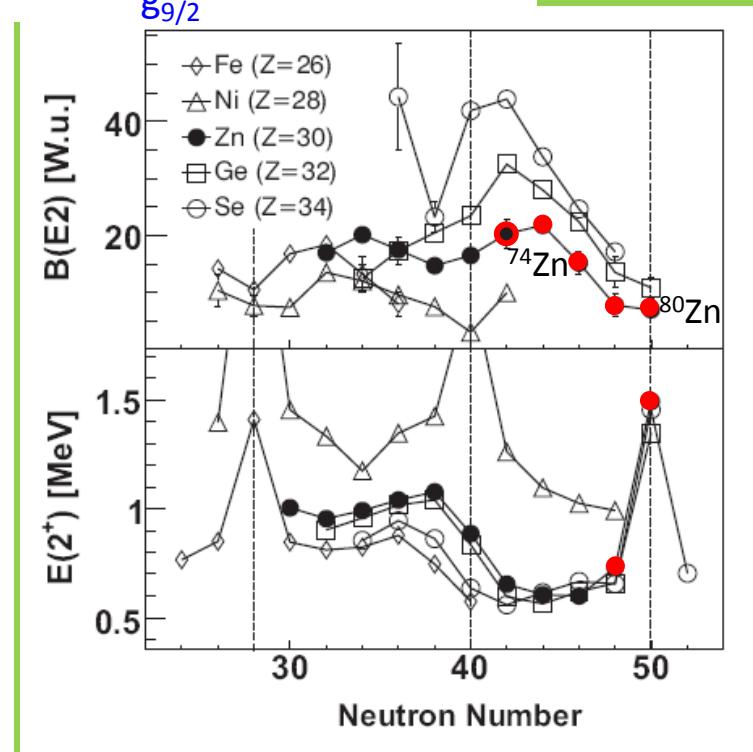
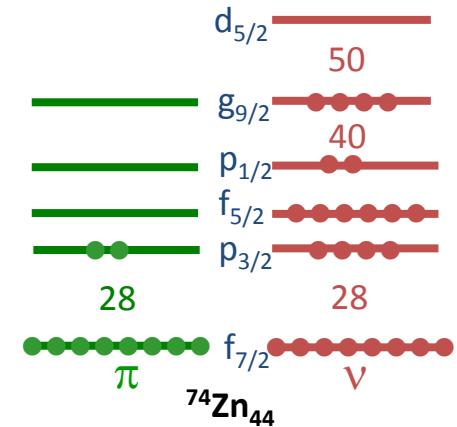
- Importance of the  $d_{5/2}$  neutron orbital in the shell model calculations

Coulomb excitation (I. Stefanescu, PRL98 (2007))

Coulomb excitation (E. Rapisarda, PRC84 (2011))

# Coulex of neutron-rich Zn isotopes

	<sup>70</sup> Ge	<sup>71</sup> Ge	<sup>72</sup> Ge	<sup>73</sup> Ge	<sup>74</sup> Ge	<sup>75</sup> Ge	<sup>76</sup> Ge	<sup>77</sup> Ge	<sup>78</sup> Ge	<sup>79</sup> Ge	<sup>80</sup> Ge	<sup>81</sup> Ge	<sup>82</sup> Ge	<sup>83</sup> Ge	
<sup>68</sup> Ga	<sup>69</sup> Ga	<sup>70</sup> Ga	<sup>71</sup> Ga	<sup>72</sup> Ga	<sup>73</sup> Ga	<sup>74</sup> Ga	<sup>75</sup> Ga	<sup>76</sup> Ga	<sup>77</sup> Ga	<sup>78</sup> Ga	<sup>79</sup> Ga	<sup>80</sup> Ga	<sup>81</sup> Ga	<sup>82</sup> Ga	
<sup>66</sup> Zn	<sup>67</sup> Zn	<sup>68</sup> Zn	<sup>69</sup> Zn	<sup>70</sup> Zn	<sup>71</sup> Zn	<sup>72</sup> Zn	<sup>73</sup> Zn	<sup>74</sup> Zn	<sup>75</sup> Zn	<sup>76</sup> Zn	<sup>77</sup> Zn	<sup>78</sup> Zn	<sup>79</sup> Zn	<sup>80</sup> Zn	<sup>81</sup> Zn
<sup>65</sup> Cu	<sup>66</sup> Cu	<sup>67</sup> Cu	<sup>68</sup> Cu	<sup>69</sup> Cu	<sup>70</sup> Cu	<sup>71</sup> Cu	<sup>72</sup> Cu	<sup>73</sup> Cu	<sup>74</sup> Cu	<sup>75</sup> Cu	<sup>76</sup> Cu	<sup>77</sup> Cu	<sup>78</sup> Cu	<sup>79</sup> Cu	<sup>80</sup> Cu
<sup>64</sup> Ni	<sup>65</sup> Ni	<sup>66</sup> Ni	<sup>67</sup> Ni	<sup>68</sup> Ni	<sup>69</sup> Ni	<sup>70</sup> Ni	<sup>71</sup> Ni	<sup>72</sup> Ni	<sup>73</sup> Ni	<sup>74</sup> Ni	<sup>75</sup> Ni	<sup>76</sup> Ni	<sup>77</sup> Ni	<sup>78</sup> Ni	
<sup>63</sup> Co	<sup>64</sup> Co	<sup>65</sup> Co	<sup>66</sup> Co	<sup>67</sup> Co											



Investigation still ongoing:  
Coulex of  $^{72}\text{Zn} \rightarrow$   
talk of Stefanie Hellgartner  
 $^{78}\text{Zn}(d,p)^{79}\text{Zn}$  by R. Orlandi;

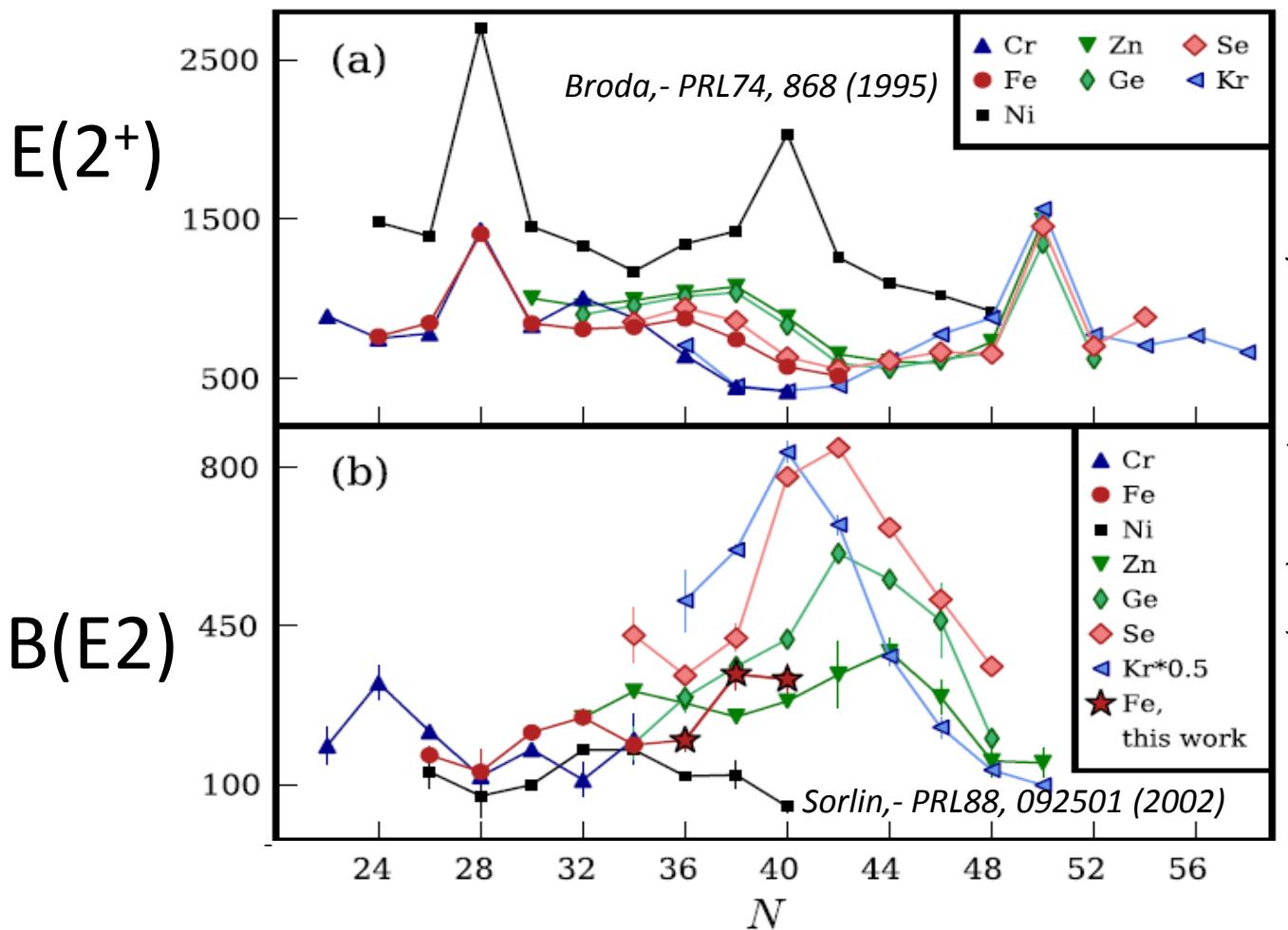
PROPOSALS:  
INTC-P-353 (2012) at HIE-ISOLDE Coulex  
INTC-P-352(2012) at HIE-ISOLDE transfer  
 $^{80}\text{Zn}(d,p)^{81}\text{Zn}$

## □ Restored N=50 shell at $^{80}\text{Zn}$ : Coulomb excitation

J. Van de Walle, PRL99 (2007) 142501

J. Van de Walle, PRC79(2009) 014309

# How magic is the double magic $^{68}\text{Ni}$ nucleus?



W. Rother et al. Phys. Rev. Lett. 106, 022502 (2011)

# 2012/2013 New experimental results on $^{68}\text{Ni}$

## Recent results:

- S. Suchyta et al., submitted to PRL (2013)
- F. Flavigny et al., in preparation (*decay spectroscopy Mn → Fe → Co → Ni*)
- F. Recchia et al., PRC **88**, 041302R (2013) ( $2nKO$ )
- R. Broda et al., PRC **86**, 064312 (2012)
- C. J. Chiara et al., PRC **86**, 041304R (2012)
- A. Dijon et al., PRC **85**, 031301R (2012) (*multinucleon transfer reactions*)

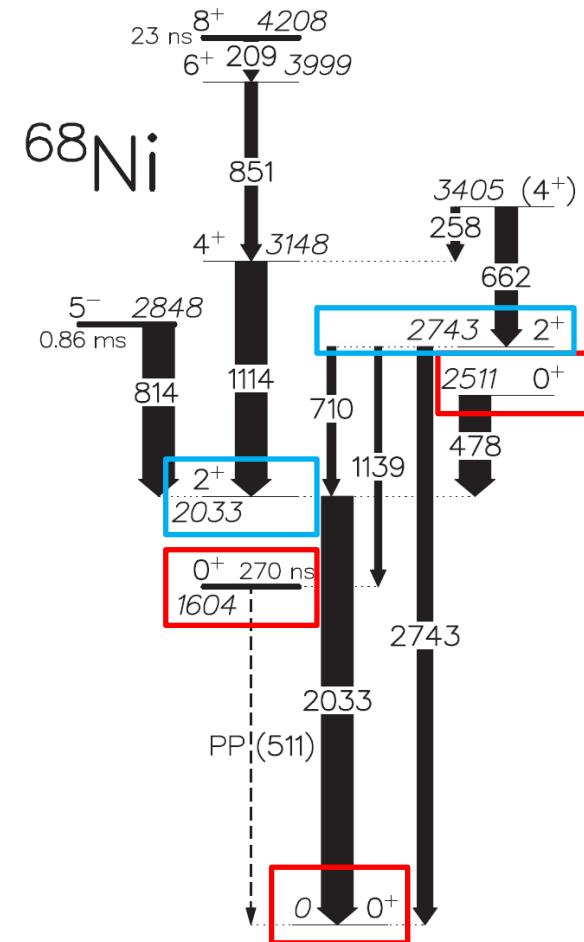
## Crucial informations:

- Precise measurement of  $0^+_2$  energy

Since 1982: 1770(30) keV using  $^{70}\text{Zn}(\text{C}, \text{O})^{68}\text{Ni}$

Now: 1603.5(3) keV

- Two transitions feeding  $0^+_2$  (1139 and 2420 keV)
- Firm assignment of several spin-parities.



Level scheme from F. Recchia et al.

PRC80, 041302R (2013)

$^{68}\text{Mn}$  β-decay (F. Flavigny et al. submitted)

Changes in the pictures of  $^{68}\text{Ni} \rightarrow$  hints to triple shape coexistence (Mixing of configurations)

# Shell Model

$2^+ 2743$

$0^+ 2511$

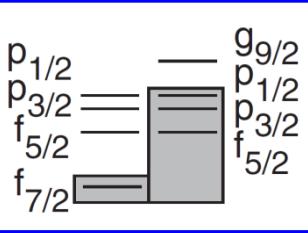
$2^+ 2034$

$0^+ 1604$

$2^+ 2505$

$0^+ 2326$

$0^+ 2040$



$0^+ 0$

$^{68}_{28} \text{Ni}_{40}$

$0^+ 0$

$^{68}_{28} \text{Ni}_{40}$



Liddick PRC87 (2013)

$\pi \text{ pf} - \nu \text{ pfg}_{9/2} ({}^{48}\text{Ca core})$

"dominant proton configuration has exactly two  $f_{7/2}$  protons less than the ground state"

$0^+ 2400$

$0^+ 1140$

"The  $0^+_1$  and  $0^+_2$  states "are characterized by "similar proton occupancies with leading  $0p-0h$  (neutron) configuration for the  $0^+_1$  ground state and  $2p-2h$  (neutron) configurations for the  $0^+_2$ ."

$0^+ 0$

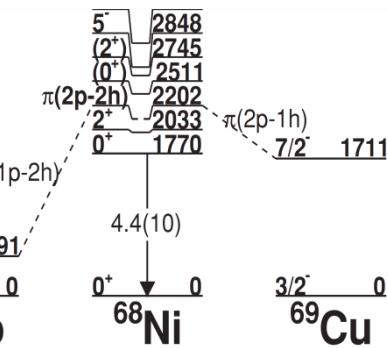
$^{68}_{28} \text{Ni}_{40}$

Lenzi PRC82 (2010)

$\pi \text{ pf} - \nu \text{ pfg}_{9/2} d_{5/2} ({}^{48}\text{Ca core})$

$0^+ 2202$

$\pi(2p-2h)$

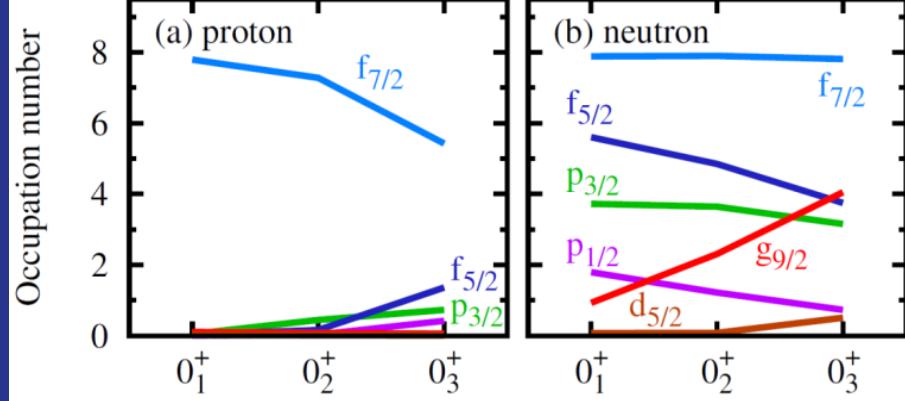
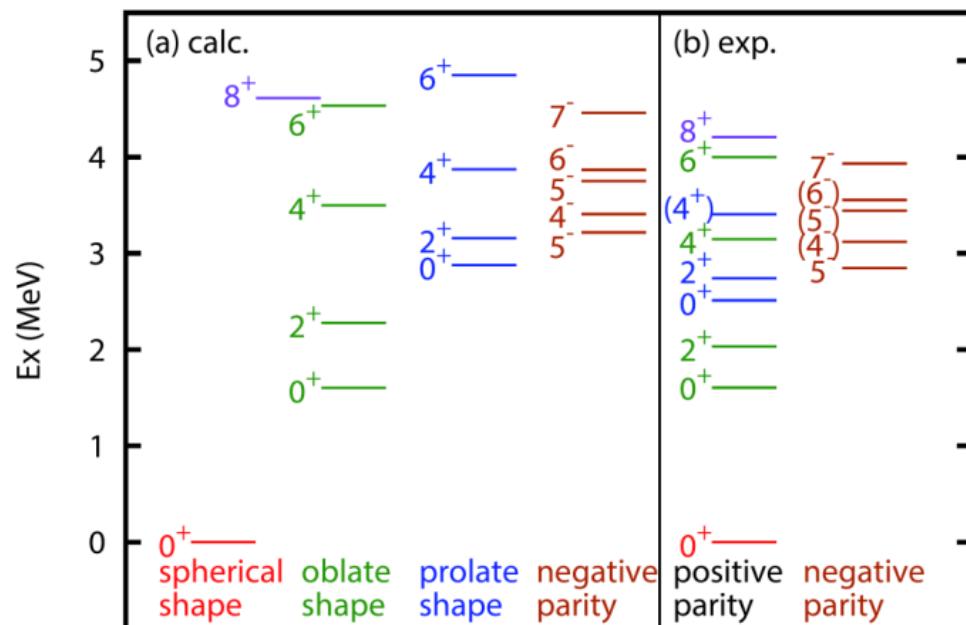
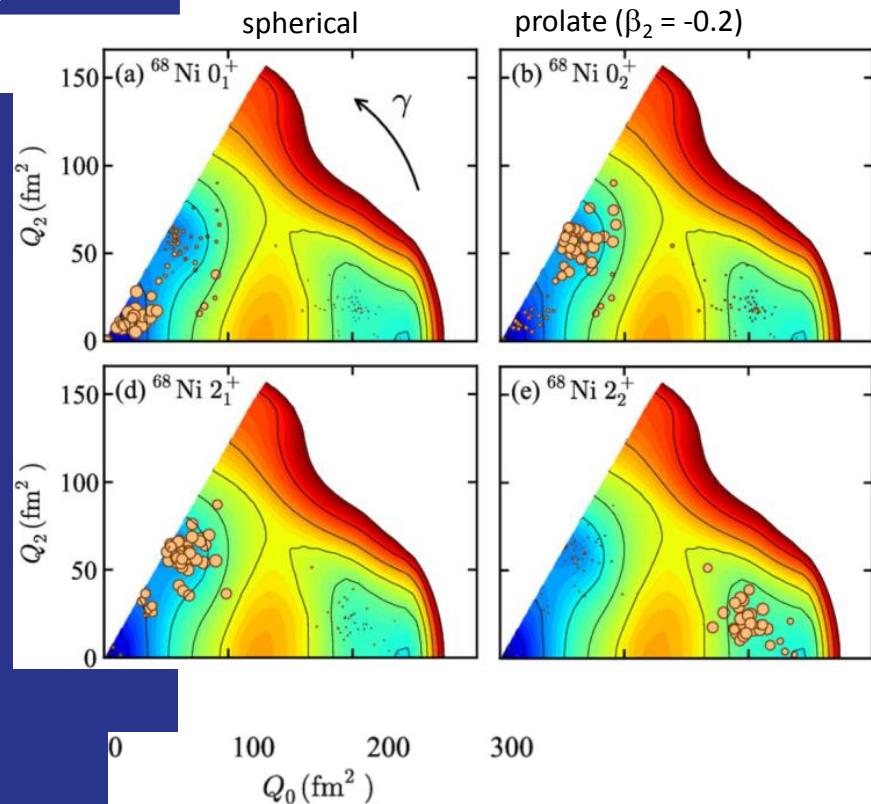


$0^+ 0$

$^{68}_{28} \text{Ni}_{40}$

Pauwels PRC82 (2010)

# MC Shell Model

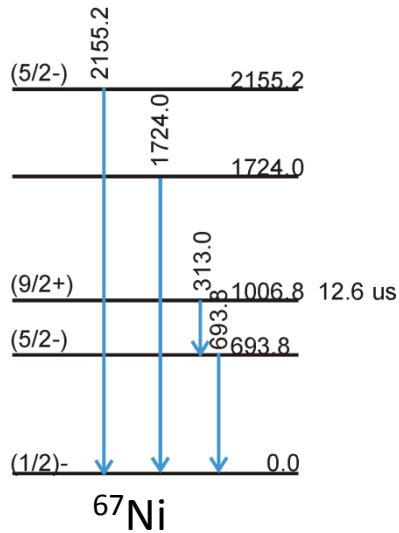


N. Shimizu, T. Otsuka et al. Prog. Theor. Exp. Phys. (2012)  
01A205

# One and two neutron transfer reactions

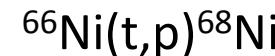


$$Q = 3.58 \text{ MeV}$$

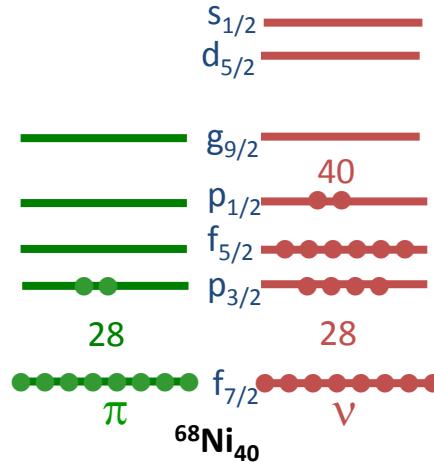


Main aim of experiment:

- Study the ground state structure ( $^{68}\text{Ni} \times n^{-1}$ )
- Determination of spin and parity of excited states (angular momentum - transfer)
- Identification of  $d_{5/2}$  positive parity states (across N=50)



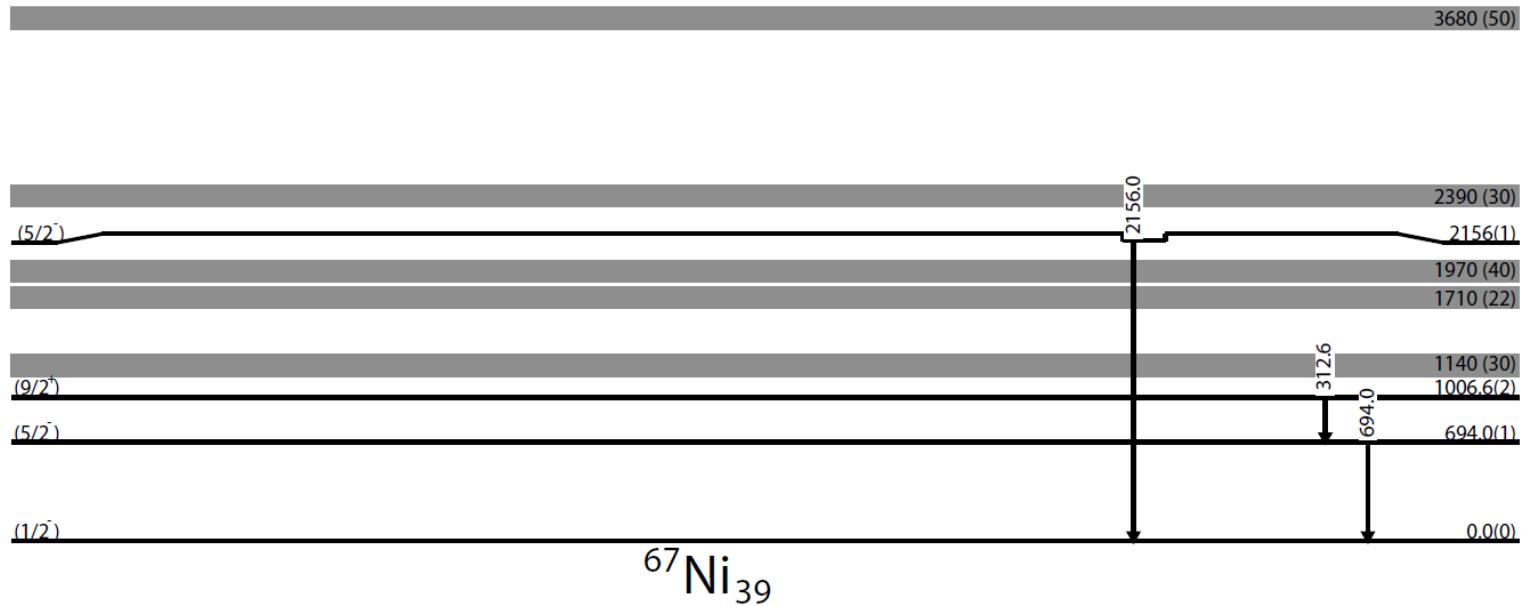
$$Q = 5.12 \text{ MeV}$$



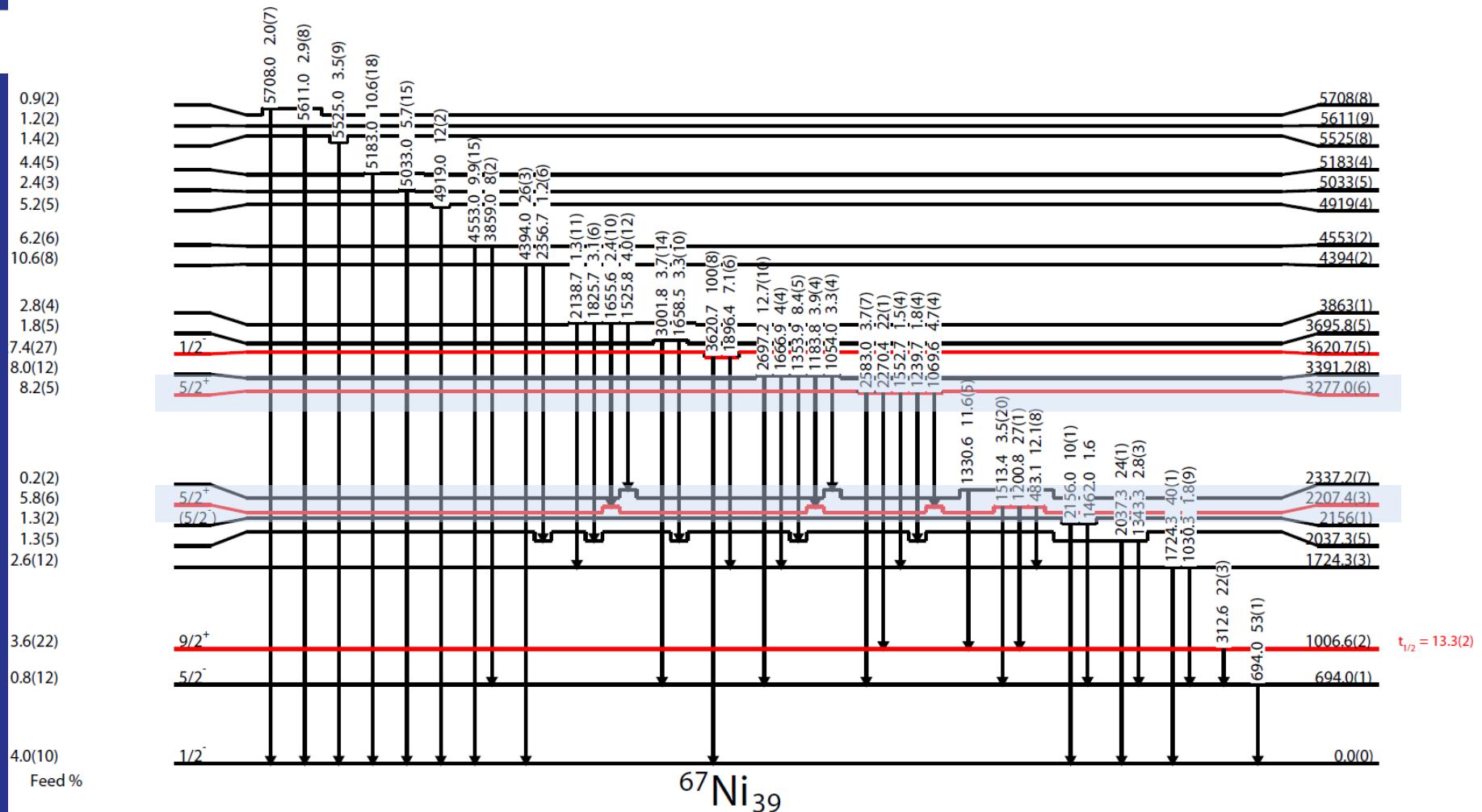
Main aim of experiment:

- Confirm and characterize the  $0^+$  states

# Improved Level Scheme for $^{67}\text{Ni}$

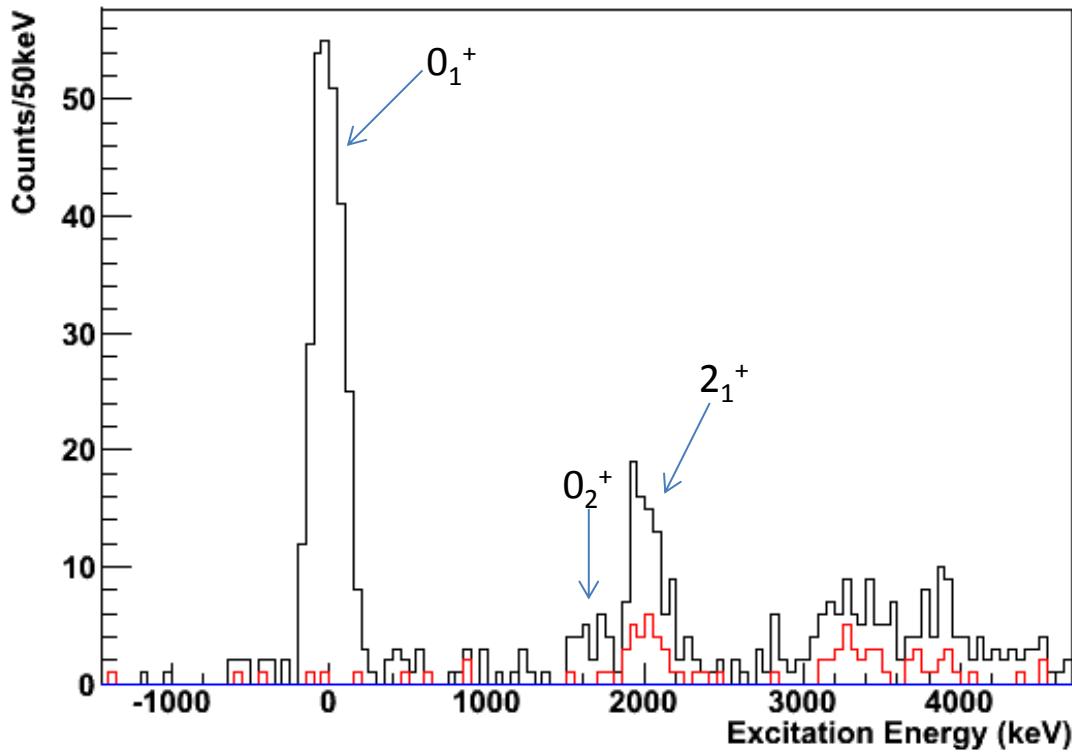


# Improved Level Scheme for $^{67}\text{Ni}$



- Identification of  $5/2^+$  states (neutron excitations above N=50,  $d_{5/2}$ )
- Identified  $d_{5/2}$  and  $s_{1/2}$  single particle strength at low excitation energy → size of the gap 2.6 MeV
  - PhD thesis of Jan Diriken, KULeuven, submitted to PRC

# $^{66}\text{Ni}(\text{t},\text{p})^{68}\text{Ni}$



Black: protons

Red: prompt proton gamma coincidences

Blue: random proton gamma coincidences

- Direct population of  $2_1^+$  state = 30(3)%
- $0_2^+$  at 1662(41)keV
- very weak direct population of  $0_2^+$  state = 5(1)% (relative to 100% gs feeding)

- PhD thesis of Jytte Elsevier, KULeuven

# Perspectives

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Out of the recent results, the  $^{68}\text{Ni}$  case is far to be concluded.

Three pairs of  $O^+$ ,  $2^+$  states identified

Triple shape-coexistence?

We need detailed spectroscopy data of the low spin states: decay properties of the mixed states, precise gamma branching ratios measurements, E0 strength of  $2+ \rightarrow 2+$  and  $0+ \rightarrow 0+$ , E2 and E0 transition strength, lifetime, etc...

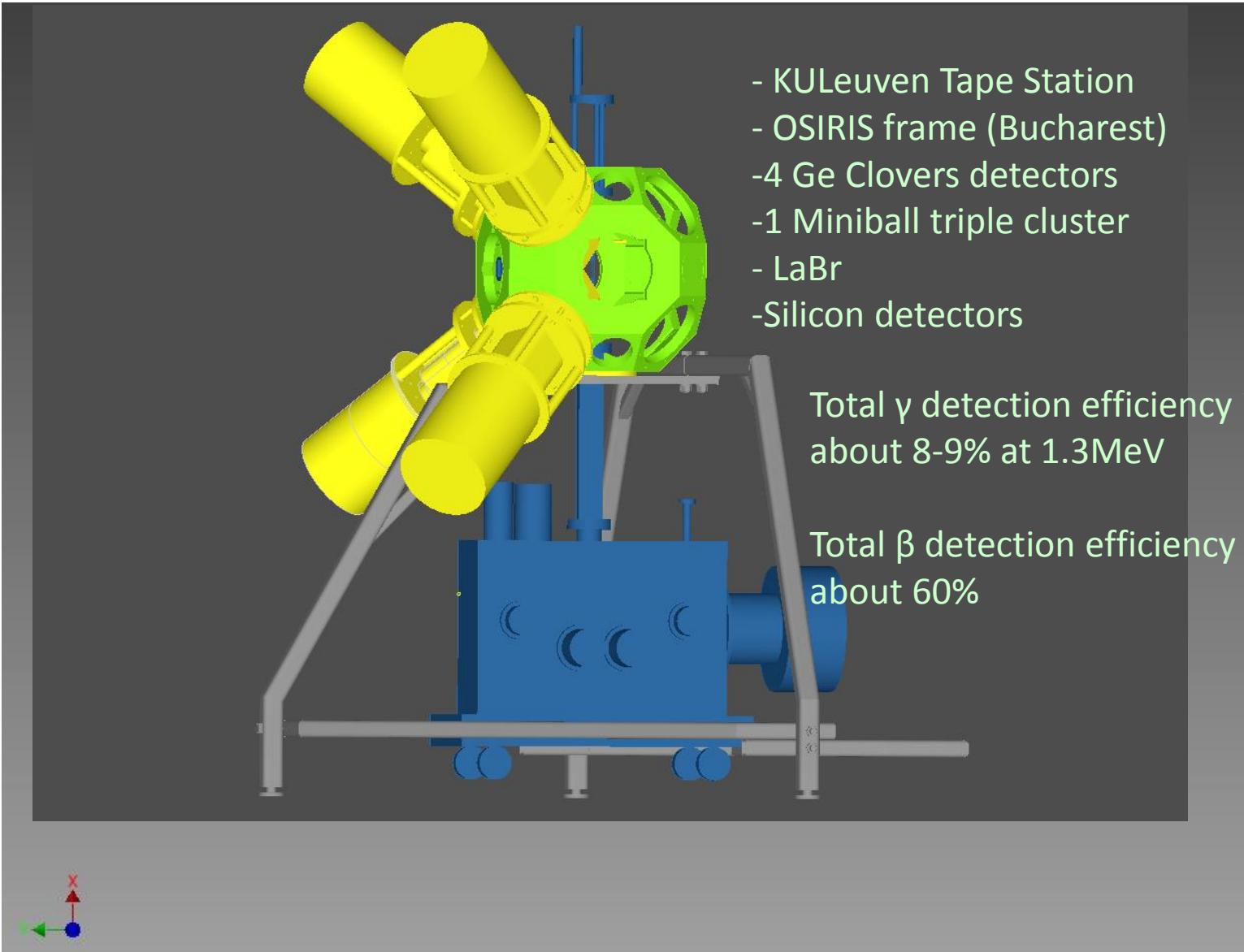
- Additional infos coming from  $^{68}\text{Mn}$  beta-decay data (IS467, KULeuven) and  
 $^{78}\text{Zn}(\text{d},\text{p})^{79}\text{Zn}$  (IS492) → *talk from Riccardo Raabe on Monday*
- New experiments at HIE-ISOLDE in the region of  $^{68}\text{Ni}$ :
  - $^{80}\text{Zn}(\text{d},\text{p})^{81}\text{Zn}$ , [R. Orlandi *et al.*, INTC-2012-051 P-352]
  - $^{70}\text{Ni}(\text{d},\text{p})^{71}\text{Ni}$ , [J.J Valiente Dobon *et al.*, INTC-2012-050 P-351]
  - $^{68}\text{Ni}(\text{d},\text{p})^{69}\text{Ni}$ , [INTC-2013]
  - Coulomb excitation of  $^{68}\text{Ni}$ ,  $^{70}\text{Ni}$  [INTC-2013]
  - Decay of  $^{68}\text{Mn}$  with the new IDS [INTC-2013]
  - LOI “Shape Coexistence in  $^{68}\text{Ni}$  and  $^{70}\text{Ni}$  [INTC-2013]

# Perspectives



Miniball has temporary left ISOLDE to spend  
**HIE-ISOLDE opens new unique opportunities beyond 2014** (August 2013)  
Coulux and transfer reaction have to wait 2015 ;

# Perspectives – Decay Spectroscopy



# Thanks for your attention

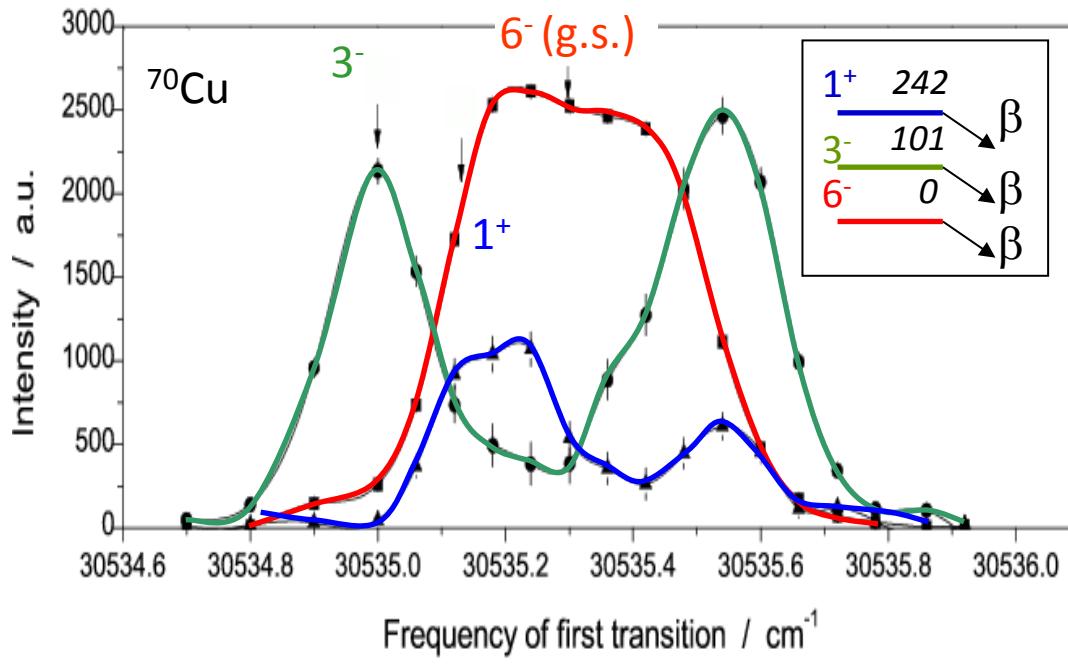


Miniball and the ISOLDE collaboration



# Isomeric Beams from REX-ISOLDE

- technique based on in-source laser spectroscopy  
(Ü. Köster et al., NIM B, 160, 528(2000); L. Weissman et al., PRC65, 024315(2000))
- set the laser frequency to select and maximize the production of the isomer of interest.



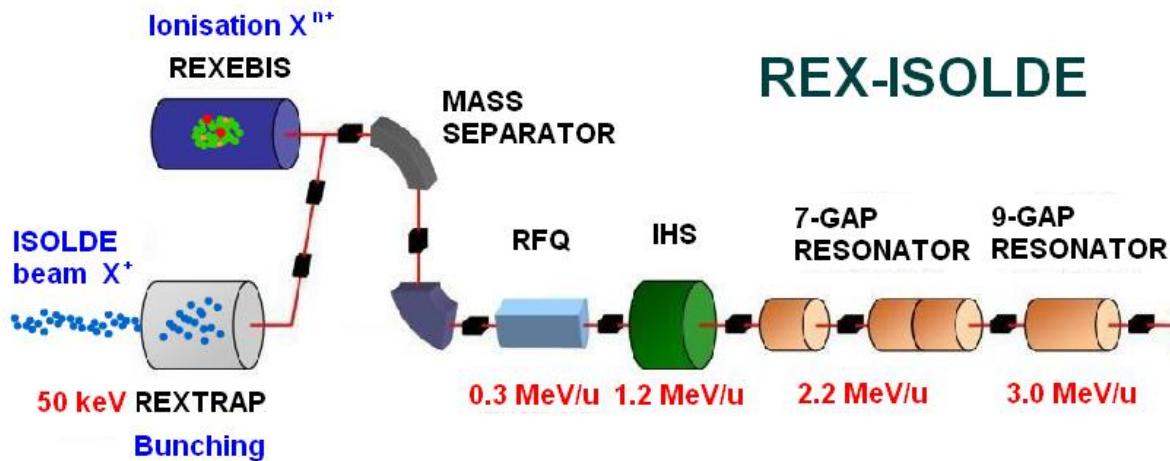
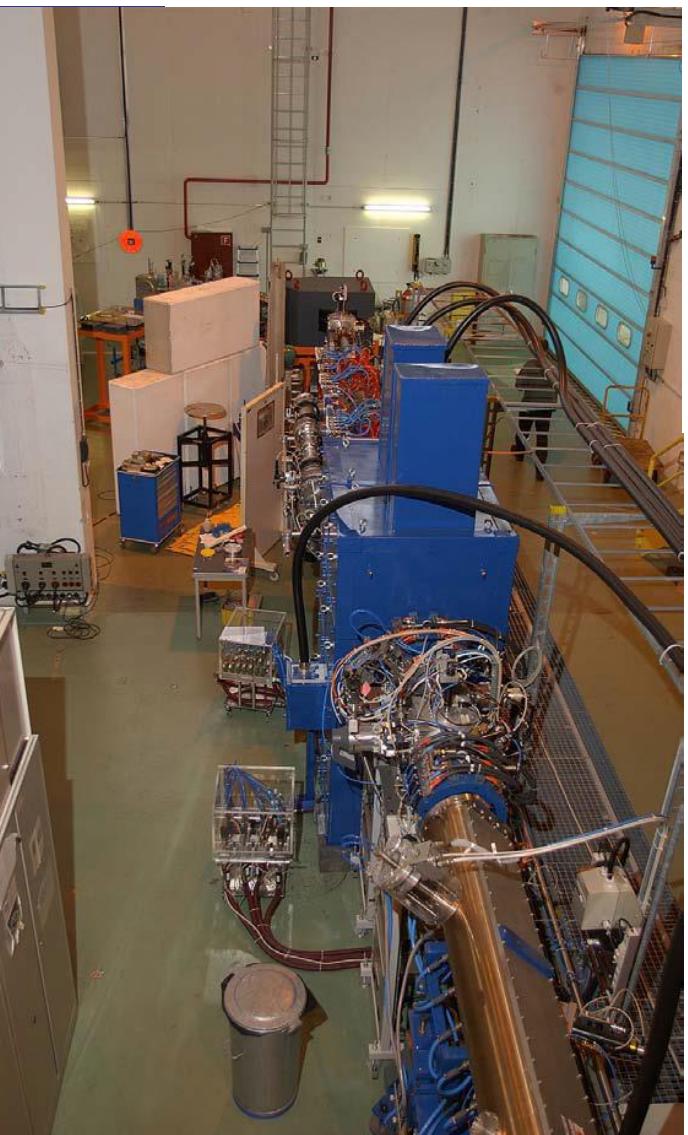
J. Van Roosbroeck et al., PRL92(2004)112501

+ postacceleration by REX-ISOLDE

# Physics Highlights

- Niedermaier,- 2005 Phys. Rev. Lett. 94 172501
- Jeppesen,- 2006 Phys. Lett. B 635 17
- Jeppesen,- 2006 Physics Letters B 642 449
- Stefanescu,- 2007 Phys. Rev. Lett. 98 122701
- Cederkall,- 2007 Phys. Rev. Lett. 98 172501
- Van de Walle,- 2007 Phys. Rev. Lett. 99 142501
- Hurst,- 2007 Phys. Rev. Lett. 98 072501
- Stefanescu,- 2008 Phys. Rev. Lett. 100 112502
- Ekstrom,- 2008 Phys. Rev. Lett. 101 012502
- Di Pietro,- 2010 Phys. Rev. Lett. 105 022701
- Wimmer,- 2010 Phys. Rev. Lett. 105 252501
- Seidlitz,-2011 Phys. Lett. B 700 181
- Alberts, -2012 Phys. Rev. Lett. **108**, 062701
- Gaffney, -2013 Nature 497, 12073

# REX-LINAC



**REX-ISOLDE**

- Wide spectrum of pure radioactive ion beams
- Energy: from ~ rest up to 3 MeV/u

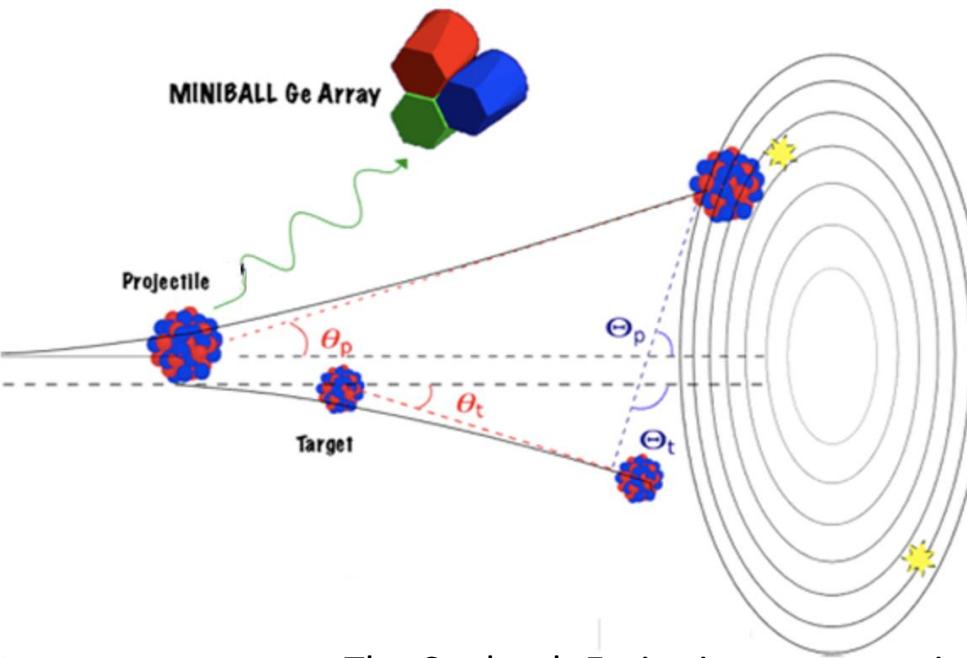
### Post accelerated beams:

$^{8,9,11}\text{Li}$ ,  $^{10-12}\text{Be}$ ,  $^{10}\text{C}$ ,  $^{17}\text{F}$ ,  
 $^{24-29}\text{Na}$ ,  $^{28-32}\text{Mg}$ ,  $^{61,62}\text{Mn}$ ,  
 $^{61}\text{Fe}$ ,  $^{68}\text{Ni}$ ,  
 $^{67-71,73}\text{Cu}$ ,  
 $^{74,76,78,80}\text{Zn}$ ,  $^{70}\text{Se}$ ,  $^{88,92}\text{Kr}$ ,  
 $^{96}\text{Sr}$ ,  $^{108}\text{In}$ ,  $^{106,108,110}\text{Sn}$ ,  
 $^{122,124,126}\text{Cd}$ ,  
 $^{138,140,142,144}\text{Xe}$ ,  $^{140,142,148}\text{Ba}$ ,  $^{148}\text{Pm}$ ,  $^{153}\text{Sm}$ ,  
 $^{156}\text{Eu}$ ,  $^{182,184,186,188}\text{Hg}$ ,  $^{202,204}\text{Rn}$

The energies available at REX-ISOLDE are optimal to exploit Coulomb Excitation and Transfer reactions

# The techniques: Coulomb Excitation

Nuclear excitation by the **electromagnetic interaction** acting between two colliding nuclei.



Target and projectile excitation possible

“Safe” Energy Requirements

Coulomb trajectories only if the colliding nuclei  
do not reach the “Coulomb barrier”

- “SAFE” Coulomb Excitation: purely electromagnetic process, NO nuclear interaction,
- calculable with high precision

The Coulomb Excitation cross-sections are a direct measurement of the matrix elements involved in the excitation

Spectroscopic tool to study single-particle versus collective properties of nuclei

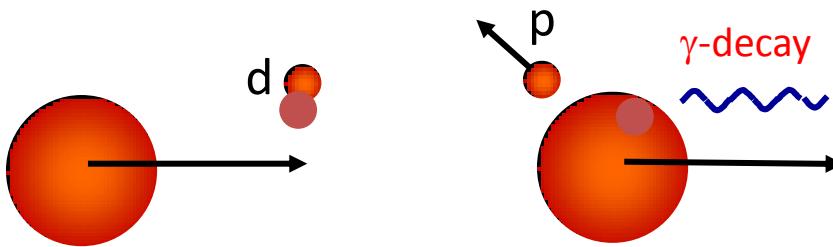
High selectivity to (1) transition with E2 transitions most probable,  
(2) collectivity

Typical reactions: heavy, closed-shell target

Observables

- energies of  $\gamma$ -rays
- Momentum of projectile and recoil target (Doppler shift correction)
- Absolute Excitation cross-section normalized to the known target excitation

# The techniques: Transfer Reaction



Spectroscopic tool to study single-particle properties of nuclei

selectivity to (1) kinematical matching (e.g.  $Q_{\text{opt}} = 0$  for n-transfer)  
(2) nuclear structure

Typical reactions: (d,p), (t,p) ...

RIBs: inverse kinematics

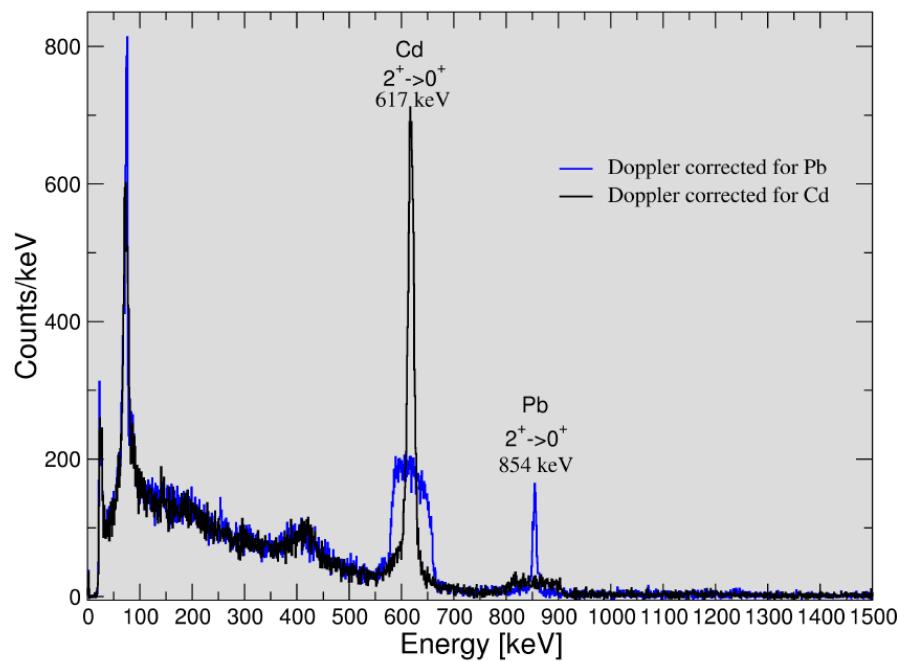
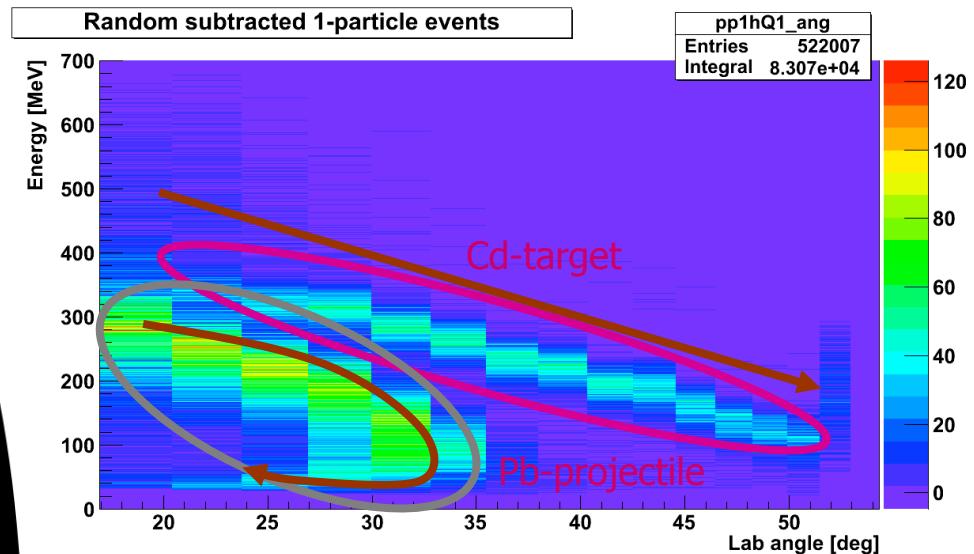
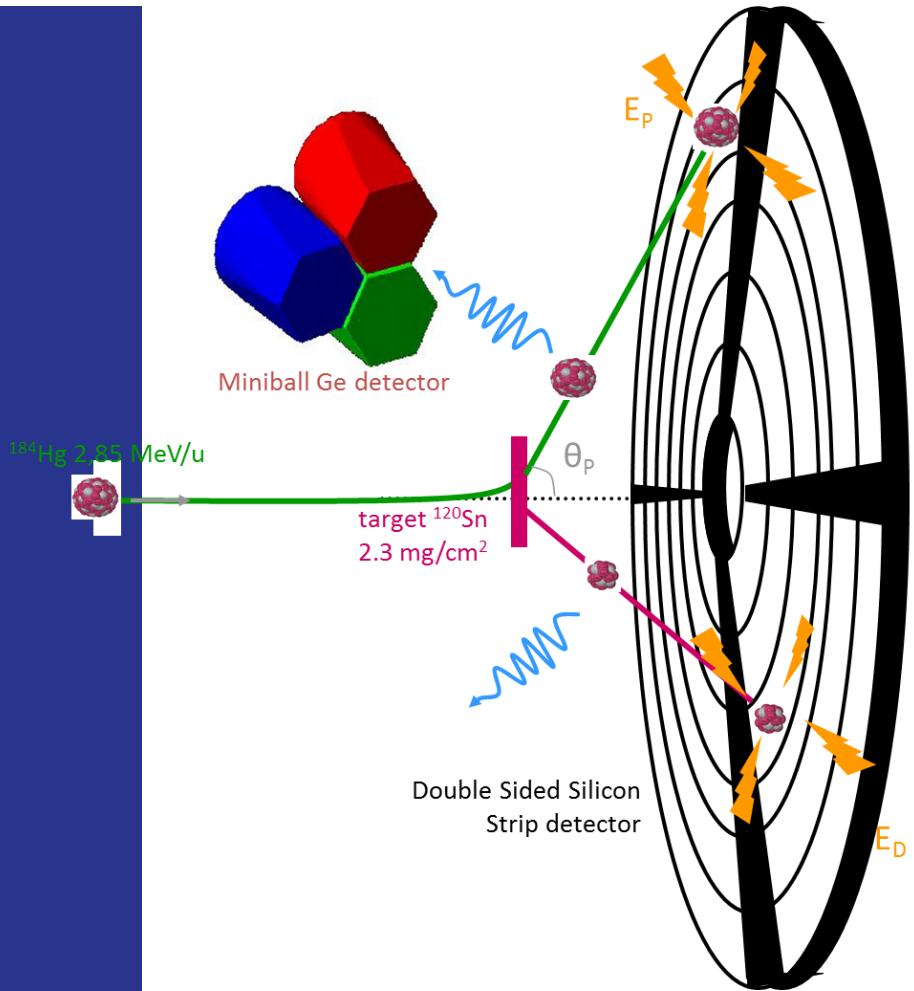
## Observables

- energies of protons (+  $E_\gamma$ )
- angular distributions of protons (+  $\gamma$ -rays)
- (relative) spectroscopic factors

→ (single-particle) level energies  
→ spin/parity assignments  
→ particle configurations

... both, successful tool in nuclear spectroscopy for more than 50 years!!!

# Coulomb Excitation



Courtesy of Janne Pakarinen

# Shell Evolution around Z=28 seen by MINIBALL

N=40 via Coulex and Transfer at MINIBALL

