Study of nucleon transfer and knockout reactions with high-resolution γ-ray spectroscopy

Thorsten Kröll

TECHNISCHE UNIVERSITÄT DARMSTADT

Bundesministerium für Bildung und Forschung

EURONS

ENSAR

HIC for FAIR
Helmholtz International Center

REX-ISOLDE

MINIBALL

Nuclear Structure Physics with Advanced Gamma-Detector Arrays Symposium NSP13
Padova 10-12 June 2013

Support by BMBF (Nr. 06DA9036I, 05P12RDCIA, 05P12RDFN8), EU through EURONS (No. 506065) and ENSAR (No. 262010), HIC for FAIR, and the MINIBALL/REX-ISOLDE collaborations

Sidereus Nuncius - 1610

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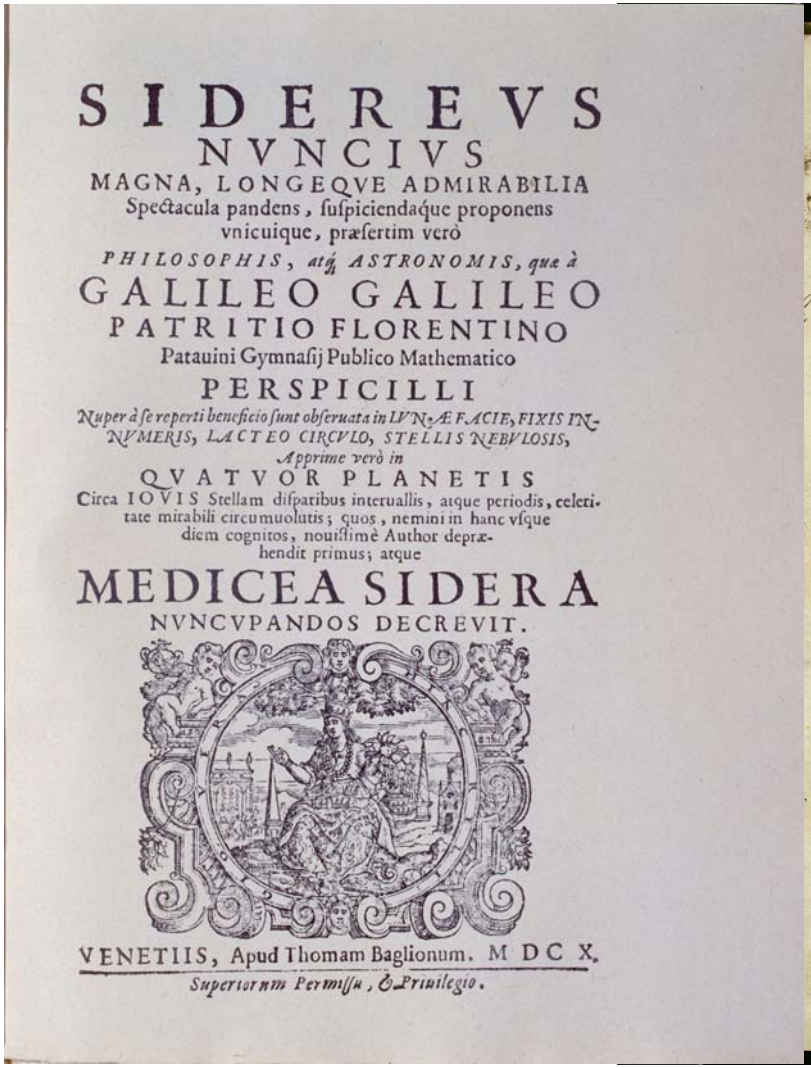
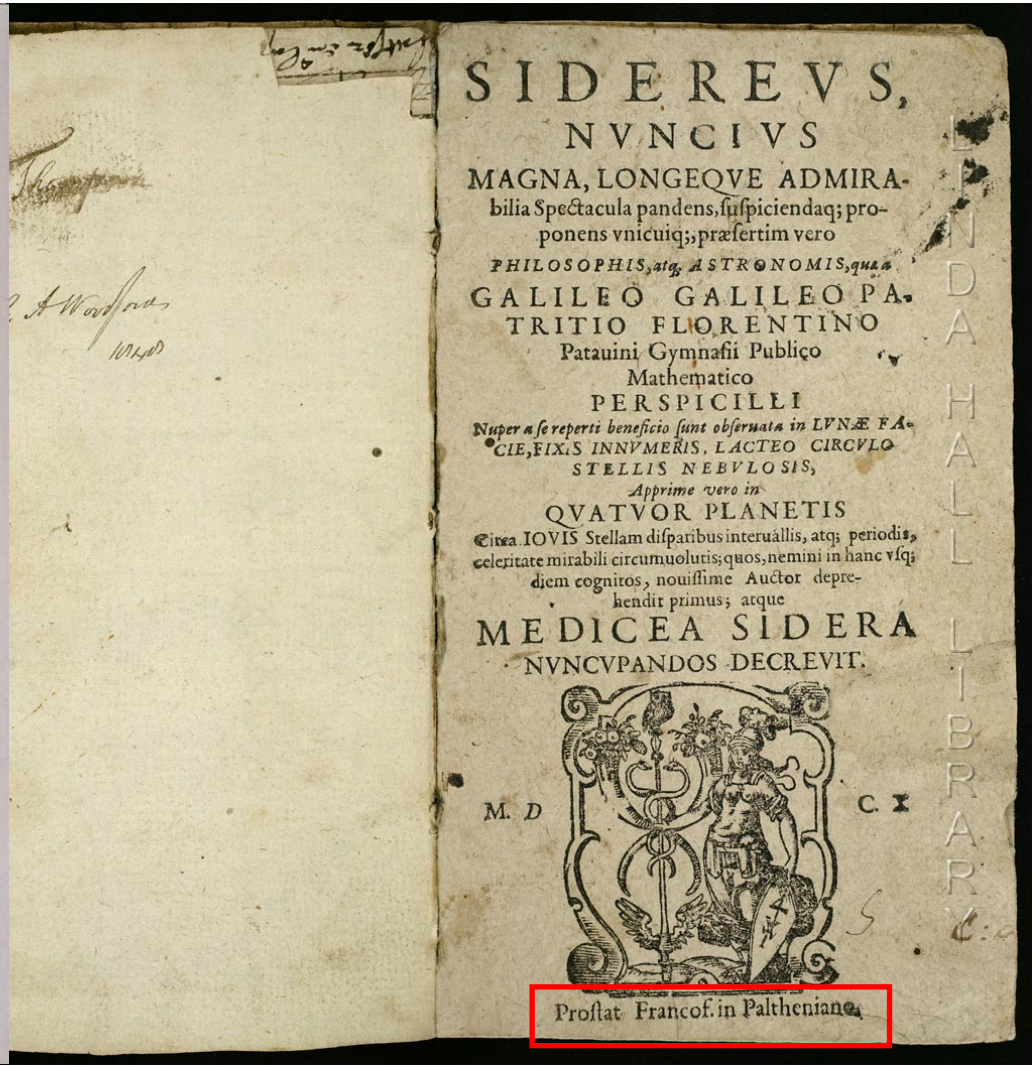


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, ſuſpiciendaque proponens
vnicuique, præſertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnaſij Publico Mathematico
PERSPICILLI
Nuper à ſe reperti beneficio ſunt obſeruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam diſparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vſque
diem cognitos, nouiſſimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permiſſu, & Priuilegio.



SIDEREVS,
NVNCIVS
MAGNA, LONGEQVE ADMIRA-
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ponens vnicuiq;, præſertim vero
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celeritate mirabili circumuolutis; quos, nemini in hanc vſq;
diem cognitos, nouiſſime Auctor depre-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

M. D C. X

Proſtat Francof. in Paltheniana.

Transfer and knockout reactions

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Nucleon transfer and knockout reactions
... not only production mechanism for exotic nuclei

Spectroscopic tool to study single-particle properties of nuclei
selectivity to (1) kinematical matching (e.g. $Q_{opt} = 0$ for n-transfer)
(2) nuclear structure

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} \propto \left|\left\langle \psi_f \left| \breve{O} \right| \psi_i \right\rangle\right|^2 \left(\frac{d\sigma}{d\Omega}(n,\ell;E,Q)\right)_{\text{theo}}$$

Nuclear structure
- spectroscopic factors
- ANCs
- ...

Reaction theory
- DWBA, CCBA
- eikonal
- ...

Combination with high-resolution γ-ray arrays
- **exclusive measurements**
- **additional information from γ-ray spectroscopy**

Light-ion induced transfer reactions

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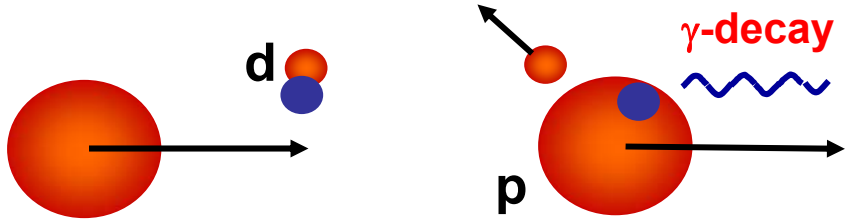

Typical reactions: (d,p), (t,p) …
RIBs: inverse kinematics

Observables

- energies of protons (+ E_γ)
- angular distributions of protons (+ γ-rays)
- (relative) spectroscopic factors

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

Conceptional limitations

- only sensitive to nuclear surface
- phenomenological description (DWBA, optical potentials)
- quenching of SF's … probes validity of IPMs, like shell model

… however, successful tool in nuclear spectroscopy for more than 50 years!!!

Experimental set-up: T-REX & MINIBALL

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Si detector array for Transfer reactions at REX-ISOLDE

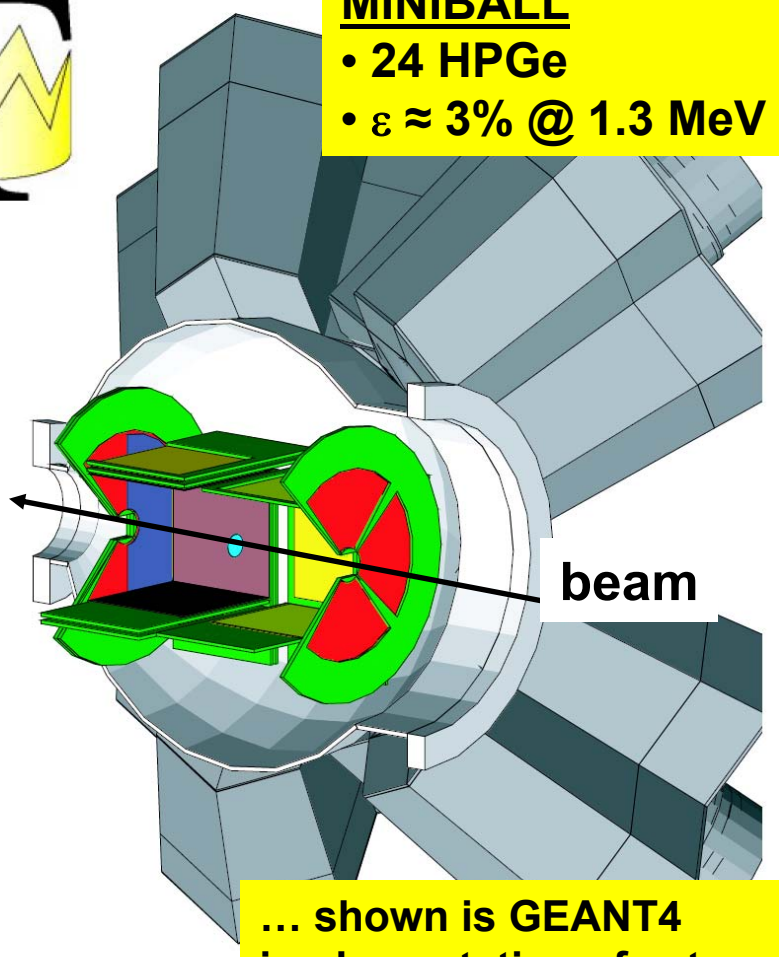
Requirements
- large solid angle
- position sensitive
- PID (ΔE-E):
  p, d, t, α, e^-(!!!), …

Implementation

Barrel:	140 μm ΔE (RSSD)
	1000 μm E
Forward CD:	500 μm ΔE (DSSSD)
	1500 μm E
Backward CD:	140 μm ΔE (DSSSD)
	500 μm E

V. Bildstein et al., Eur. Phys. J A 48, 85 (2012)

MINIBALL
- 24 HPGe
- ε ≈ 3% @ 1.3 MeV



… shown is GEANT4 implementation of set-up

Experimental set-up: T-REX & MINIBALL

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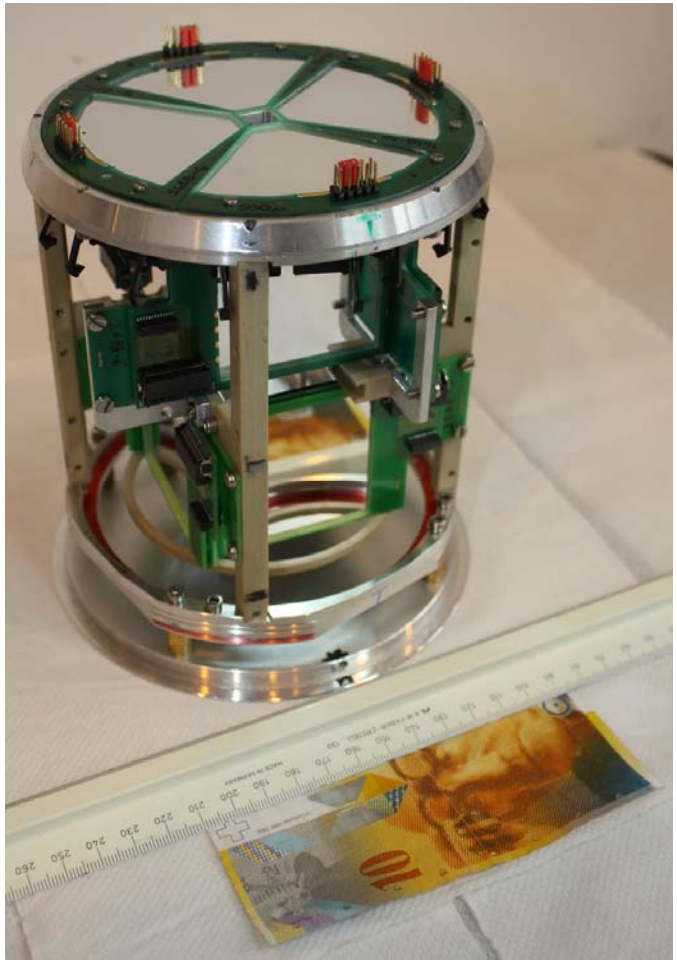
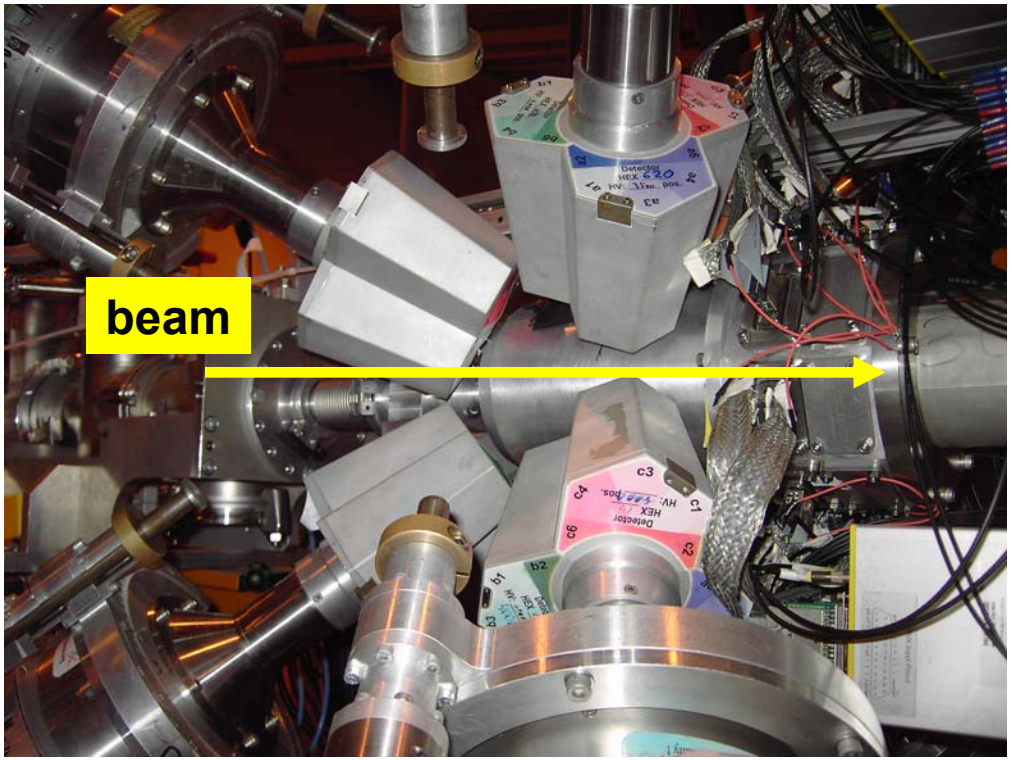




Shore of the island of inversion

… 35 years after its discovery

C. Thibault et al., Phys. Rev. C 12, 644 (1975)

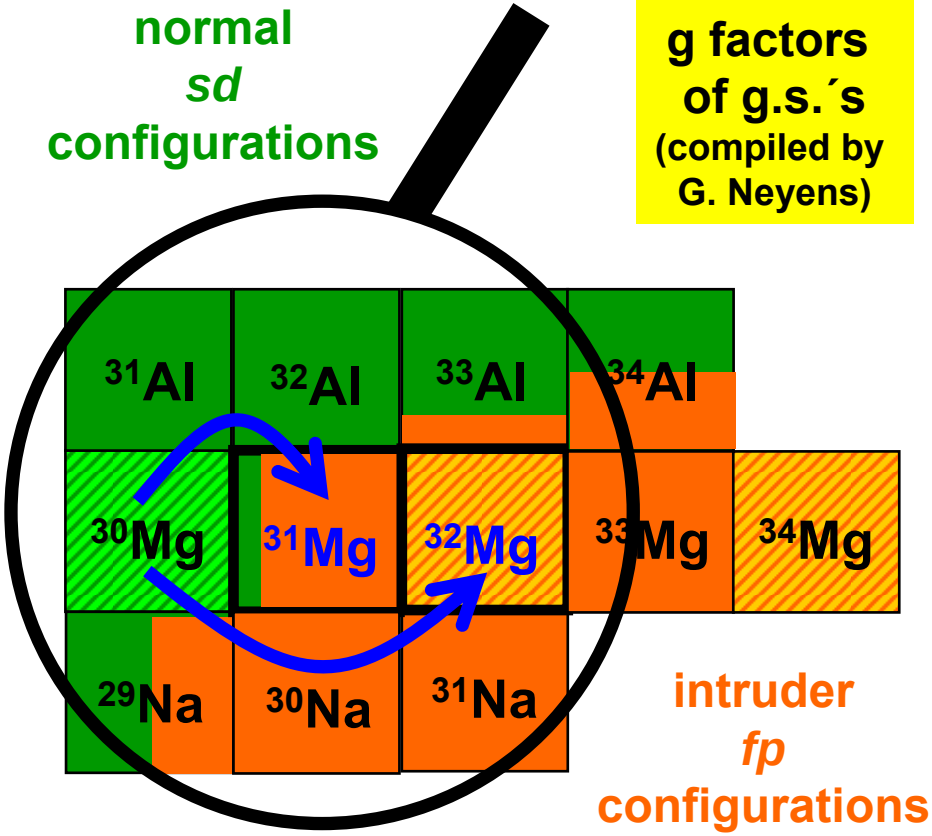
- Competing *sd* and *fp* configurations
- Disappearance of shell closure at N=20

… physics case seems to be reasonably well understood???

Still open questions!!!

normal *sd* configurations

g factors of g.s.´s (compiled by G. Neyens)



intruder *fp* configurations

Our first experiments:
^{2,3}H (^{30}Mg, ^{31,32}Mg) ^{1}H

Shape coexistence at the shore of the island of inversion - the second 0^+ in ^{32}Mg

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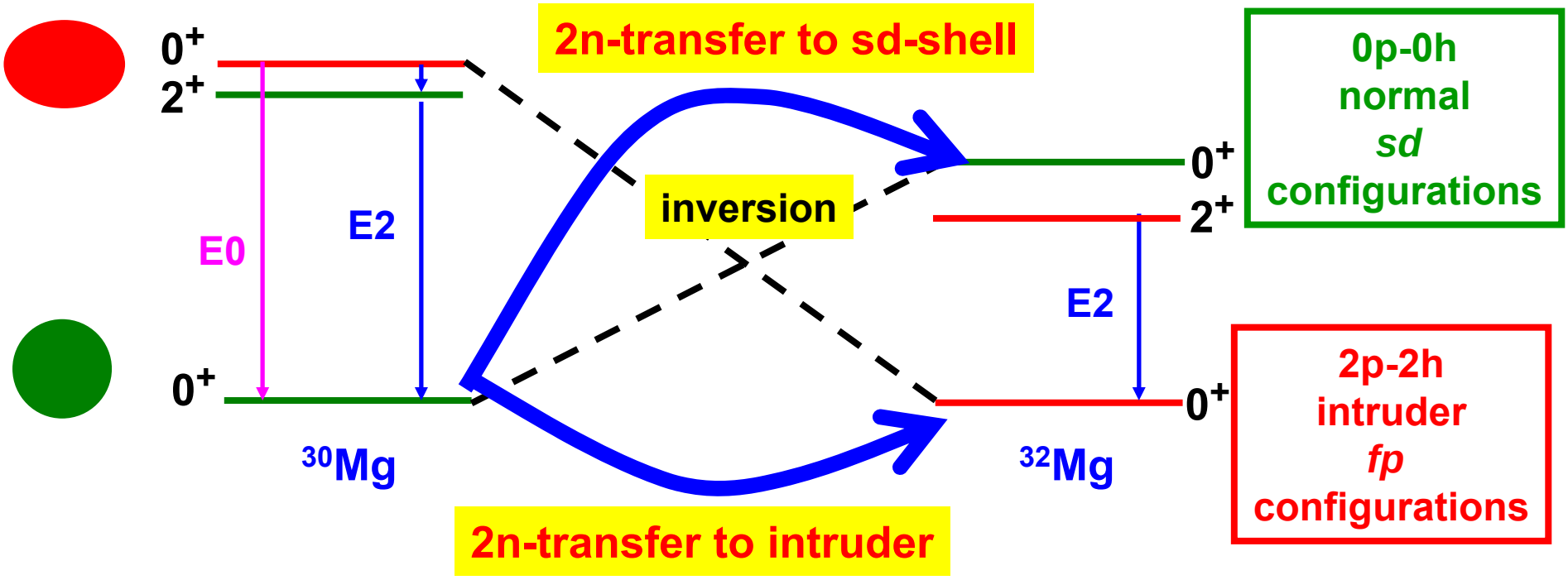
Coexistence of spherical and deformed states



Similar particle-hole configurations ⇔ large overlap of wave functions
➔ large spectroscopic factor for transfer

t(^{30}Mg, ^{32}Mg)p – two-neutron transfer

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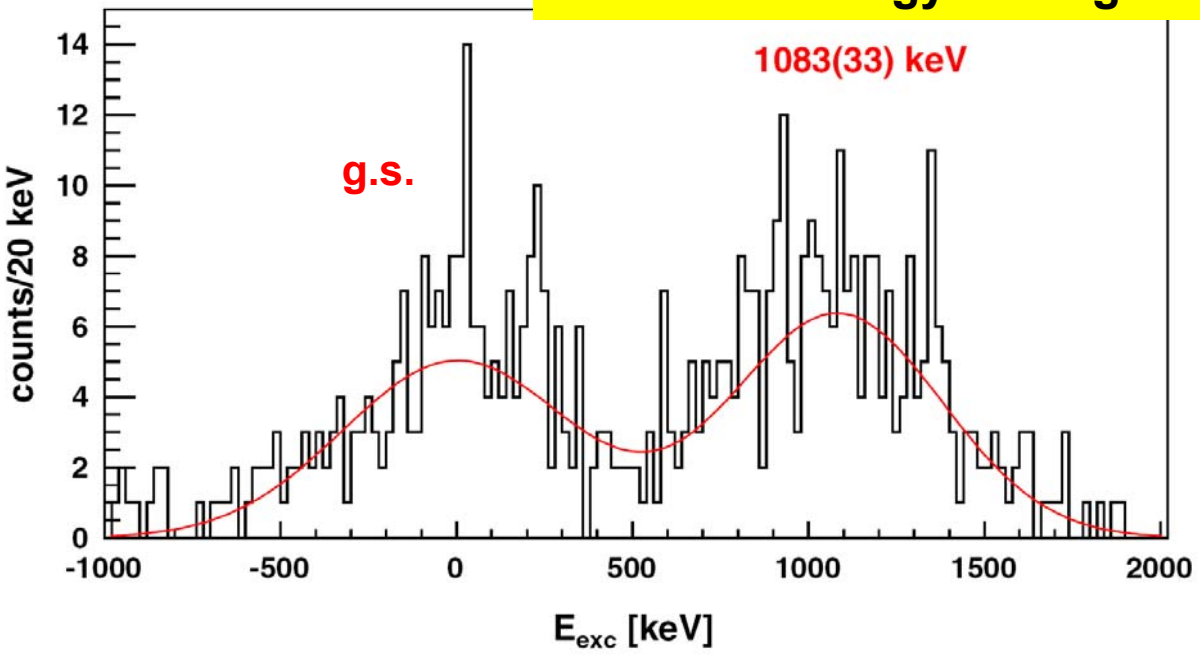
- ^{3}H loaded Ti foil (40 μg/cm^2 ^{3}H, 10 GBq)
- ^{30}Mg beam ($T_{1/2}$ = 335 ms)
- E_{beam} = 1.8 MeV/u (to avoid fusion with Ti!!)
- 4·10^4 part/s / 150 h beam on target
- Q_{00} = -295(20) keV

Kinematically reconstructed excitation energy in ^{32}Mg



- Moderate resolution due to kinematics
- Two states populated: ground state and <u>new state at 1083(33) keV</u> … candidate for the second 0$^+$ state!!!

Kathrin Wimmer (PhD, TU München 2010)
PRL 105, 252501 (2010)

^{32}Mg – coincident γ-ray spectrum

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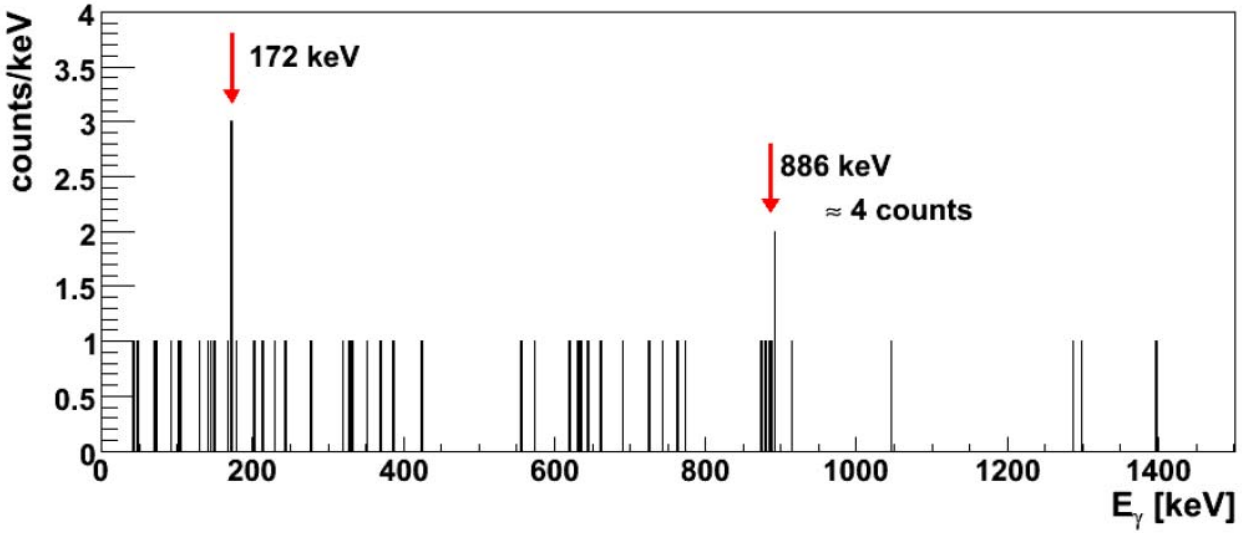
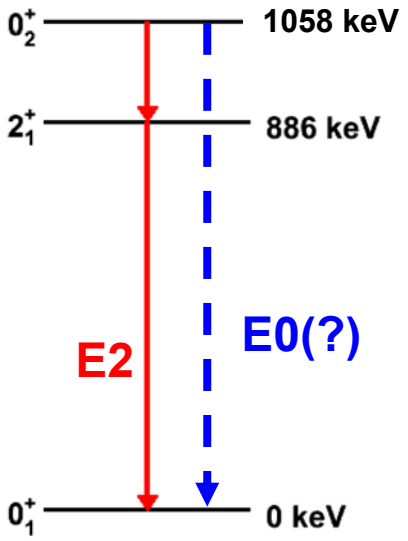
- Coincidence with population of 1083 ± 33 keV state
- Doppler correction assuming θ(^{32}Mg)=0°





- NO strong $2^+ \rightarrow 0^+$ transition
  - no direct population of 2^+ state ... protons only from transfer to 0^+ states
  - E_γ=172 keV → E(0^+) = 1058 keV → 2^+ … consistent with 1083 ± 33 keV
    estimated γ-ray yield : 18(3) counts
    ➔ state decays outside of MINIBALL … rough estimate τ > 10 ns

Transfer to excited 0^+ state in ^{32}Mg

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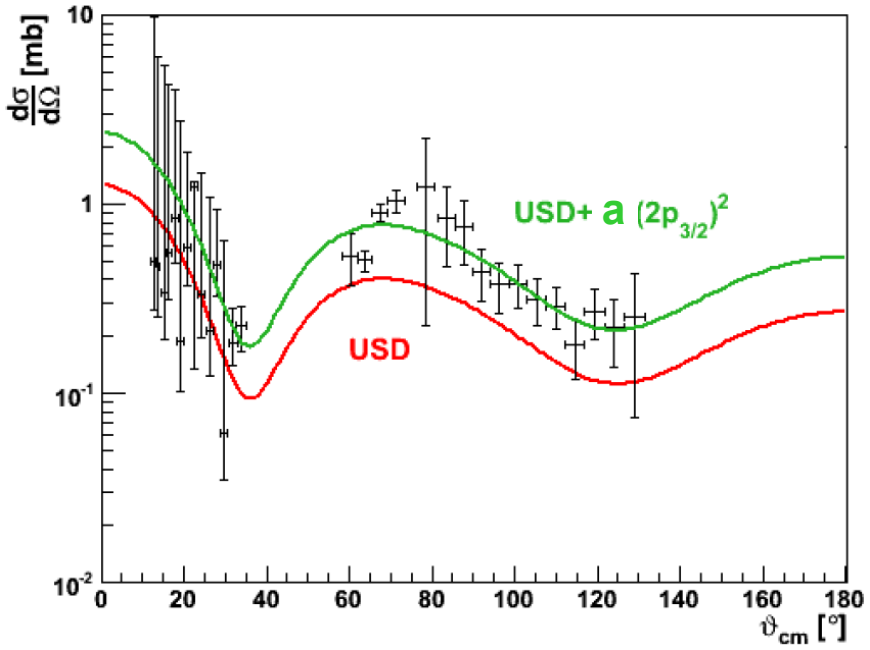
Angular distribution of protons



Wave function similar to g.s. in ^{30}Mg

Two-neutron spectroscopic amplitudes for pure sd → sd transitions calculated with USD interaction

- **cross section underestimated**
- **small $(p_{3/2})^2$ amplitude ($a \approx 0.3$) has to be added**

… observed also in neutron knockout from ^{30}Mg

J. R. Terry et al., PRC 77, 014316 (2008)

Challenge for theory: explain <u>both observations</u>

- **(large) cross section ... excludes 4p-4h configurations etc.**
- **low excitation energy ... only reproduced assuming very deformed state**

d(^{66}Ni,^{67}Ni)p – the ^{68}Ni region (N=40)

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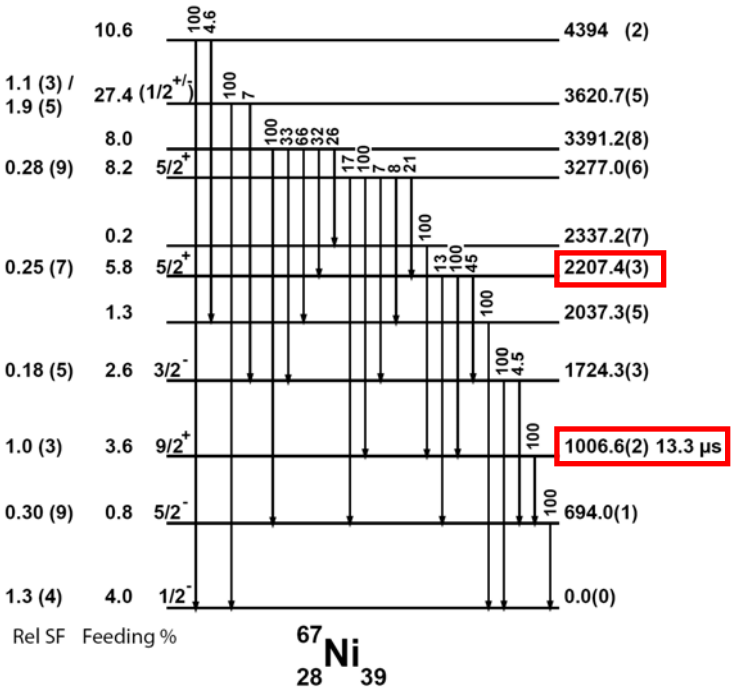
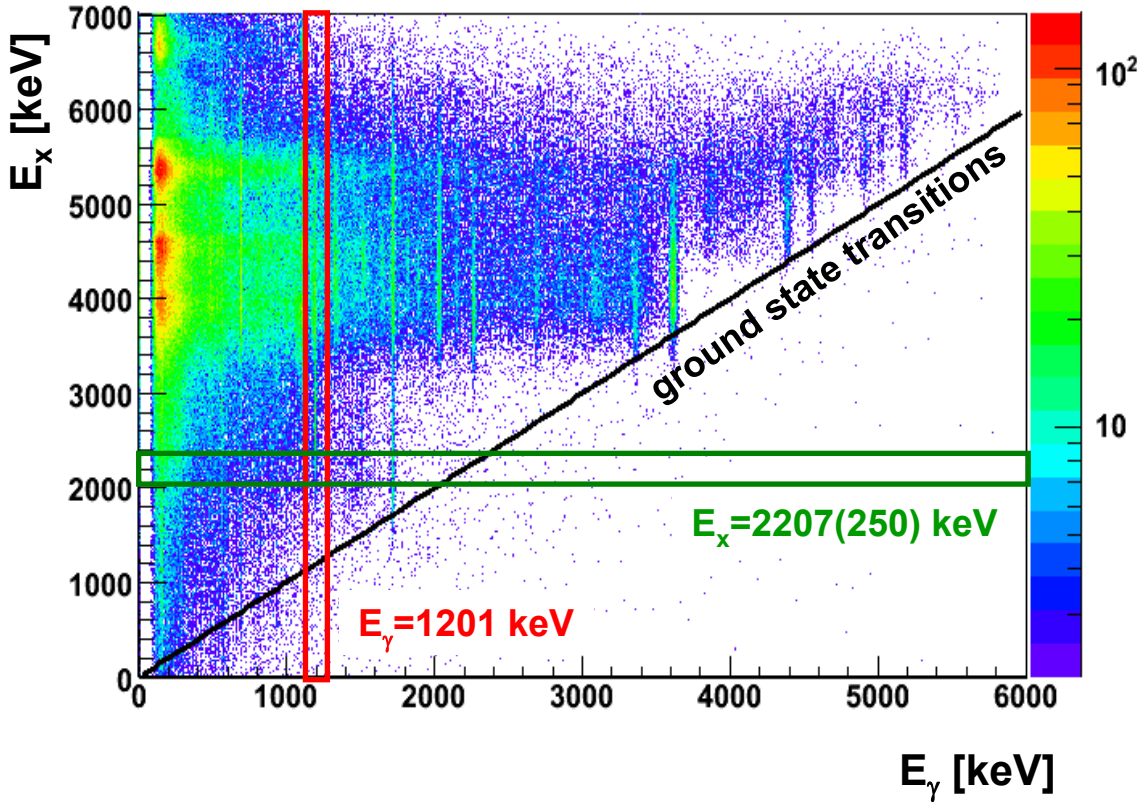
… MINIBALL needed to resolve states!





Jan Diriken
(PhD project at KU Leuven)

d(^{66}Ni,^{67}Ni)p – the ^{68}Ni region (N=40)

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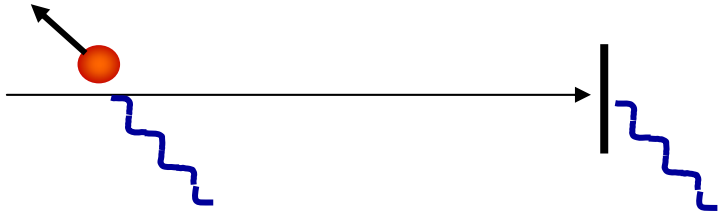
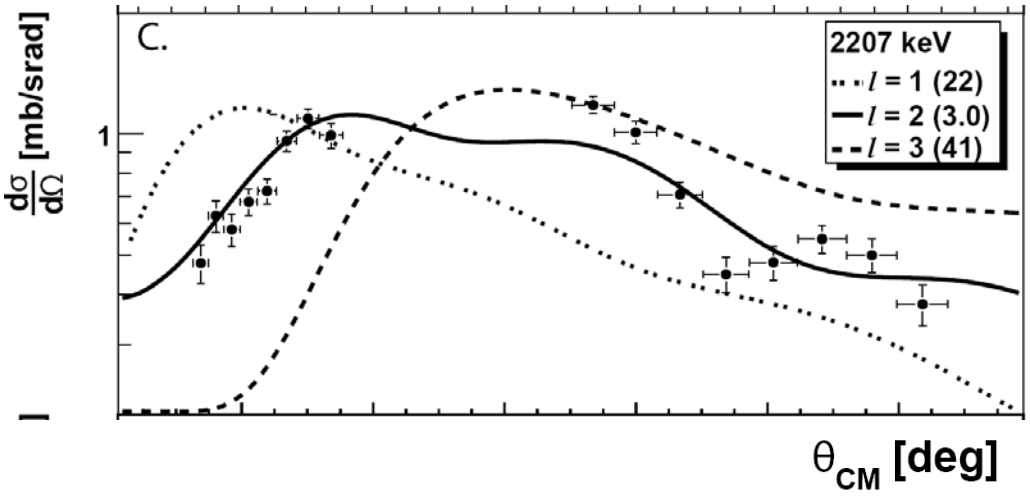
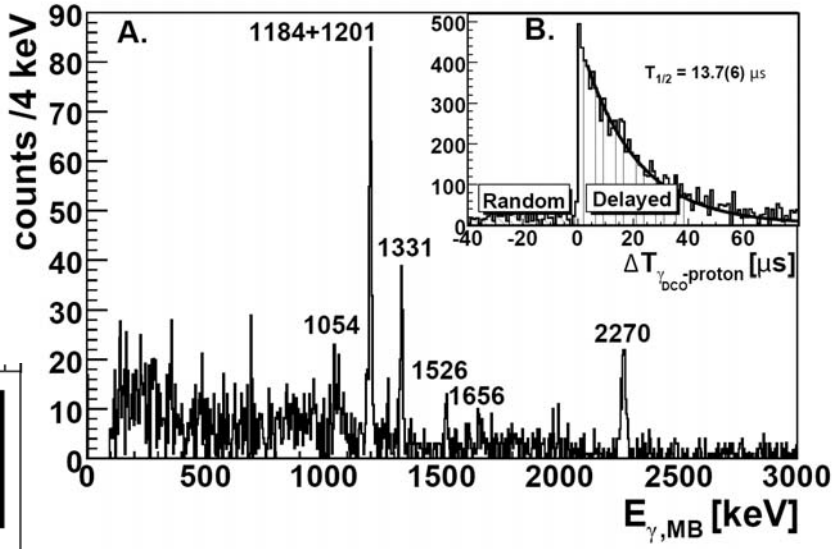


Isomer tagging:
$W_p(\Theta)$ - γ_{prompt} - $\gamma_{delayed}$



Prompt γs gated by decay of isomer



- ΔL=2 clearly favoured
- strong γ-transition to 9/2$^+$ ...

➔ **spin/parity I$^\pi$ = 5/2$^+$**

- SF ≈ 0.25 (rel. to 9/2$^+$)

Jan Diriken (PhD, KU Leuven)
submitted to PRL

t(^{66}Ni,^{68}Ni)p … weak evidence for population of second 0$^+$

… towards HIE-ISOLDE

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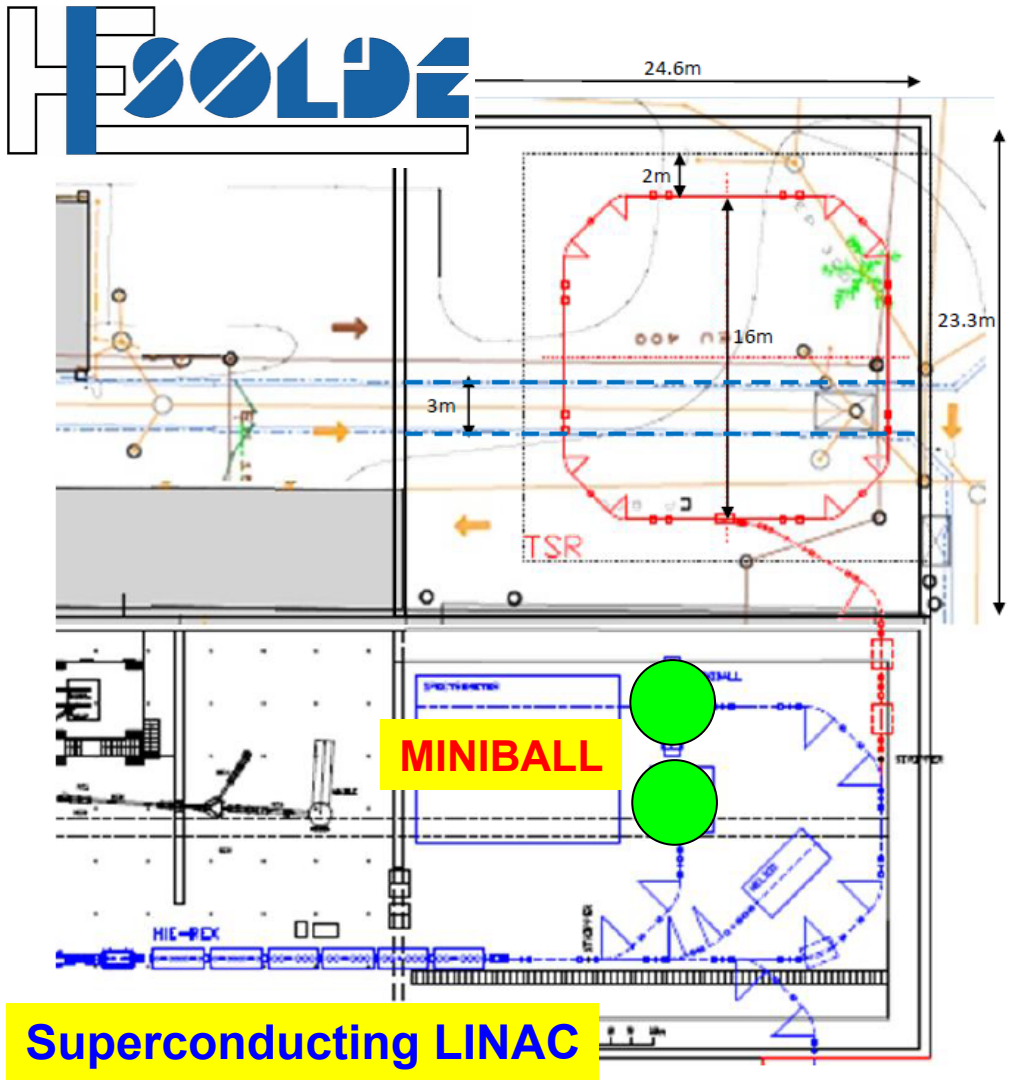

Stepwise upgrade to 5.5 MeV/u ...10 MeV/u

- **higher intensities**
- **better beam quality / purity**

Set-up 2013 … 2018 (LINAC4)

Extension of physics programme, e.g. A≈200

… as low-energy beams unique to ISOLDE

- **transfer reactions … pronounced angular distributions**

New opportunity: Transfer reactions in storage ring TSR with internal target

Shell closures at N=28,32,34

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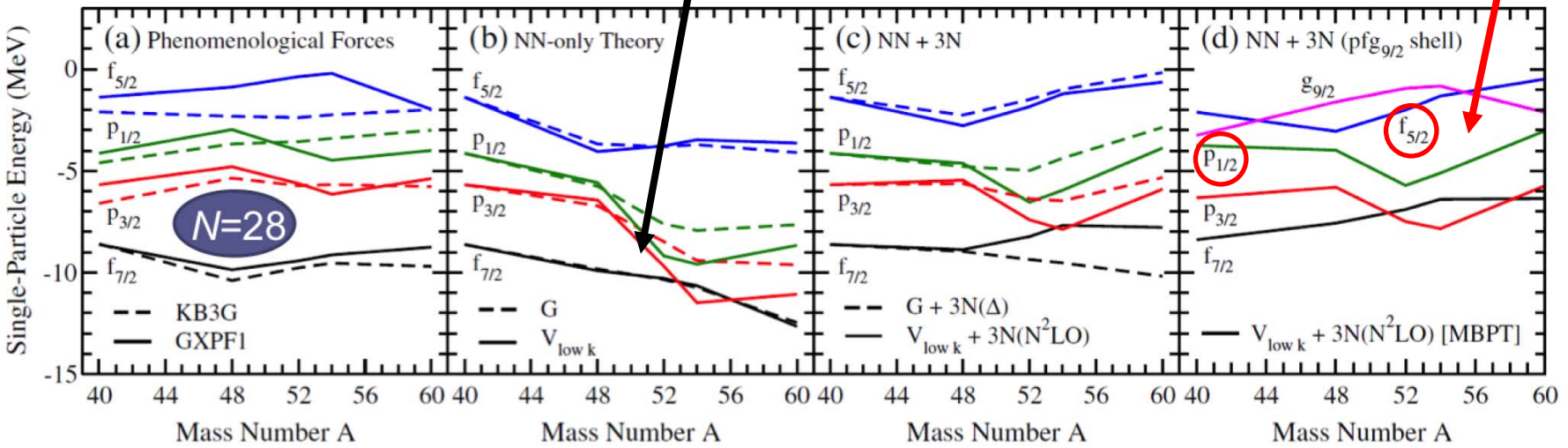
Phenomenological and realistic interactions ➔ different predictions

NO shell closure at N=28!!

NEW shell closure at N=34!!



M. Honma *et al.*,
PRC 65, 061301 (2002)
EPJA 25, 499 (2005)

J.D. Holt et al., J. Phys. G **39** (2012) 085111

Beyond Mean Field: N=32 **T. R. Rodríguez, J.L. Egido, PRL 99, 062501 (2007)**

Neutron knockout from ^{56}Ti (N=34)

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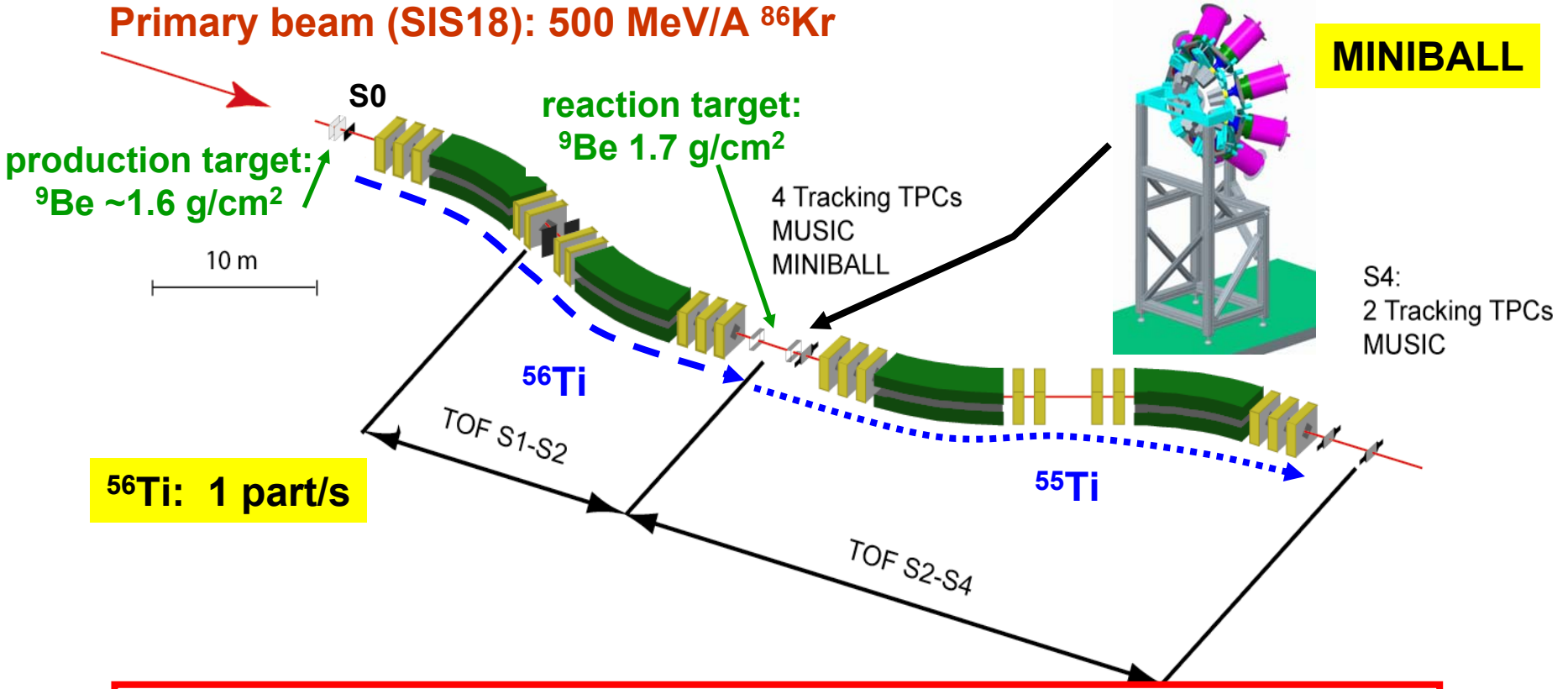
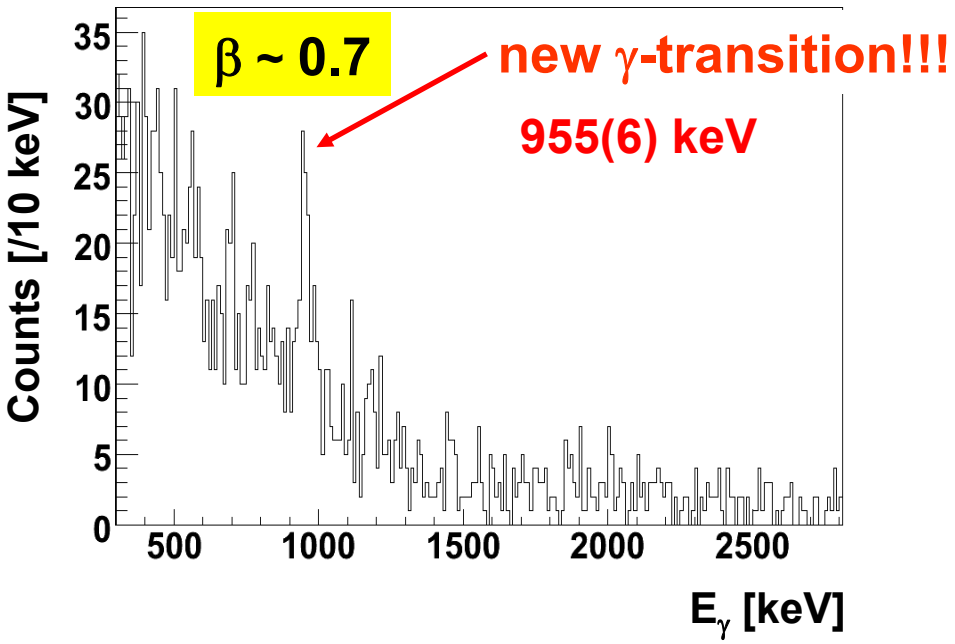


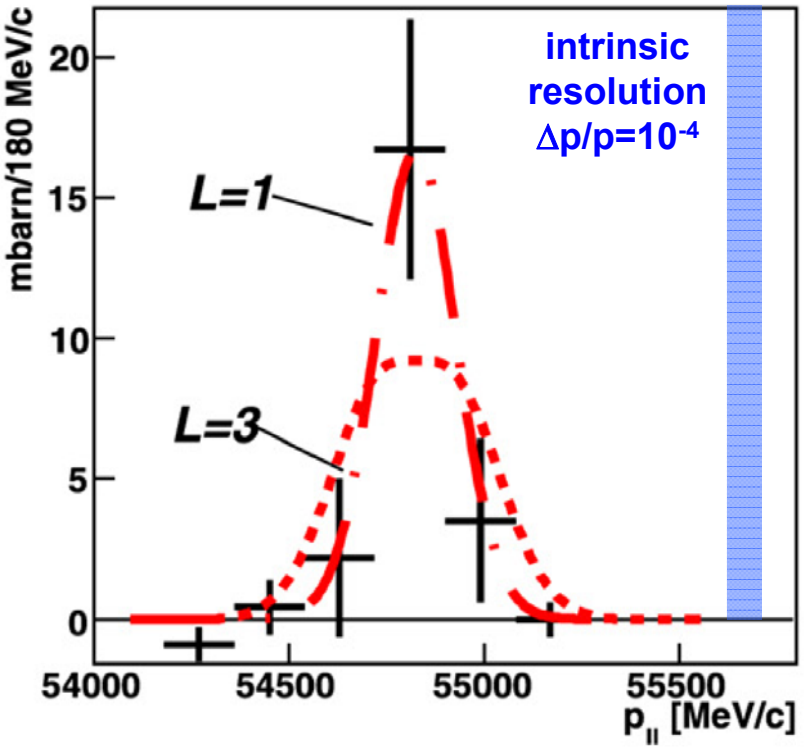
- Event-by-event identification of primary and secondary fragment
- Parallel momentum of secondary fragment
- γ-rays from decay of excited states ➔ exclusive measurement
- Assumptions of reaction theory best fulfilled at GSI energies

New excited state in ^{55}Ti

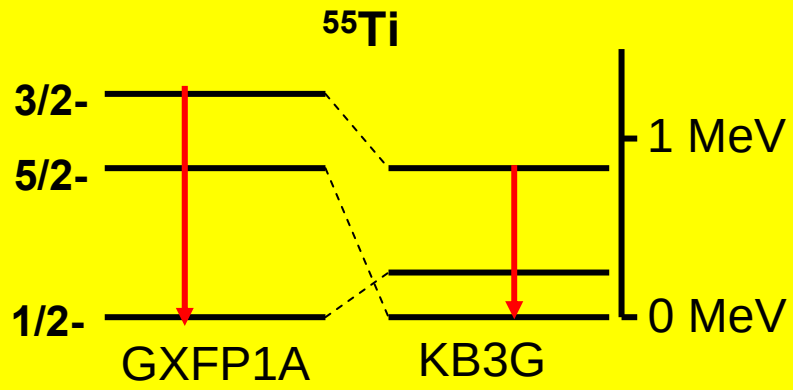


- ΔL=1 is favoured
- Neutron from $p_{1/2}$ or $p_{3/2}$
- From comparison with theory
  ➔ $I^\pi = 3/2^-$

Exclusive momentum distribution

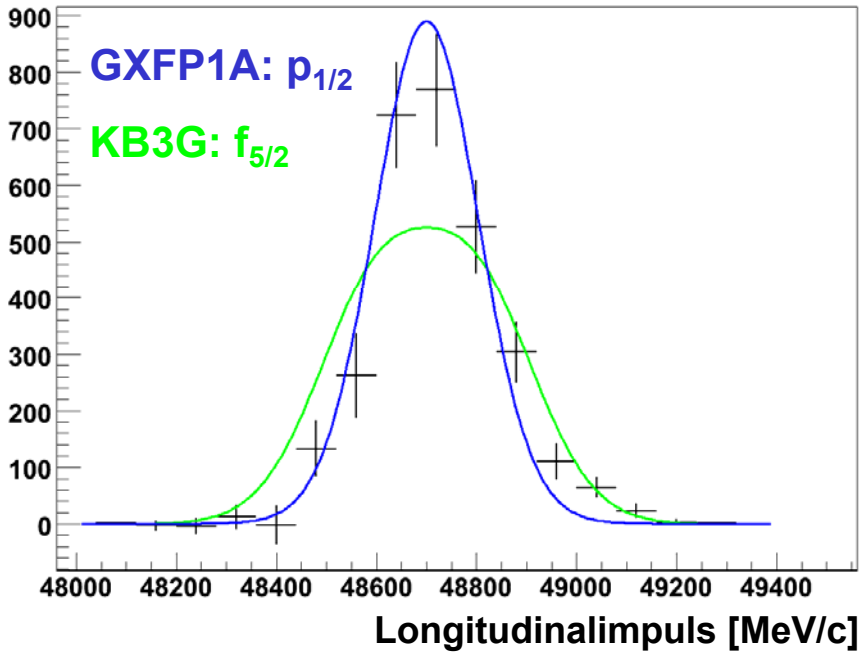


New shell closure at N=34



M. Honma et al., EPJ A25, 499 (2005)

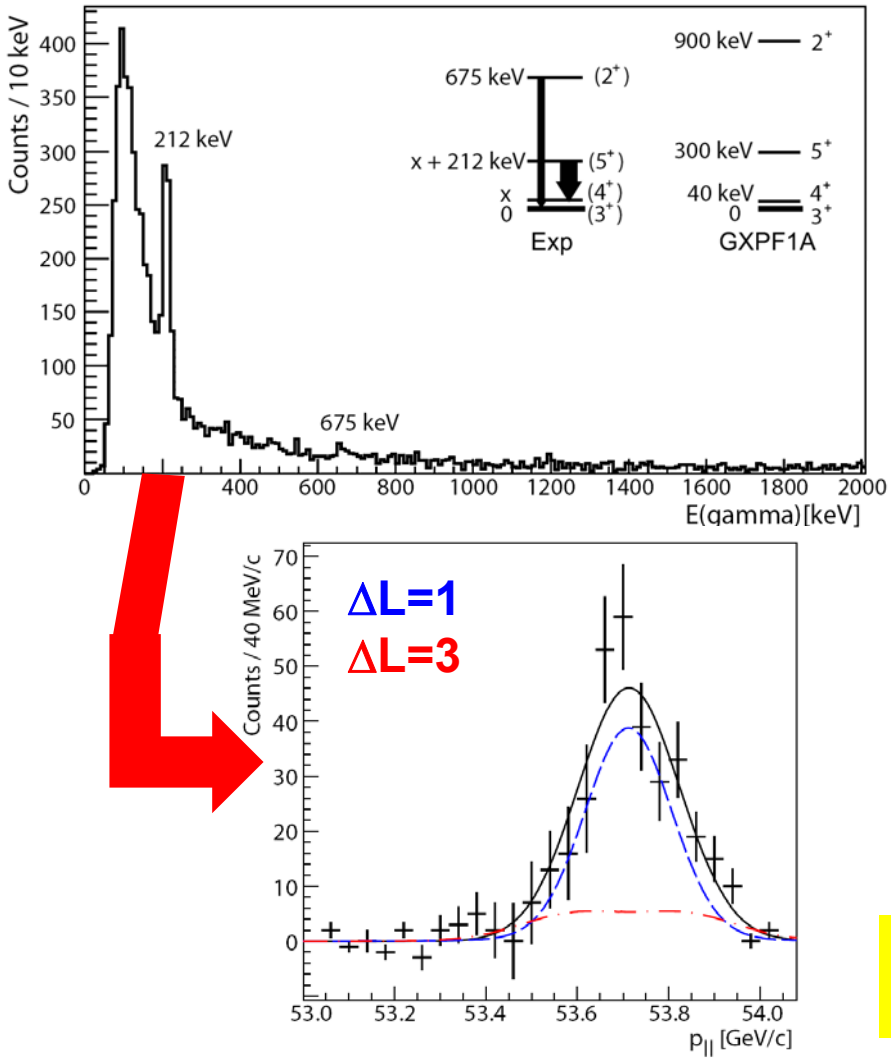
Inclusive momentum distribution - all coincidences with γs ➔ „exclusive“ momentum distribution for ground state



For ground state …
knockout of *p*-neutron
➔ $I^{\pi} = 1/2^{-}$
… better description with GXFP1A
… indirect indication for shell closure at N=34

Peter Maierbeck (PhD, TU München 2009)
PLB 675, 22 (2009)

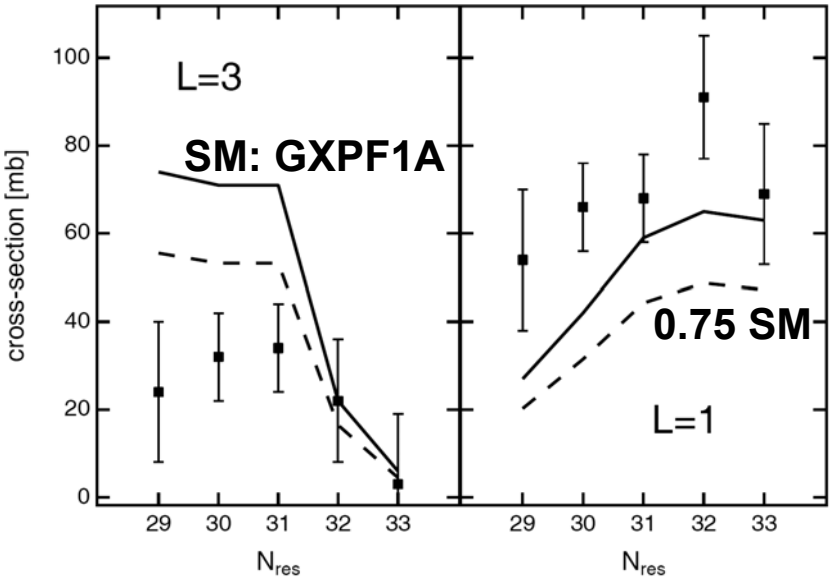
Neutron knockout from Sc isotopes



Open questions:

- **ΔL=3 contribution too large**
- **ΔL=1 contribution too low**

... because shell gap at N=34 is even stronger??



Sabine Schwertel (PhD, TU München 2010)
EPJA 48, 191 (2012)

... „Island of Inversion“ again

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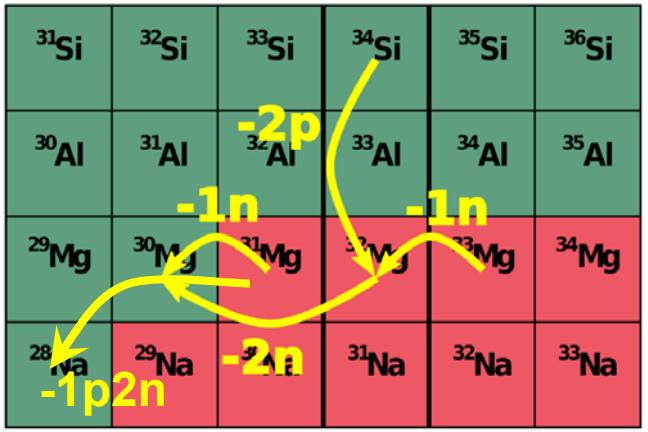
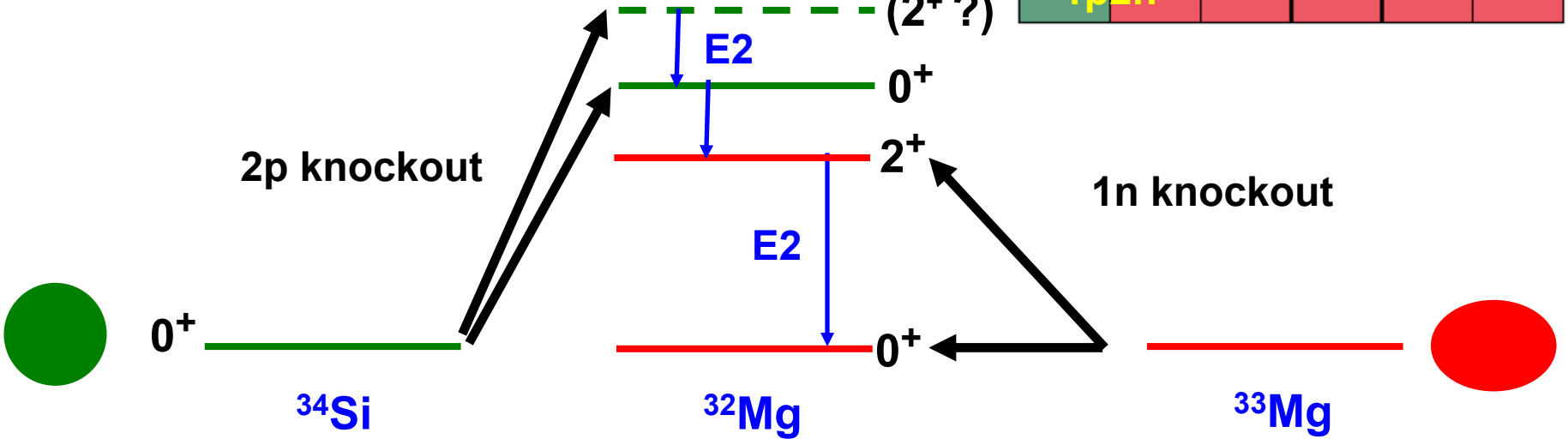
Knockout reactions

... same idea as for transfer:
Depending on the initial nucleus different states can be populated
(Experiment at NSCL in March 2013)





Kathrin Wimmer (CMU)

Set-up at NSCL

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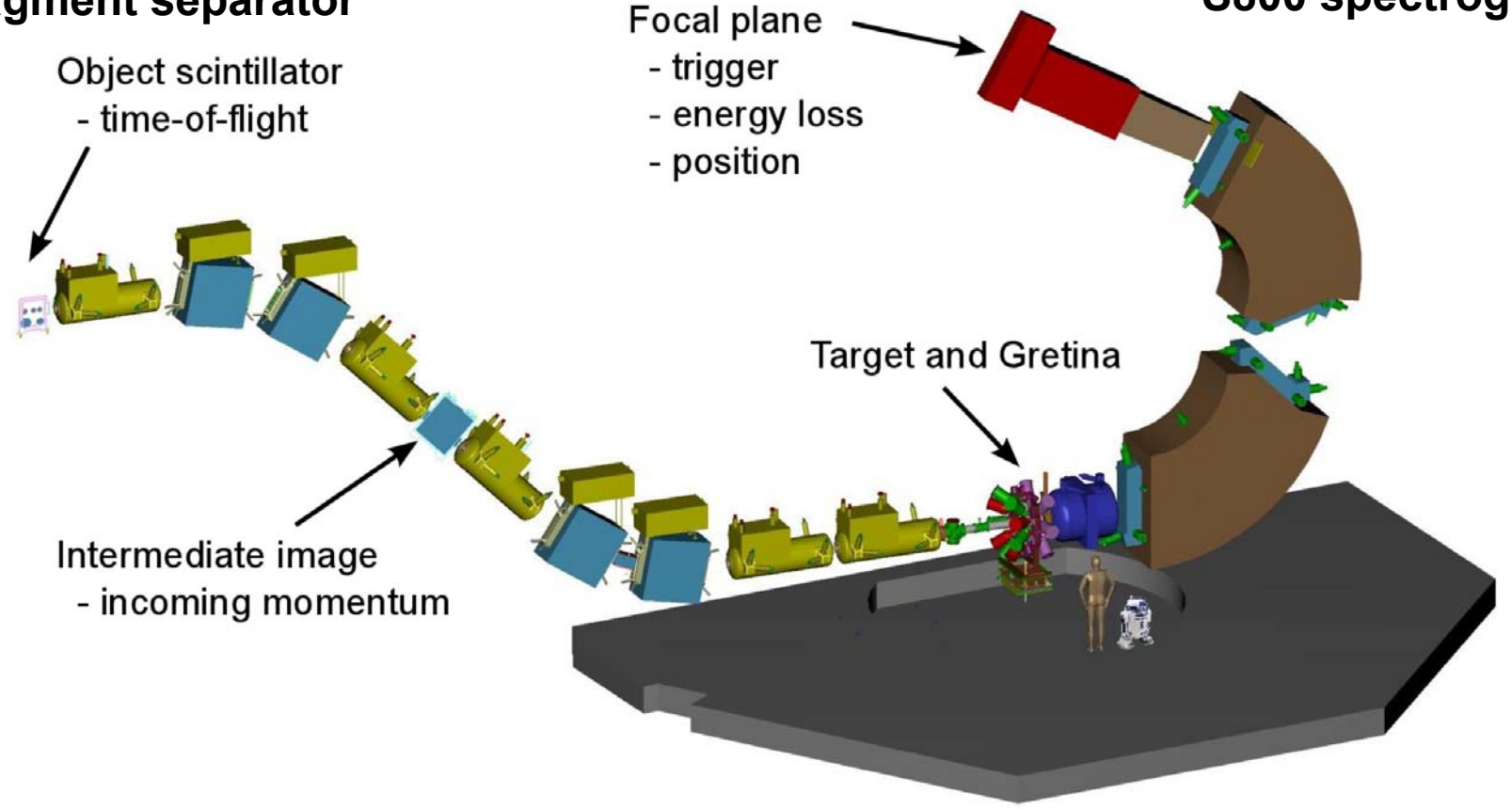
A1900
Fragment separator

S800 spectrograph



Details ... see talks by I-Yang Lee and Dirk Weisshaar

1n knockout from ^{31}Mg - $\gamma\gamma$ matrix

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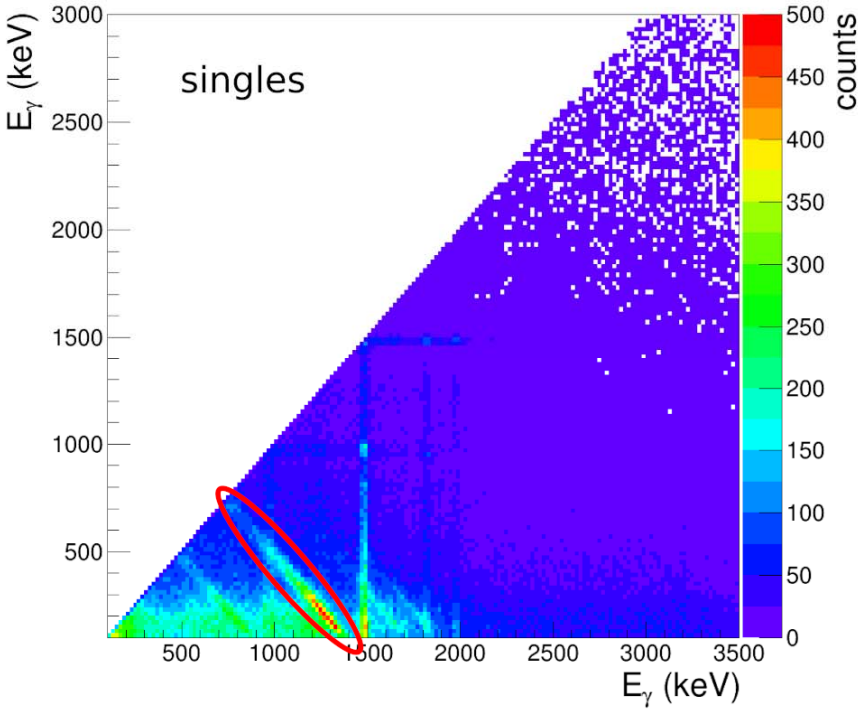
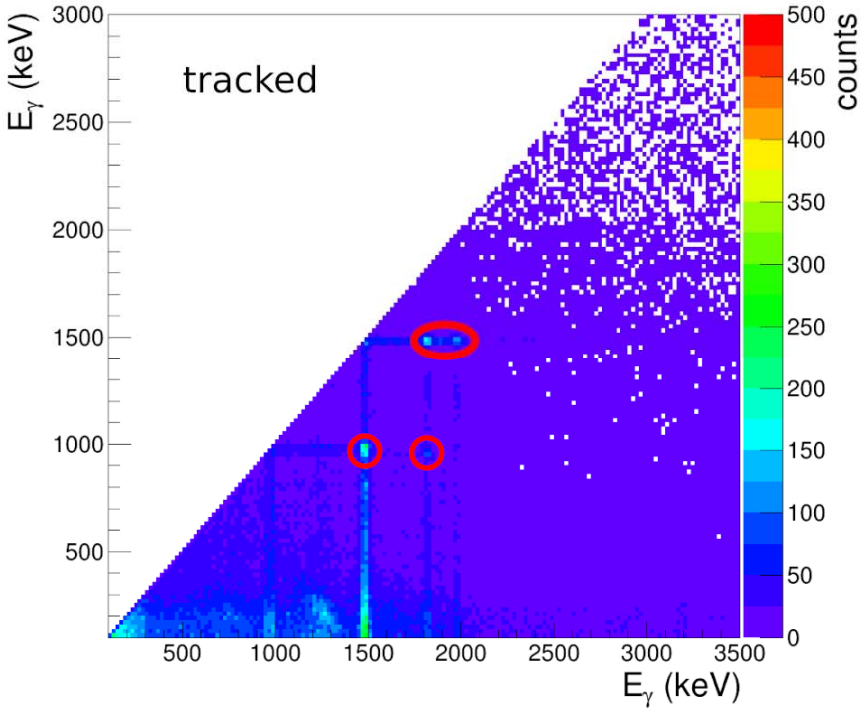
Without tracking



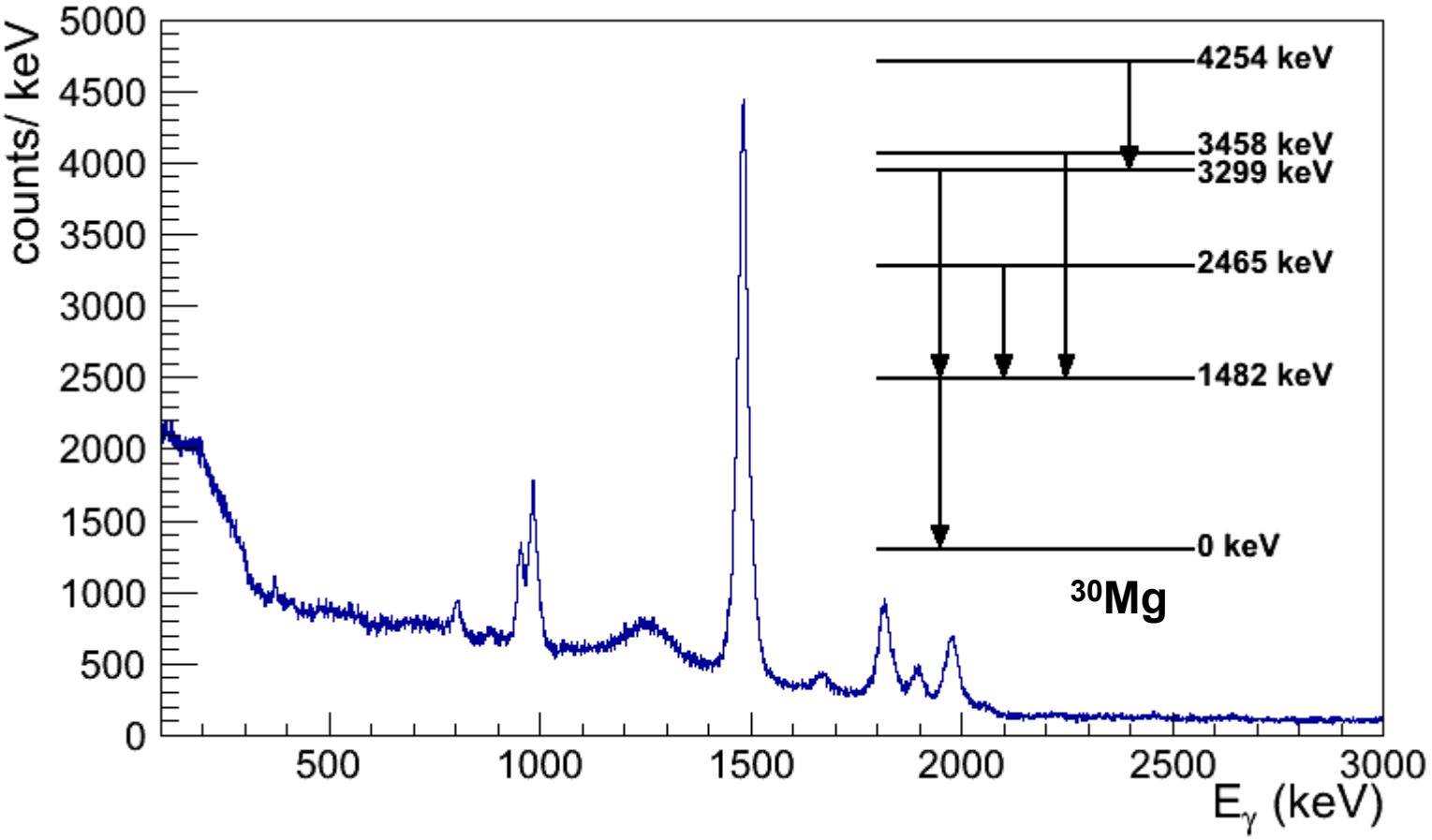
With tracking



Scattering between Ge detectors
... well known for MINIBALL ☹☹☹

Kathrin Wimmer (CMU)

1n knockout from ^{31}Mg - level scheme



Kathrin Wimmer (CMU)

Knockout as production mechanism

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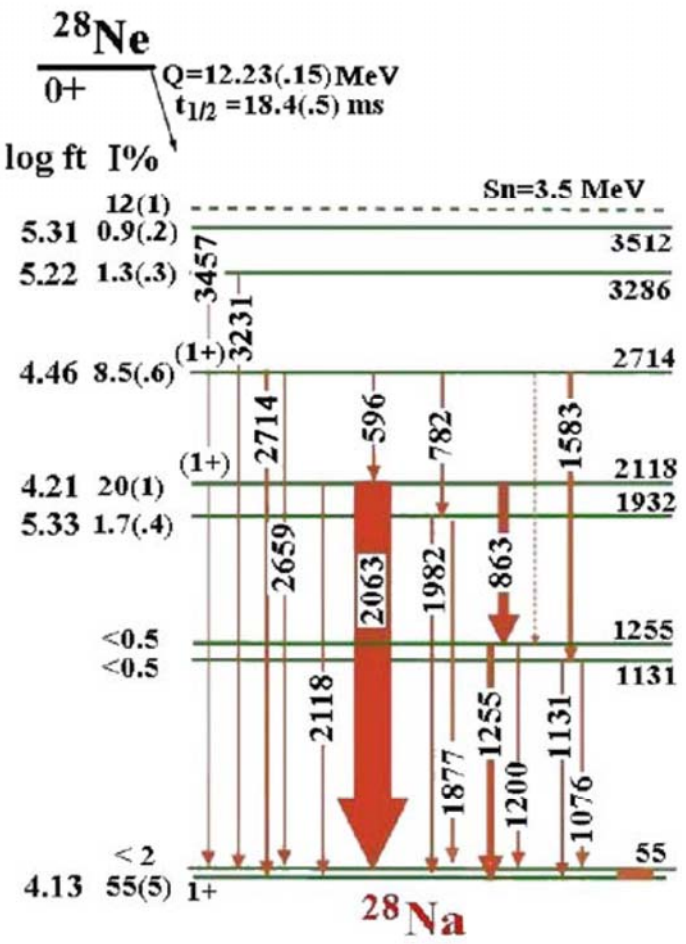

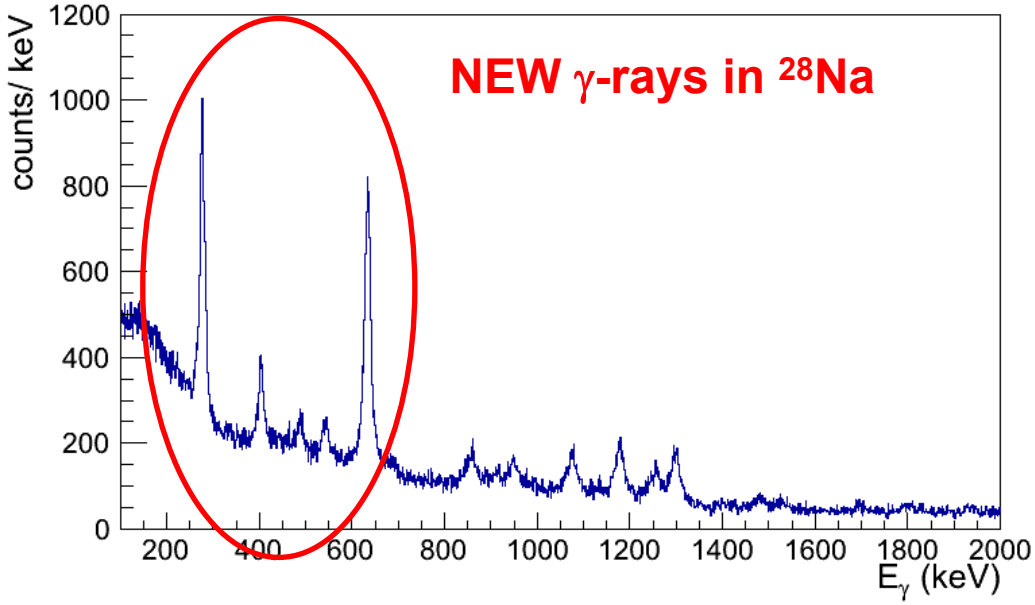

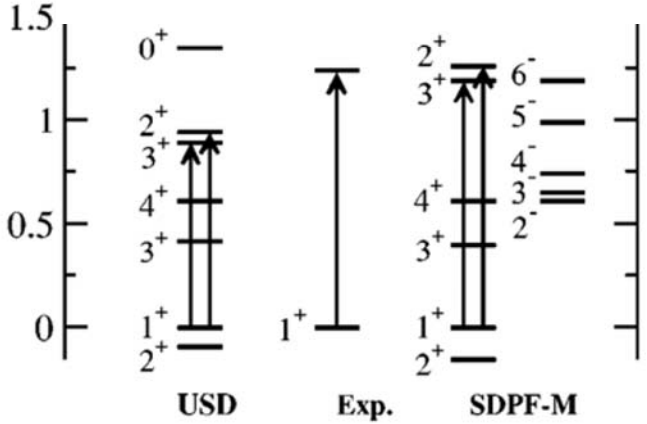

Kathrin Wimmer (CMU)

V. Tripathi et al., PRC 73, 054303 (2006)

Y. Utsuno et al., PRC 70, 044307 (2004)

CALIFA for R3B at FAIR

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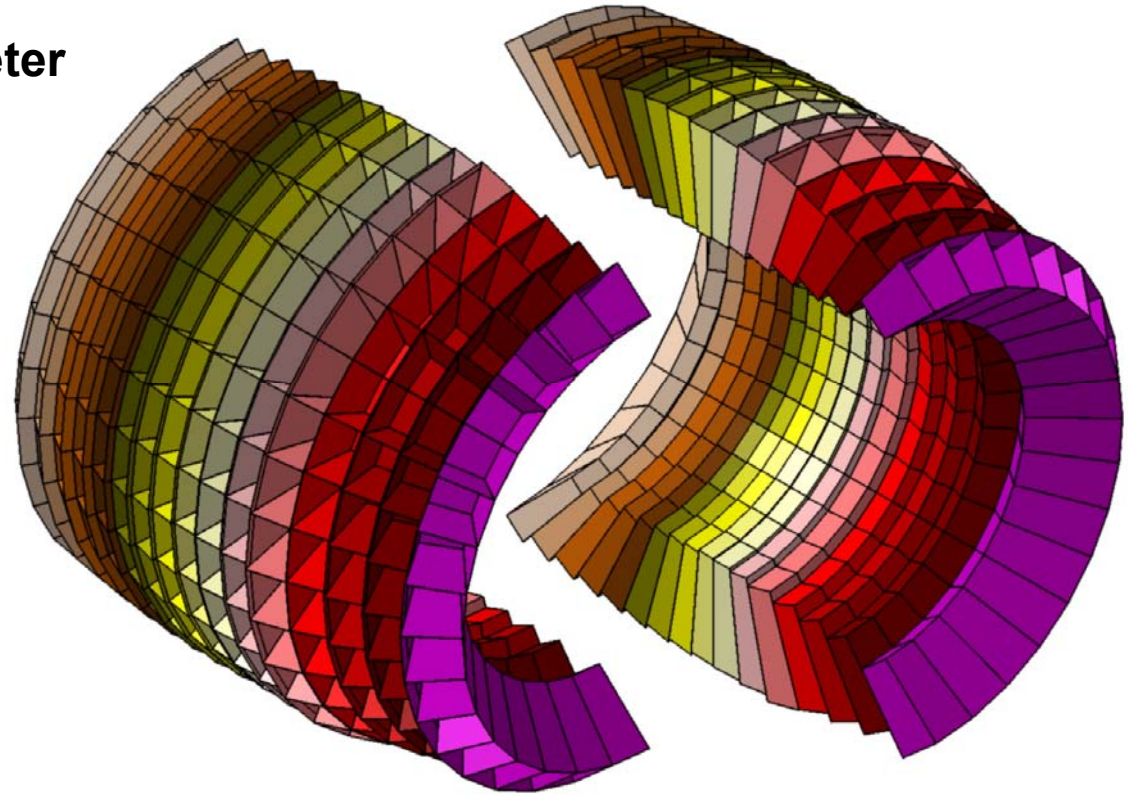
CALIFA

Multi purpose instrument

- **Calorimeter and spectrometer for γ-rays and protons**
- **Large dynamic range from 100 keV to 300 MeV**

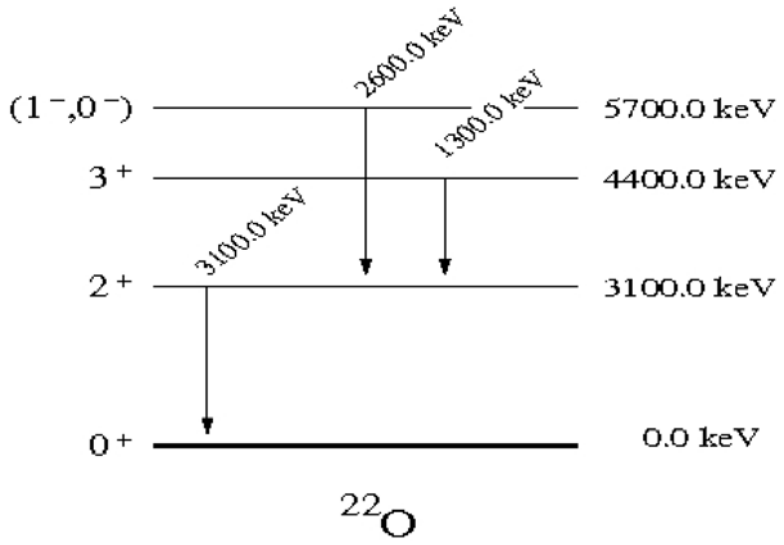
CALIFA - Barrel

- **1952 CsI(Tl) crystals**
- **APD readout**



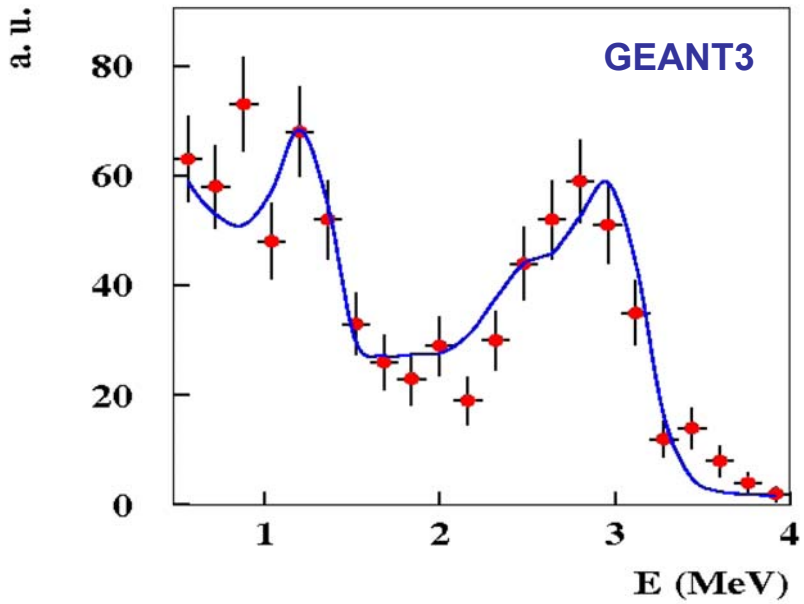
+ forward endcap ... still to be designed

Example experiment



- 1n-knockout from ^{23}O
- E = 939 MeV/u
- Next to dripline at ^{24}O (no excited bound state)

Measured with 32 NaI(Tl) crystals



D. Cortina-Gil et al., PRL 93, 062501 (2004)

CALIFA / AGATA at large β

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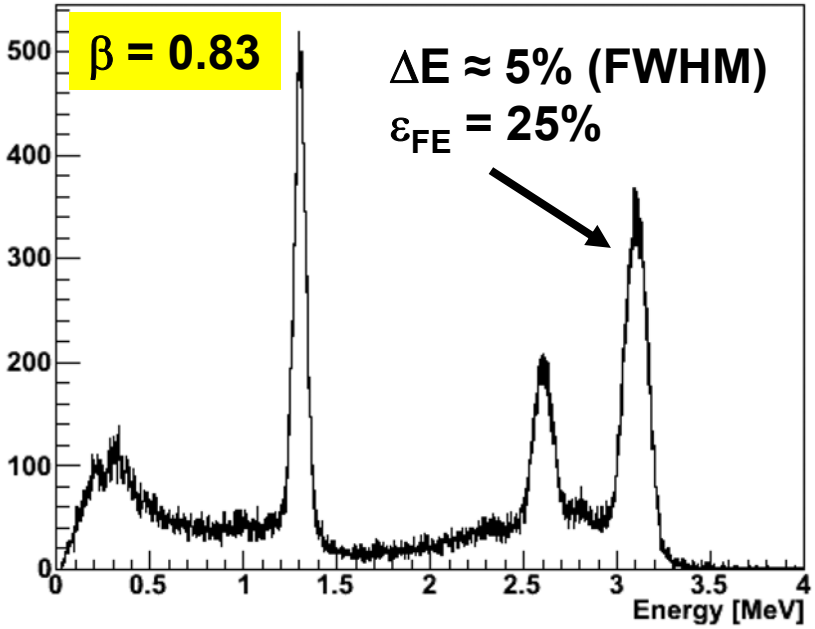
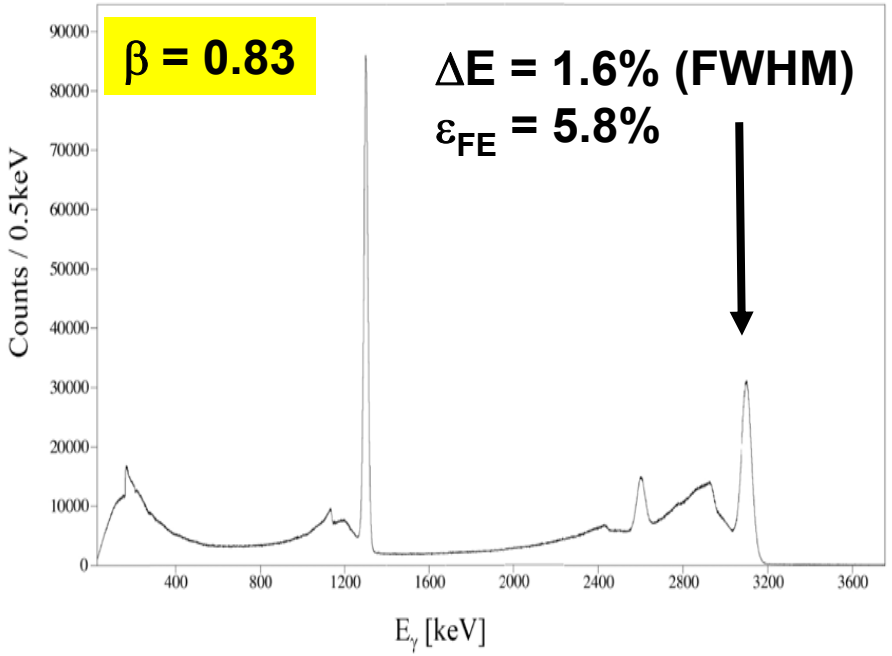
CALIFA Barrel
(43°-143°)



TDR for CALIFA-Barrel (2011)

1π of AGATA
15 triple cluster



Simulation by Enrico Farnea

... for many experiments with exotic nuclei scintillators still compete with Ge!!!

Summary and Outlook

TECHNISCHE UNIVERSITÄT DARMSTADT

- **Nucleon transfer and knockout reactions are an well established tool to study single-particle properties of nuclei**

Similar reaction types:
multinucleon transfer, e.g. with PRISMA
(p,2pγ) ... quasi free scattering with R3B @ FAIR
(p,p'γ) with EXL @ FAIR
(e,e'γ) at S-DALINAC

- **Complementary to Coulex, decay spectroscopy …**

Looking forward to new opportunities at HIE-ISOLDE, FRIB, FAIR, SPES ...

Ciao Enrico!!!