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Recent results on transfer reactions using the MINIBALL/T-REX set-up

Thorsten Kröll

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

EURONS

HIC for FAIR Helmholtz International Center

TUM LMU Excellence Cluster Universe

MINIBALL

REX-ISOLDE

Work supported by BMBF (Nr. 06DA9036I and 06MT238), EU (EURONS Nr. 506065), HIC for FAIR, DFG (Excellence Cluster Universe), and the MINIBALL/REX-ISOLDE collaborations

Transfer reactions

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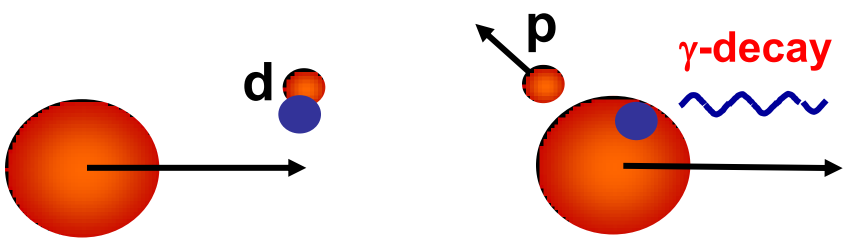
<u>Spectroscopic tool</u> to study single-particle properties of nuclei
selectivity to (1) kinematical matching (e.g. Q_{opt} = 0 for n-transfer)
(2) nuclear structure

<u>Typical reactions</u>: (d,p), (t,p) …
RIBs: inverse kinematics



<u>Observables</u>
- energies of protons (+ E_γ)
- angular distributions of protons (+ γ-rays)
- (relative) spectroscopic factors

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

<u>Conceptional limitations</u>
- only sensitive to nuclear surface
- phenomenological description (optical pot., DWBA)
- "meaning" of SF's?

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = SF \times \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

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

Challenges and (open) questions

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<u>Optical potentials</u> (input for DWBA) for radioactive nuclei are not known

- elastic scattering of target nuclei
- extrapolation from stable systems (global description needed)

<u>Low beam energy</u> … current limit is 3 MeV/u … <u>and low Q values</u>

- small proton energies in backward direction
- smooth angular distributions
- spectroscopic factors are consistent?

  ➔ study of $^{54}Fe(d,p)^{55}Fe$ at different energies M. Mahgoub et al. EPJA 40, 35 (2009)

  - large spectroscopic factors agree well
  - small spectroscopic factors can change ... not yet understood

<u>Direct transfer reaction or rather fusion-evaporation reaction?</u>

- evaporation➔ thermal energy spectra / isotropic angular distribution
- d(^{30}Mg,^{31}Mg)p @ 2.2 MeV/u ... NO protons from evaporation
- neutron-rich nuclei: $S_n << S_p$ ➔ neutrons will be evaporated (confirmed by Hauser Feshbach calculations)

➔ protons originate from direct transfer process! M. Pantea, PhD Thesis, TUD (2005)

Overview of experiments done so far …

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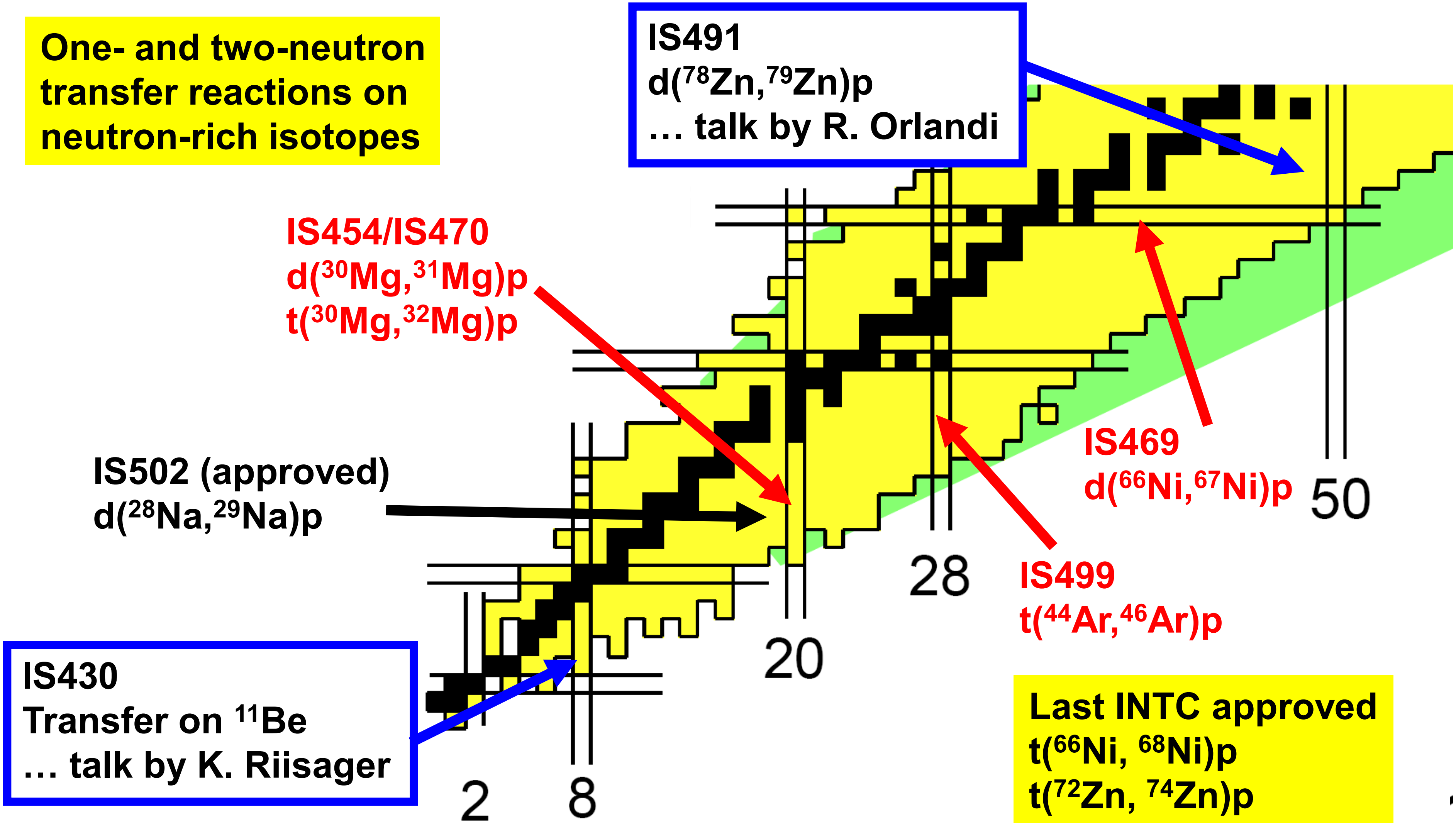
One- and two-neutron transfer reactions on neutron-rich isotopes



Last INTC approved
t(^{66}Ni, ^{68}Ni)p
t(^{72}Zn, ^{74}Zn)p

T-REX – Si particle detector array

T-REX … Si detector array for Transfer experiments at REX-ISOLDE

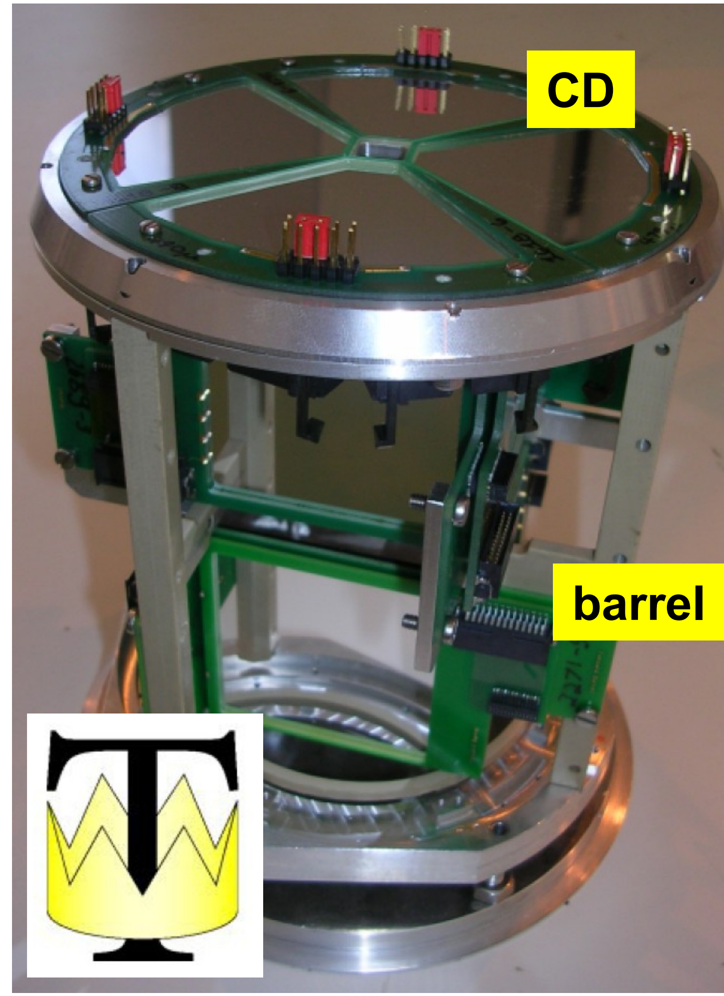
- large solid angle (58% of 4π)
- position sensitive
- PID (ΔE-E): p, d, t, α,
  … and e^- from β-decay (!)

Technical details:

Barrel: 140 μm ΔE / 16 resistive strips
1000 μm E / pad

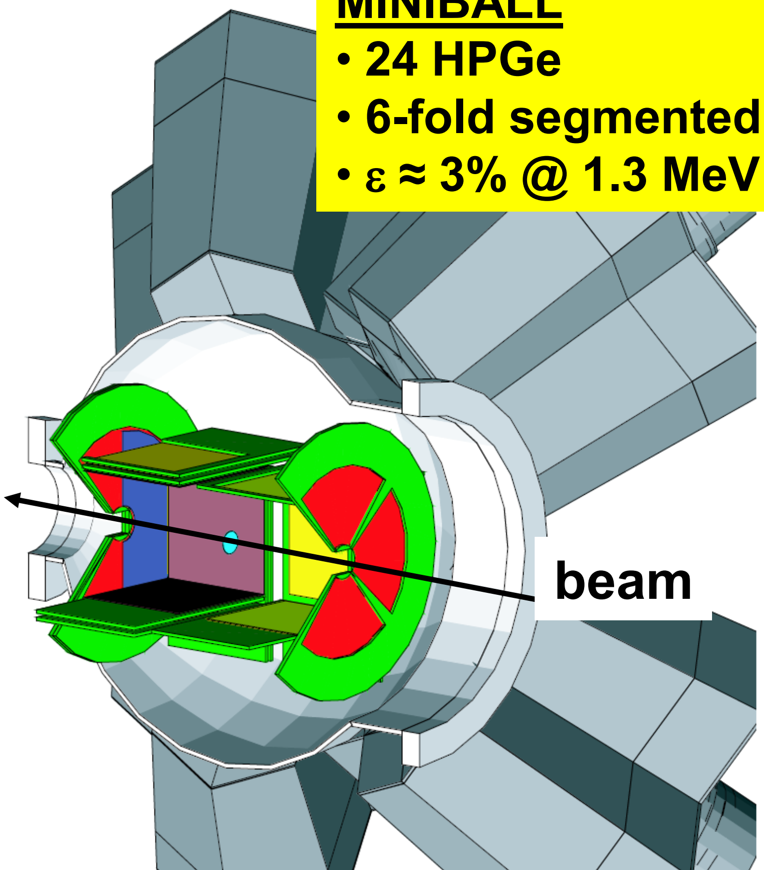
Backward CD: 500 μm ΔE / DSSSD
500 μm E / pad

V. Bildstein, K. Wimmer, Th. Kröll, R. Gernhäuser et al.
(funded by TU München, KU Leuven, U Edinburgh, CSNSM Orsay, TU Darmstadt)

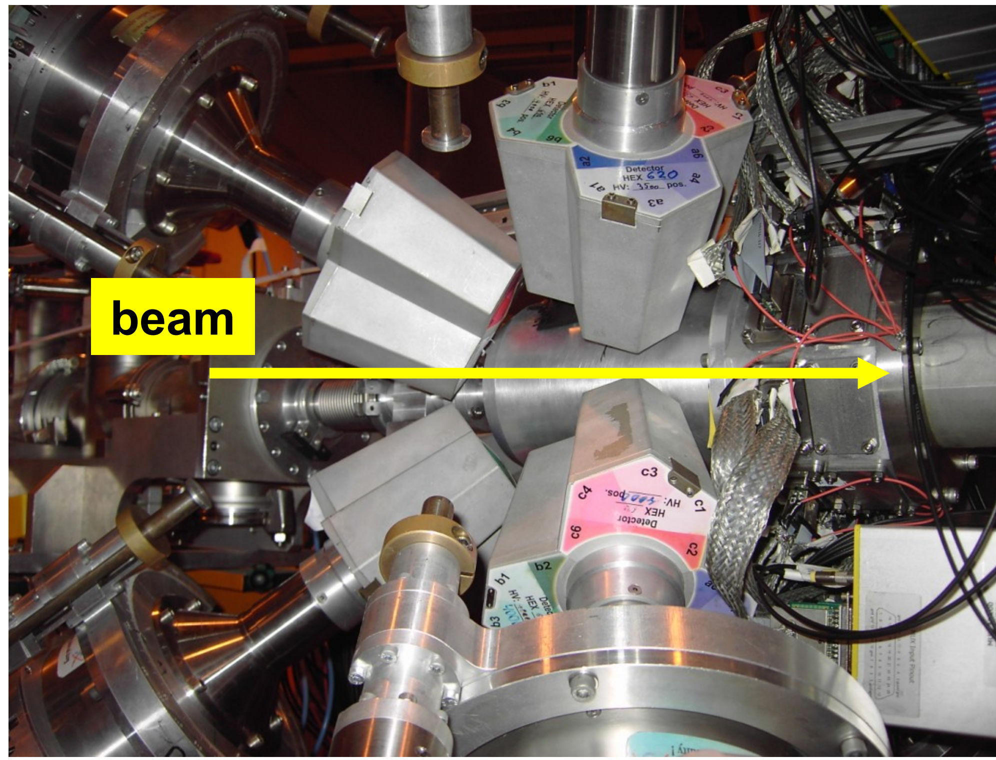


Experimental set-up: T-REX & MINIBALL

MINIBALL
- 24 HPGe
- 6-fold segmented
- ε ≈ 3% @ 1.3 MeV



… shown is GEANT4 Implementation of set-up



^{31}Mg … isotope right on the beach

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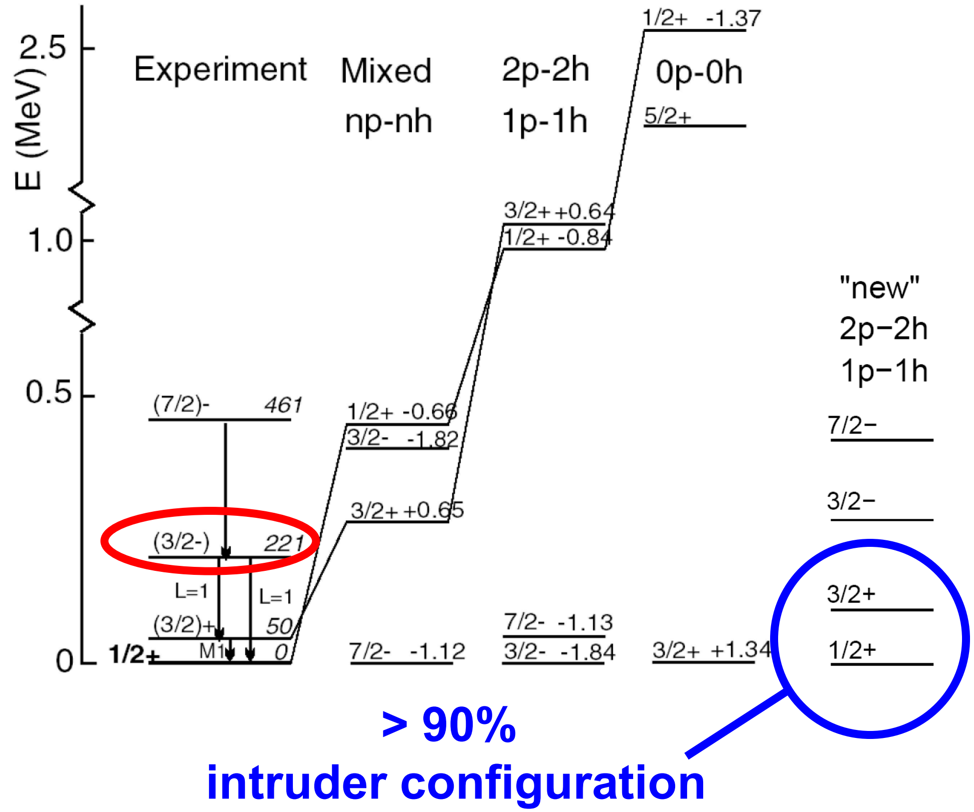
Island of Inversion again
… 35 years after its discovery?
C. Thibault et al., Phys. Rev. C 12, 644 (1975)

Intruder *fp* orbitals compete with *sd* orbitals ➔ breaking of N=20

Models describing well ^{30,32}Mg fail to reproduce the 1/2$^+$ spin/parity assignment for the g.s. of ^{31}Mg!?!

➔ after adaption of a few matrix elements agreement with exp. data for g.s. of ^{31}Mg achieved

<u>Our aim</u>:
Investigation of single-particle structure of <u>excited states</u>

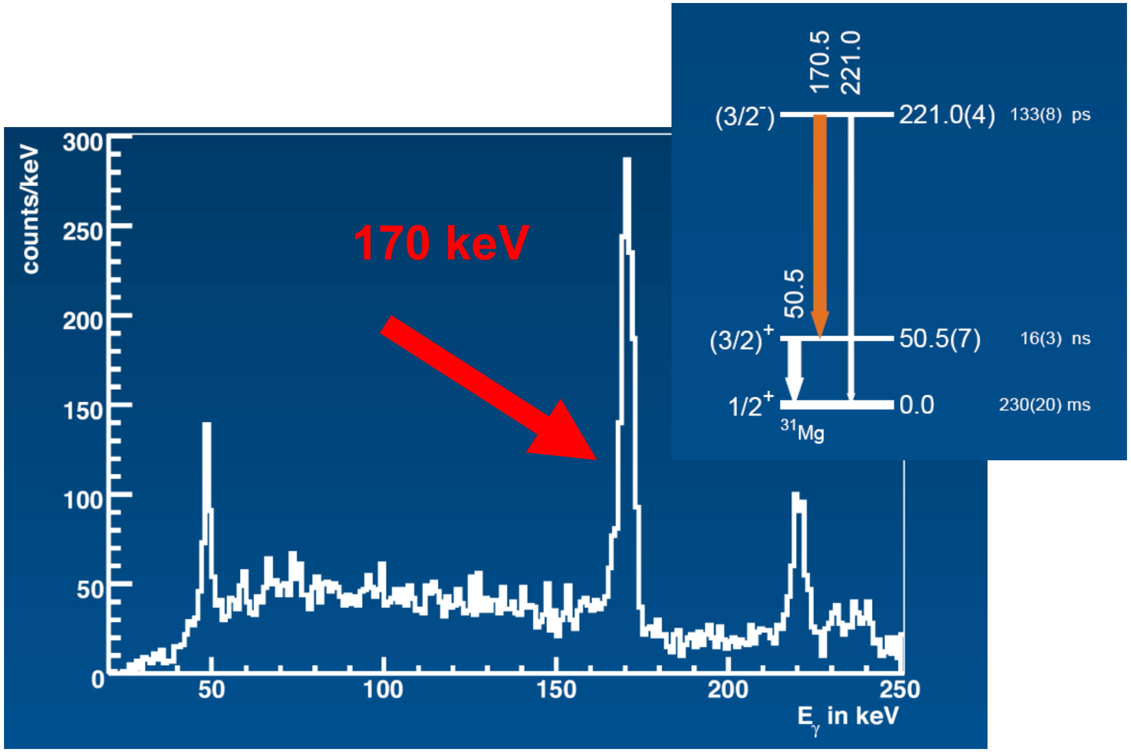


V. Bildstein, Dipl. Thesis (Heidelberg, 2005)
M. Kowalska et al., EPJA 25, s01, 193 (2005)
G. Neyens et al., PRL 94, 022501 (2005)
F. Maréchal et al., PRC 72, 044314 (2005)

d(^{30}Mg, ^{31}Mg)p – γ-ray spectrum

- Q_{00} = 0.18 MeV
- ^{30}Mg @ 2.86 MeV/u
- 1- 4 · 10^4 part/s
- 1 mg/cm^2 deuterated PE
- populated states not resolved in proton spectrum
- γ-rays needed

- γ-rays in coincidence with protons
- Doppler correction assuming θ(^{31}Mg) = 0°



Analysis by <u>Vinzenz Bildstein</u> (PhD Thesis at TU München)

d(^{30}Mg, ^{30}Mg)d – elastic scattering

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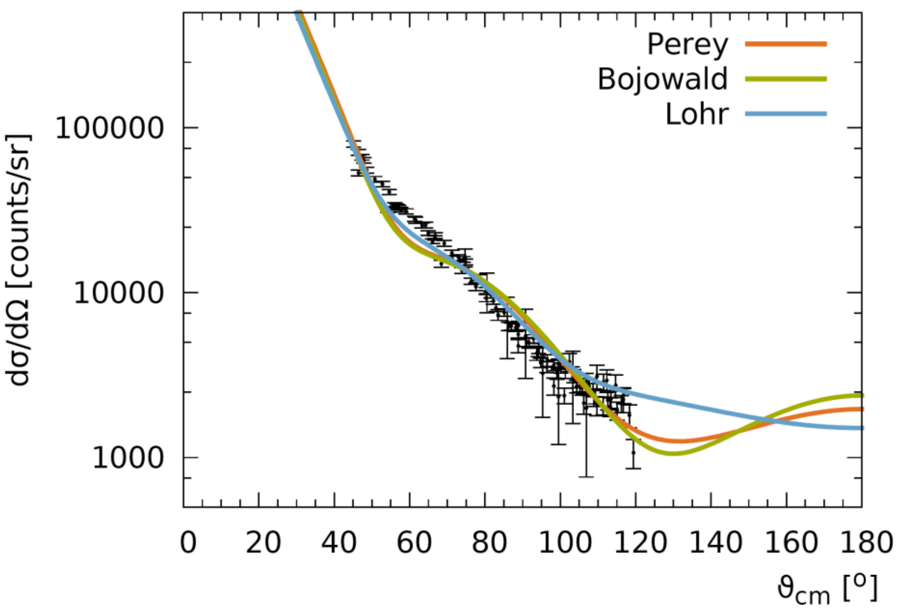
^{30}Mg @ 2.86 MeV/u: elastic scattering ➔ luminosity
All DWBA calculations with FRESCO I. J. Thompson, Comp. Phys. Rep. 7, 167 (1988)

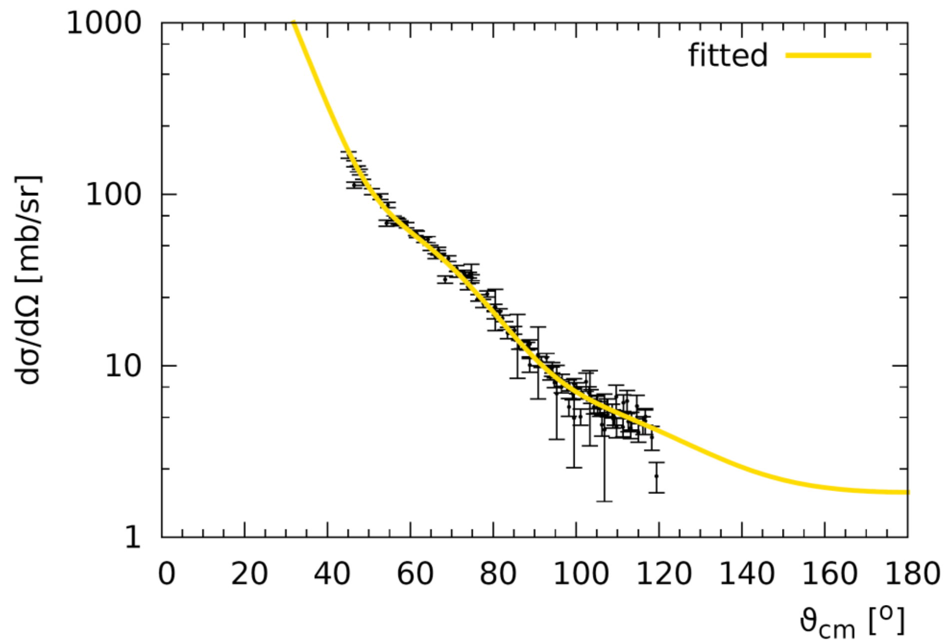
Extrapolation of global parameter sets for optical potentials



Total luminosity: 529 mb^{-1}

… includes beam contaminations!

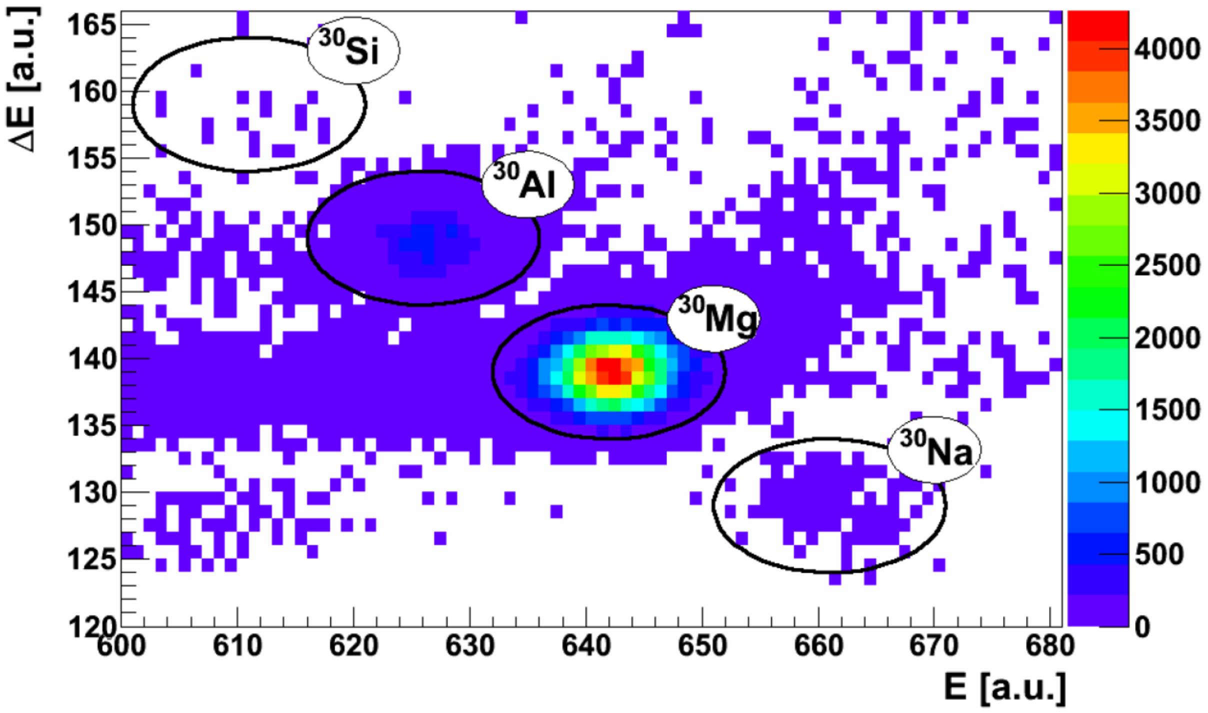
Fit to elastic scattering data



Analysis by Vinzenz Bildstein (PhD project at TU München)

^{30}Mg – beam composition

- **Analysis of release curves**
- **Bragg chamber in beam dump**



89% ^{30}Mg
11% ^{30}Al
<1% others

… directly from ISOLDE
+ decay products

Proton spectra from reactions are NOT affected by ^{30}Al because of different Q value

^{31}Mg – angular distribution of protons

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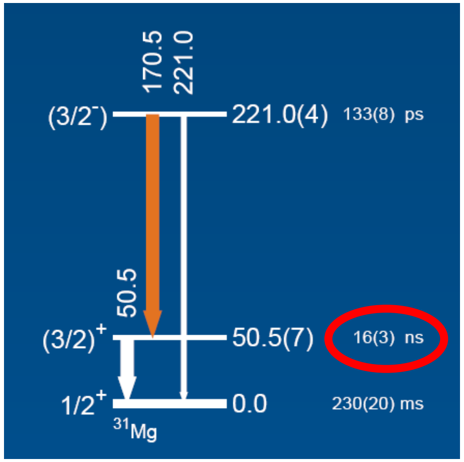
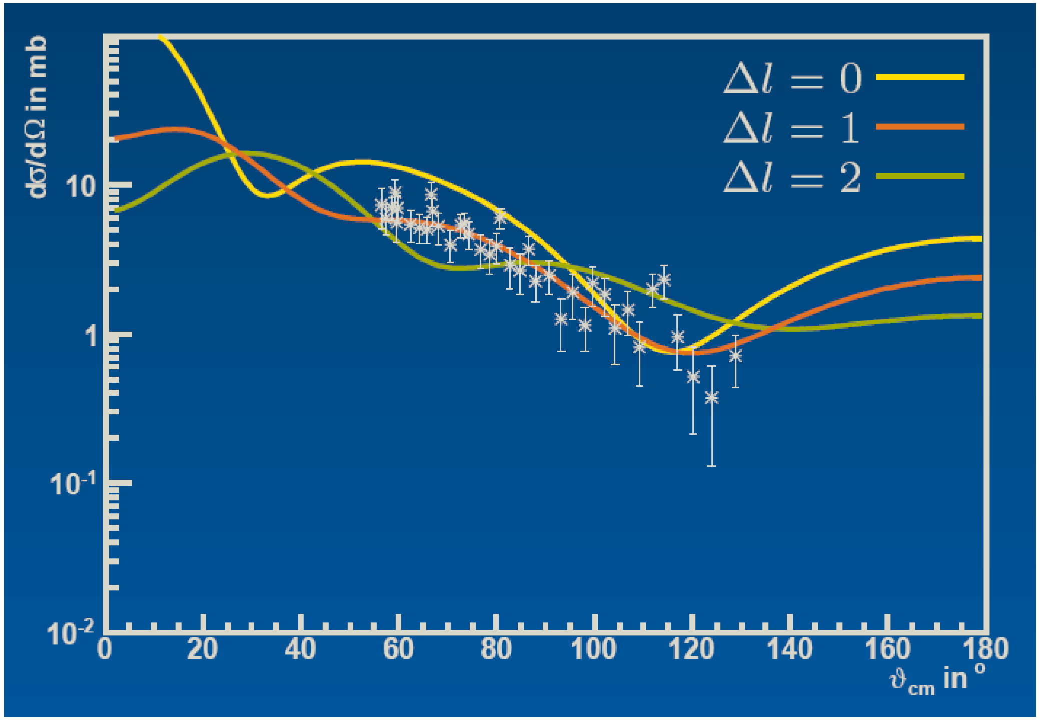
- protons in coincidence with 170 keV γ-transition
- analysis using fitted potential parameters

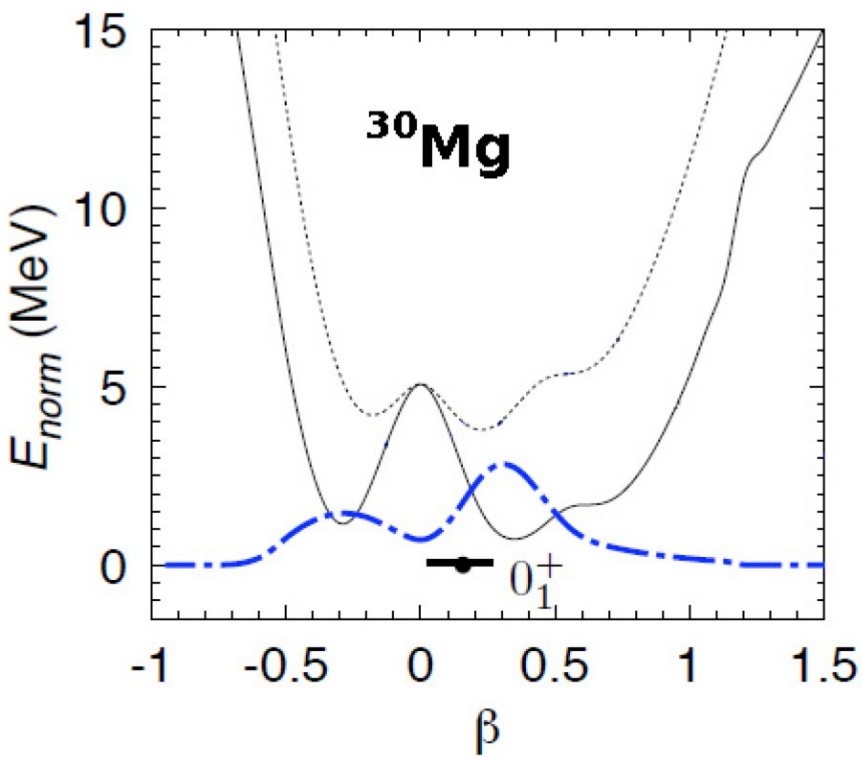




- ΔL=1
  ➔ state has negative parity
- „spectroscopic factor“
  S(221 keV) ≈ 0.084

Fit to ALL protons (keeping ΔL=1 contribution fixed)
➔ ΔL=0 for g.s., ΔL=2 for 50 keV state, „spectroscopic factors“ S ≈ 0.27

Neutron coupled to ^{30}Mg core



T. Rodriguez, J. L. Egido;
priv. communication (2008)

… qualitative discussion:

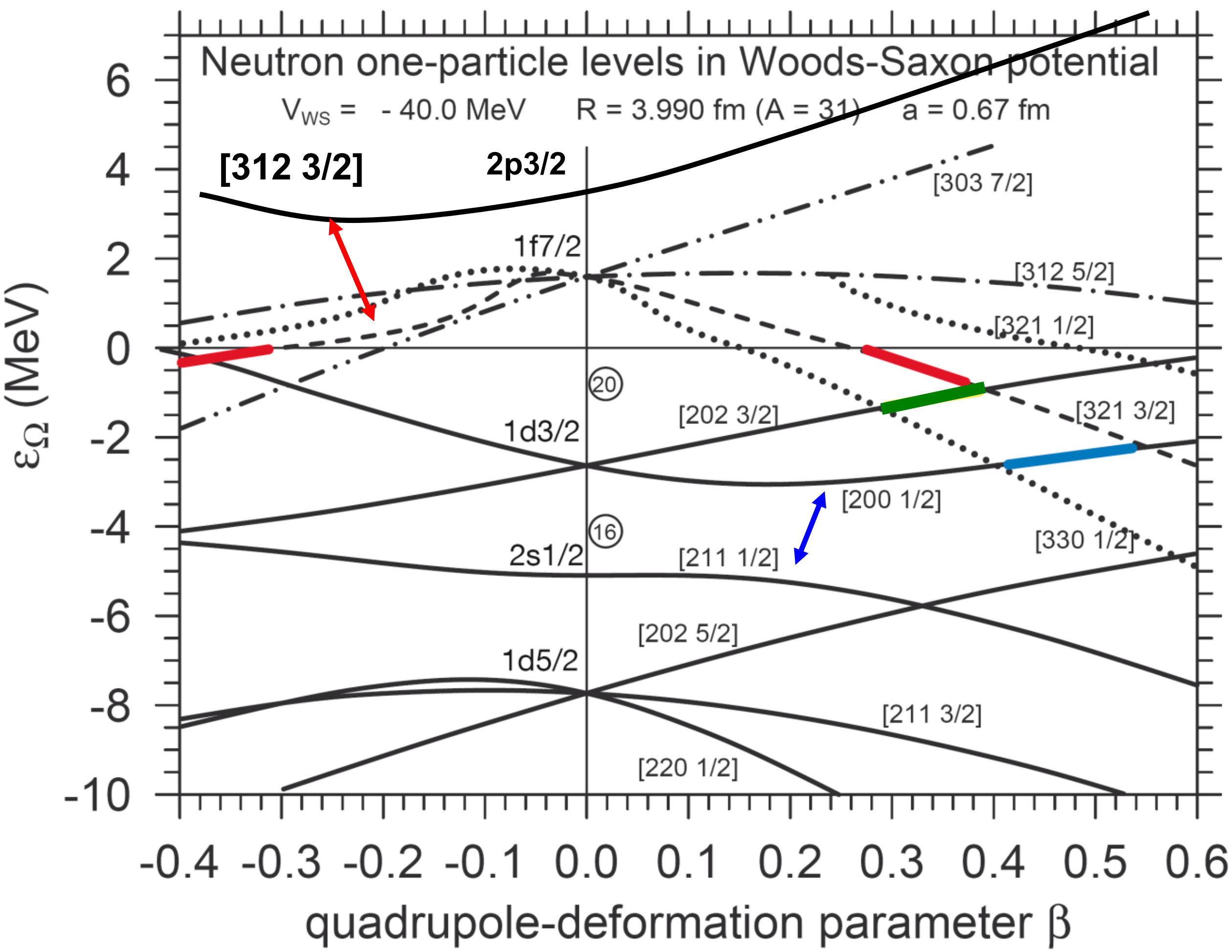
$$\left|{}^{31}\mathrm{Mg}\right\rangle = \left|\mathrm{neutron}\;\; ; nlj \ldots\right\rangle \otimes \left|{}^{30}\mathrm{Mg}\right\rangle$$

^{30}Mg: Beyond Mean Field (BMF)
- projection on angular momentum and particle number
- configuration mixing
➔ ^{30}Mg nearly spherical

Transfer will populate states with neutron coupled to <u>prolate configurations</u>
➔ larger spectroscopic factor
or <u>oblate configurations</u>
➔ smaller spectroscopic factor

The small SFs indicate that core changes entering the „Island of Inversion“!!!

Shape coexistence in ^{31}Mg?



I. Hamamoto, PRC 76, 054319 (2007)

221 keV:
3/2⁻[321], oblate
Mixed, mainly 2p3/2
ΔL=1 ✓

~~**221 keV:**~~
~~**3/2⁻[321], prolate**~~
~~**1f7/2 orbital**~~
~~**ΔL=3**~~

50 keV:
3/2⁺[202], prolate
1d3/2 orbital
ΔL=2 ✓

g.s.:
1/2⁺[200], prolate
Mixed, mainly 2s1/2
ΔL=0 ✓

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

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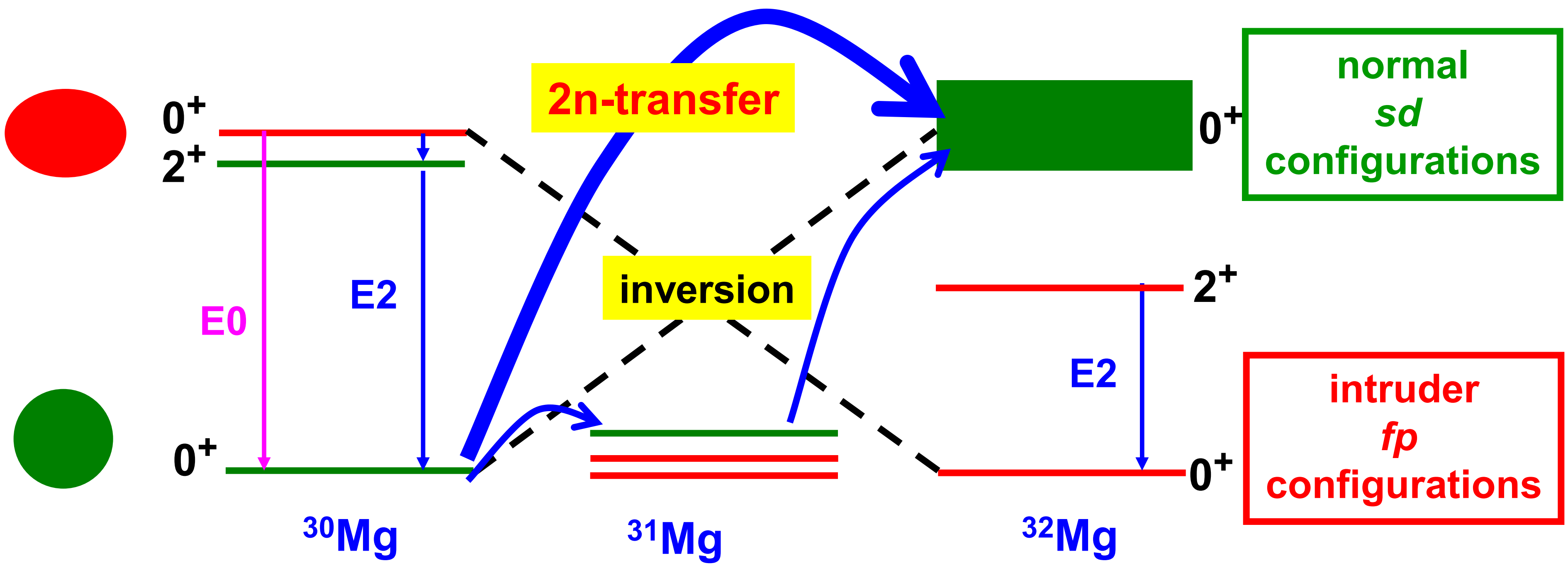
Coexistence of spherical and deformed states

Missing part is second 0^+ in ^{32}Mg … has not been observed so far !!!

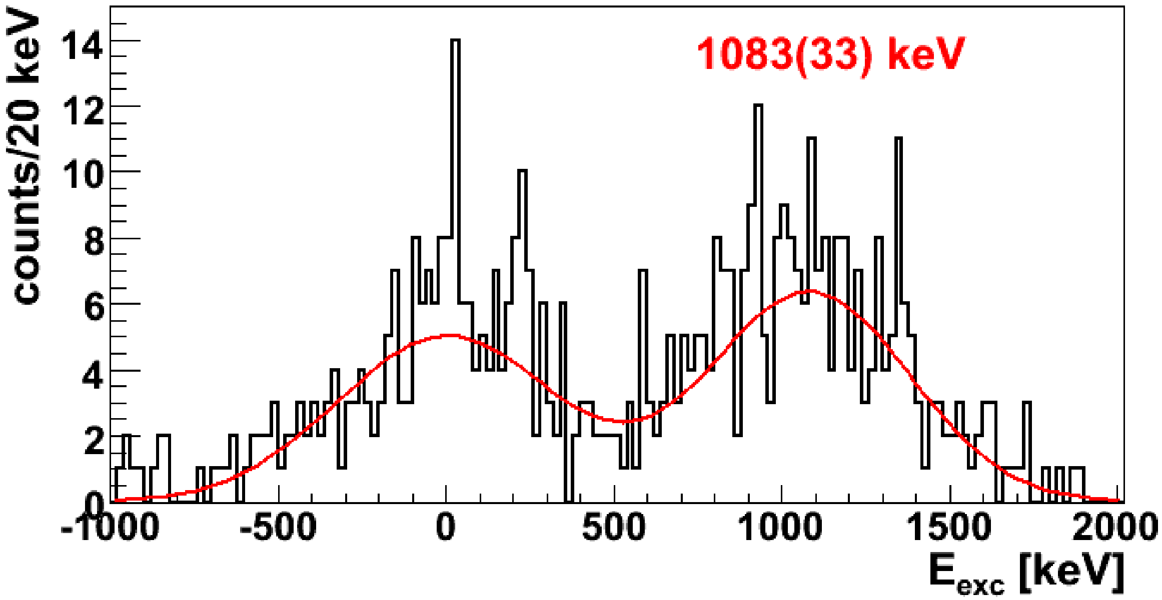


Similar particle-hole configurations ↔ large overlap of wave functions
➔ large spectroscopic factor for transfer

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

- ^{3}H loaded Ti foil (40 μg/cm² ^{3}H, 10 GBq)
- ^{30}Mg @ 2 MeV/u (to avoid fusion with Ti!!)
- $4 \cdot 10^{4}$ 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!!!

Analysis by <u>Kathrin Wimmer</u> (PhD Thesis at TU München)
Phys. Rev. Lett. (in press)

^{32}Mg – coincident γ-ray spectrum

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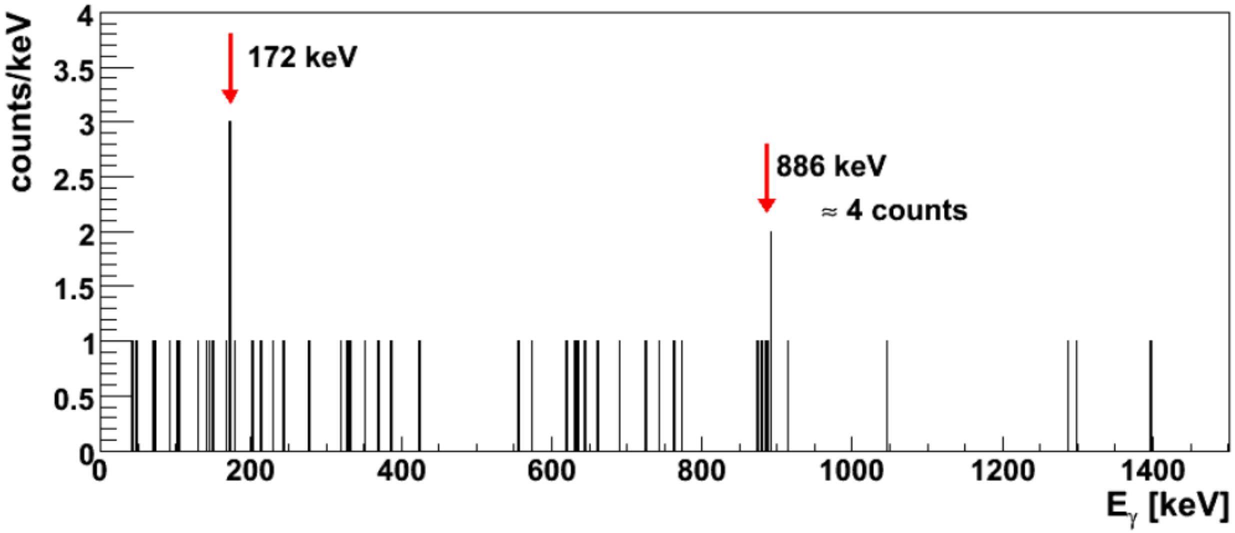
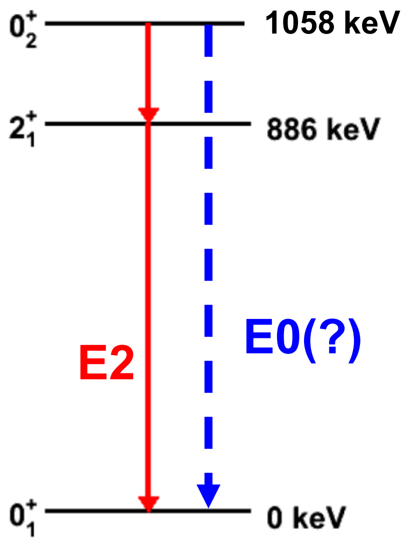
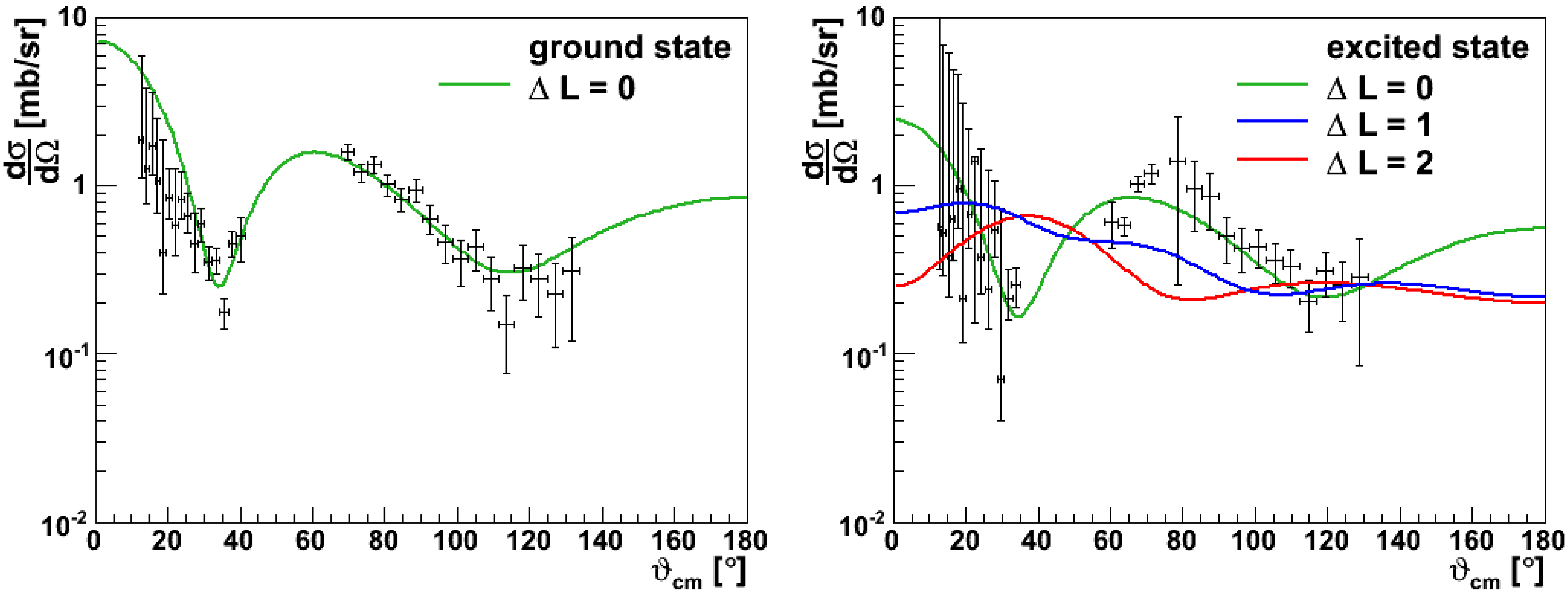
- Coincidence with population of 1083 ± 33 keV state
- Doppler correction assuming θ(^{32}Mg)=0°





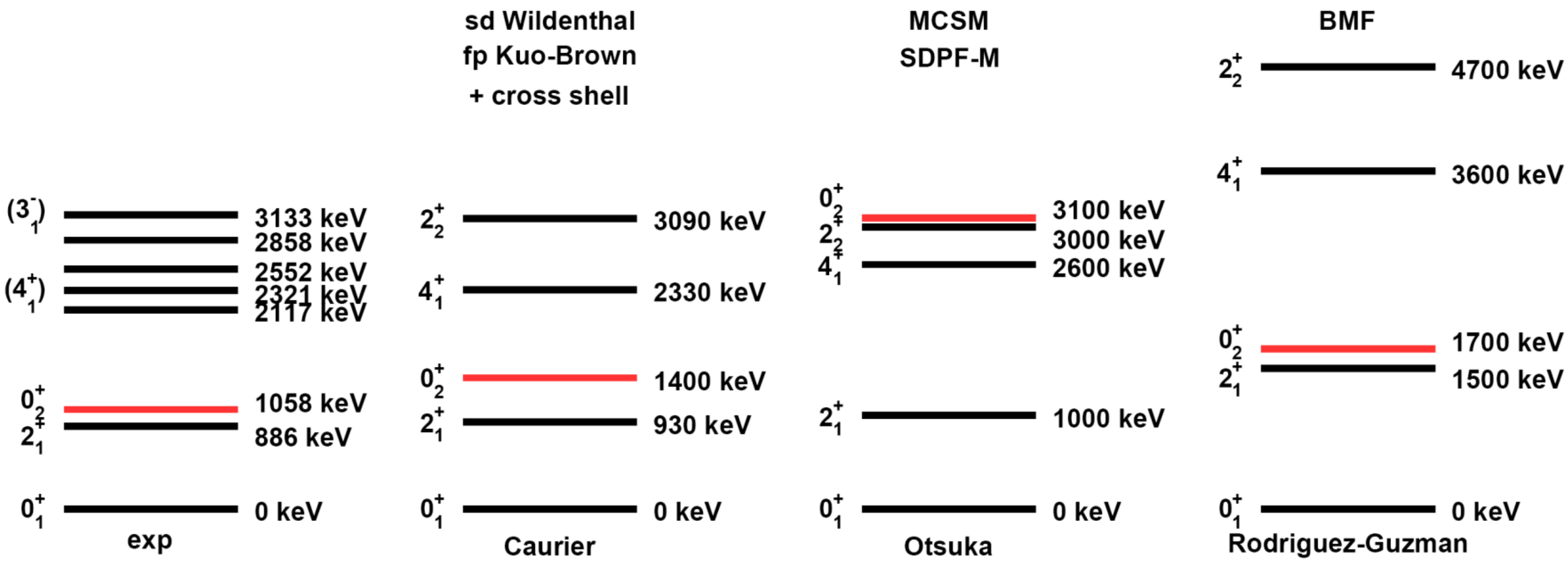
- **NO strong $2^+ \rightarrow 0^+$ transition**
  - no direct population of 2^+ state ... protons only from transfer to 0^+ states
  - E_γ=172 keV → E(0^+) = 1058 keV → 2^+ … consistent with 1083 ± 33 keV
    estimated γ-ray yield : 18(3) counts
    ➔ state decays outside of MINIBALL … rough estimate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

Angular distributions of protons



- optical model parameters fitted to elastic scattering data, very similar results with exptrapolation from systematics
  C. M. Perey & F. G. Perey, At. Data Nucl. Data Tab. 17, 1 (1976)
- almost pure pair transfer, sequential transfer negligible
- both angular distributions are well described with ΔL=0 transfer ➔ 0^+ states

^{32}Mg levels – comparison with theory



Predictions by theory for the excitation energy of the second 0^+ state in ^{32}Mg are all considerably higher than the experimental value!

E. Caurier et al., Nucl. Phys. A 693, 374 (2001); T. Otsuka et al., Eur. Phys. J. A 20, 69 (2004);
R. Rodriguez-Guzmán et al., Nucl. Phys. 709, 201 (2002)

Transfer to ground state in ^{32}Mg

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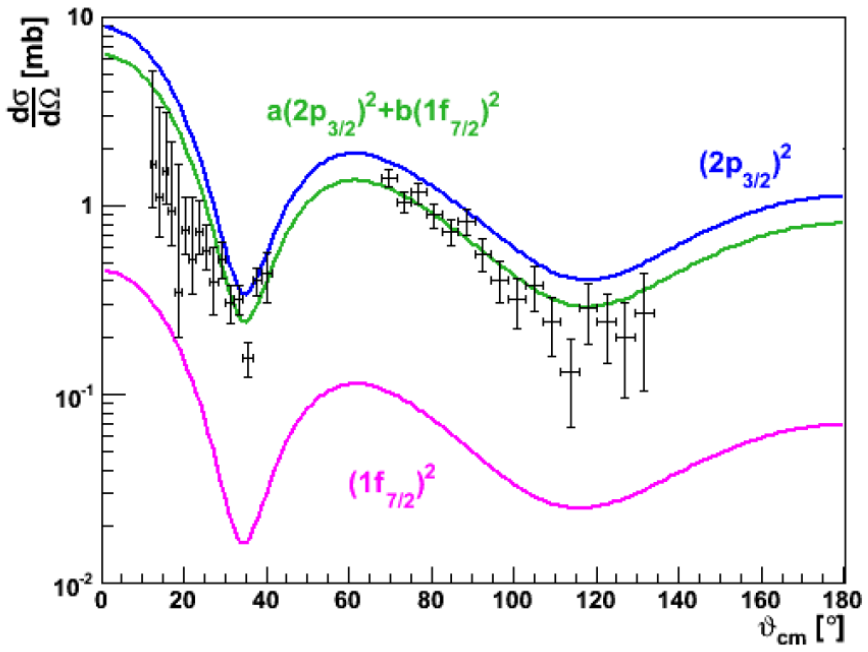
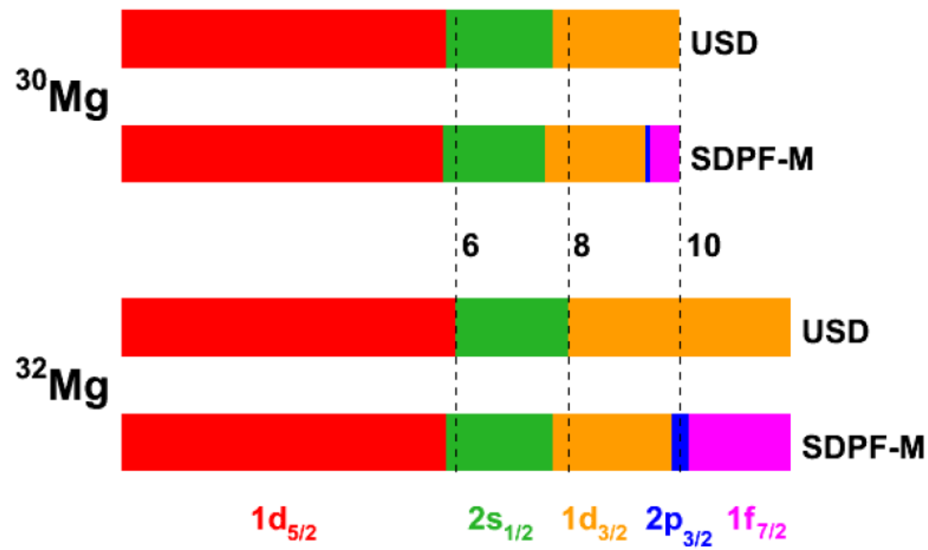


g.s. occupation numbers using effective USD / SDPF-M interactions

B. H. Wildenthal, Prog. Part. Nucl. Phys. 1, 5 (1984)

T. Otsuka et al., Prog. Part. Nucl. Phys. 47, 319 (2001)



- **pure transfer to $(f_{7/2})^2$ by far to small (radial mismatch)**
- **large contribution from $(p_{3/2})^2$ needed (a > 0.7)**

… SDPF-M underestimates the $\nu p_{3/2}$ content in the wave functions

… similar to results obtained in neutron knockout from ^{32,33}Mg

J. R. Terry et al., Phys. Rev. C 77, 014316 (2008); R. Kanungo et al., Phys. Lett. B 685, 253 (2010)

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

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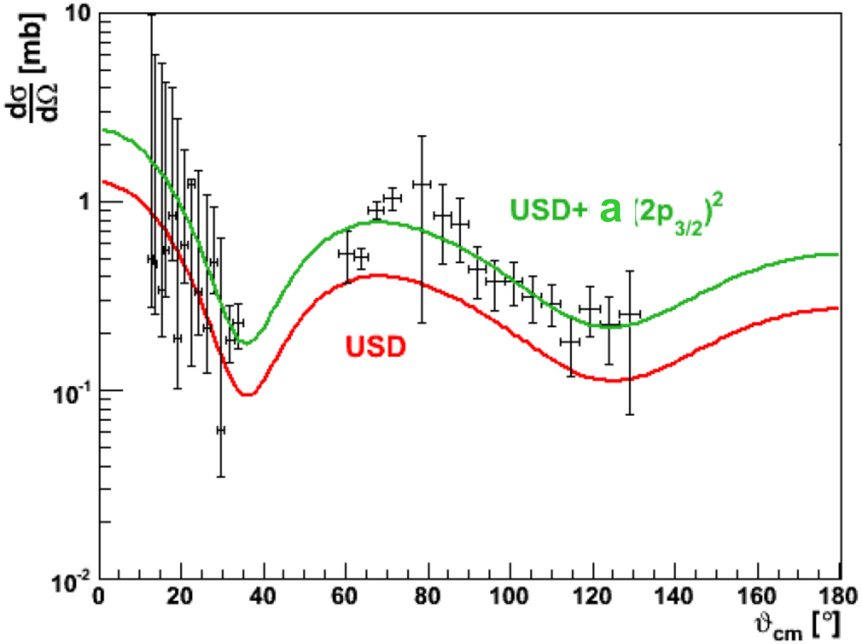

Wave function similar to g.s. in ^{30}Mg

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

$(1d_{5/2})^2$	$(2s_{1/2})^2$	$(1d_{3/2})^2$
-0.209	-0.184	-0.808

- **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., Phys. Rev. C 77, 014316 (2008)

d(^{28}Na,^{29}Na)p - IS502 … approved

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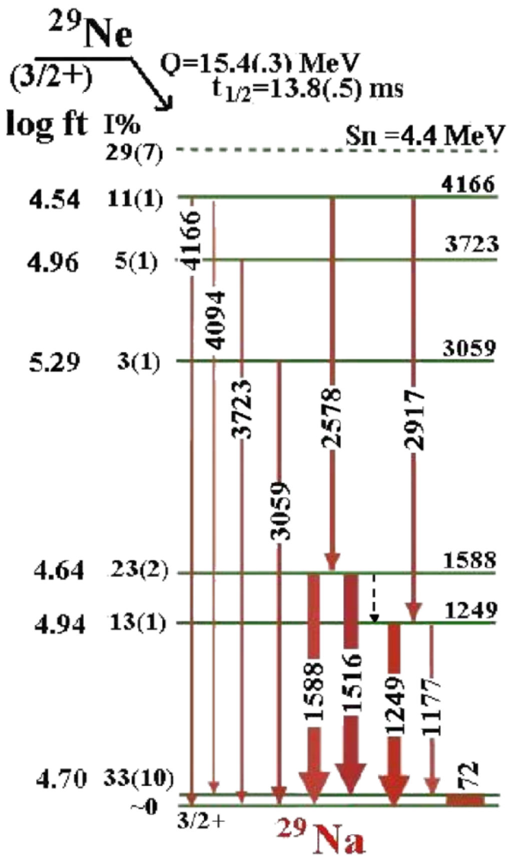
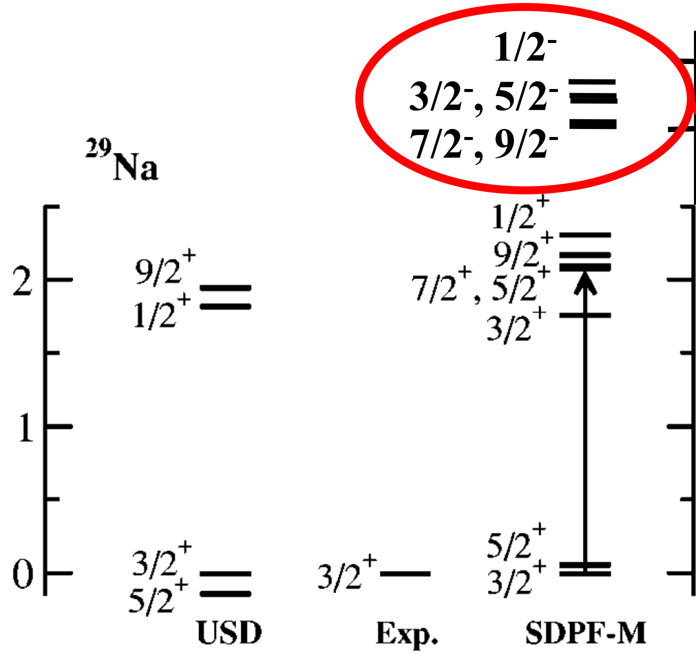
- **50%/50% mixture normal/intruder in gs wave function (from g factor)**
- **<u>Excited states</u>: correspondence exp ⇔ theory not obvious?!?**
  No spin assigments, no configurations





Negative parity states predicted by MCSM
➔ … Size of the N=20 gap

V. Tripathi et al., PRL 94, 162501 (2005)

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

t(^{44}Ar,^{46}Ar)p – probing N=28

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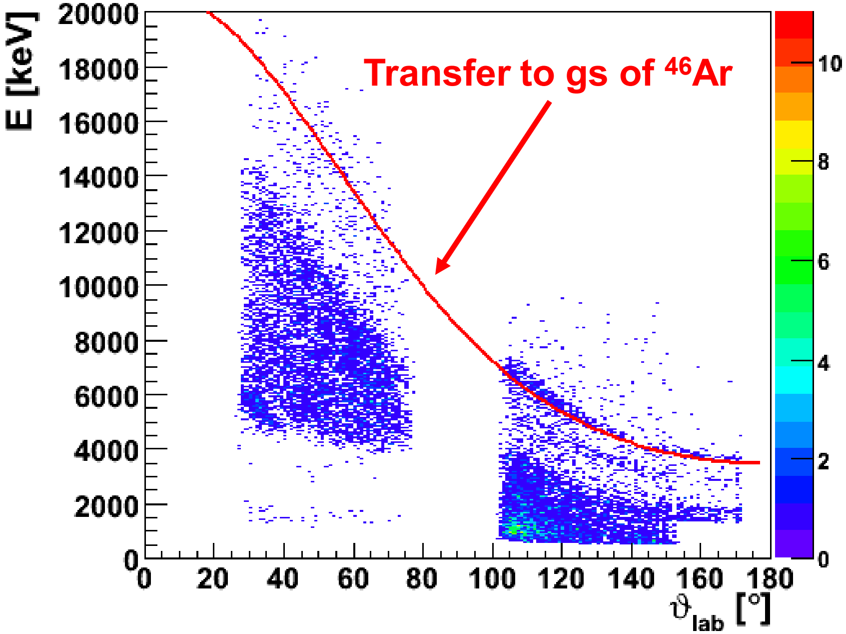
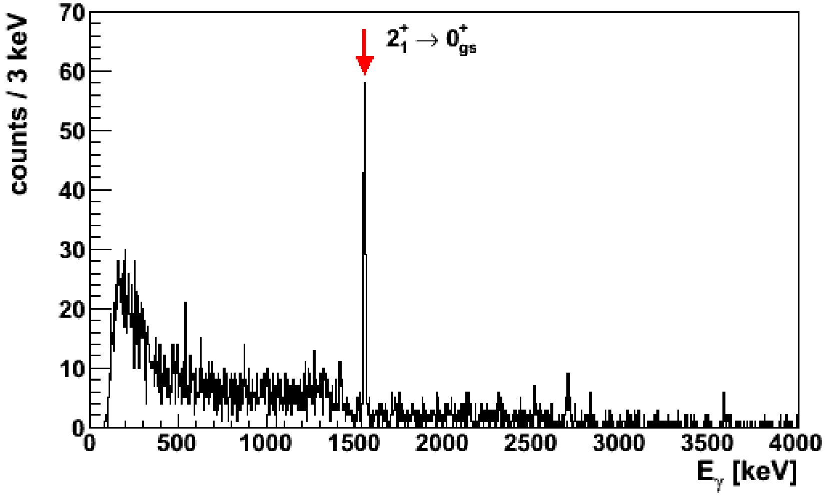
Weakening of N=28 closure below ^{48}Ca?
➔ onset of deformation / shape coexistence???
looking for the second 0^{+}

Fresh data from October 2010!!!

Identified protons



γ-rays in coincidence with protons



Analysis by <u>Katharina Nowak</u>
(PhD project at TU München)
Spokesperson/online-analysis: K. Wimmer

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

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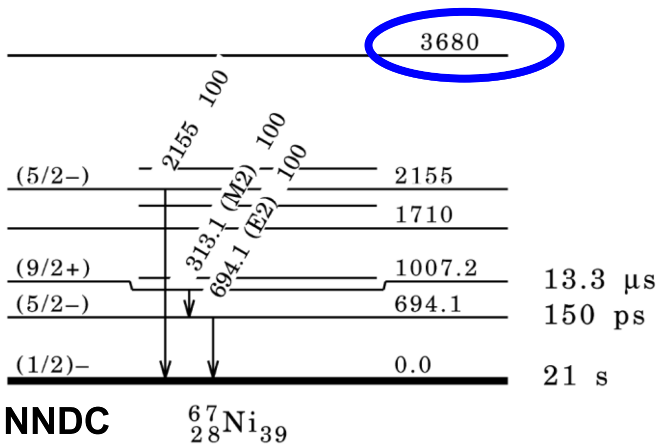
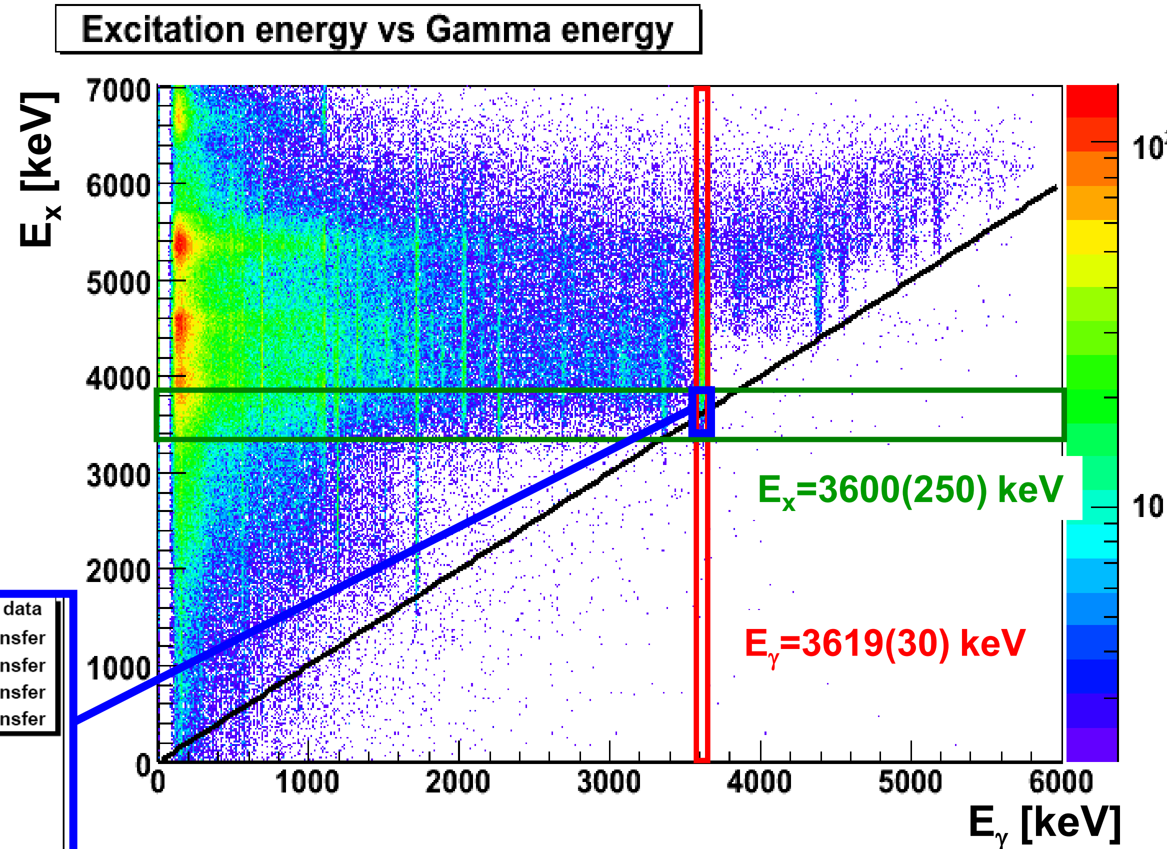
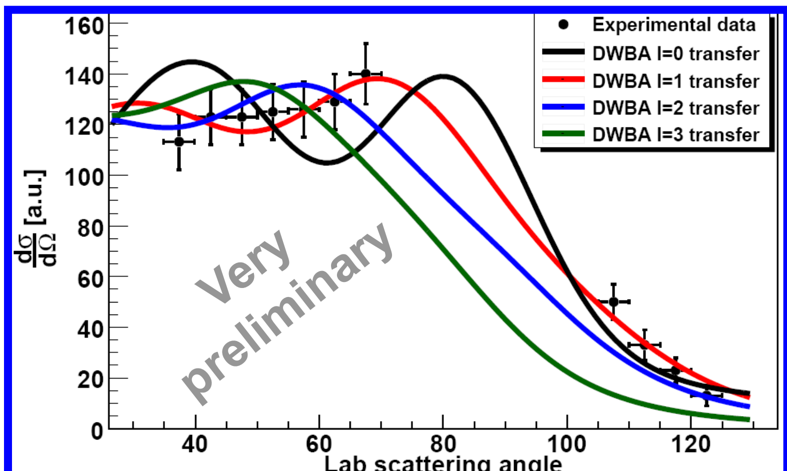
Exists shell closure at N=40?







… MINIBALL needed to resolve states!

Analysis by <u>Jan Diriken</u>
(PhD project at KU Leuven)

Transfer reactions at HIE-ISOLDE

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Higher energies at HIE-ISOLDE allow for transfer reactions also with heavy beams!

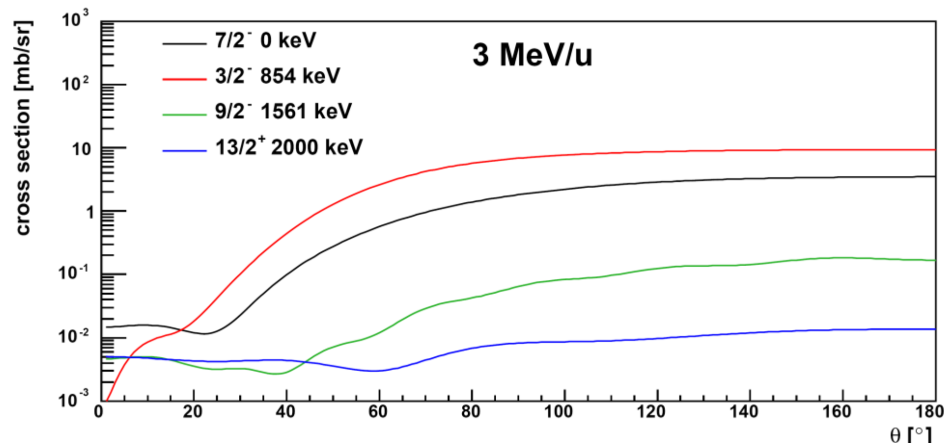
Several LoI's for HIE-ISOLDE involve nucleon transfer reactions with MINIBALL & T-REX:

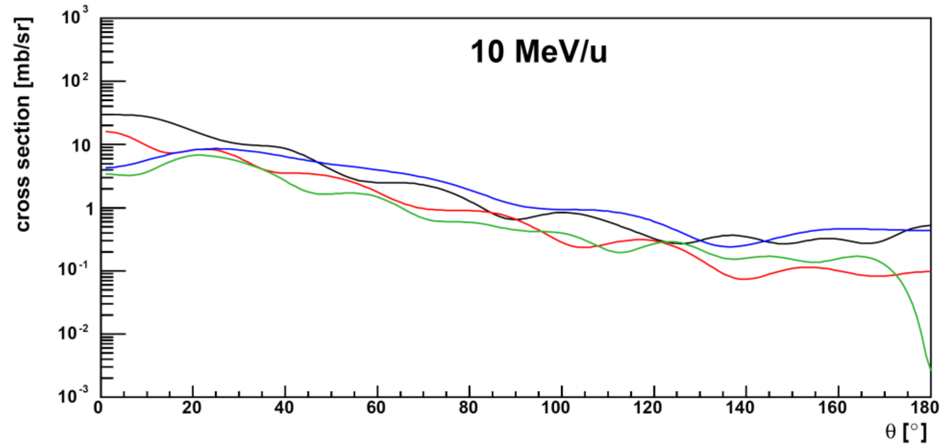
- **shell evolution**
- **shape coexistence**
- **pairing correlations ⇔ pair transfer**
- **nuclear astrophysics: (d,p) ⇔ (n,γ) capture reactions**

Upgrade of T-REX … more flexible geometry of Si detectors

Spectrometer planned to identify heavy transfer products

Showcase example: d(^{132}Sn,^{133}Sn)p





FRESCO calc's by K. Wimmer (NSCL, MSU)

A kind of summary ...

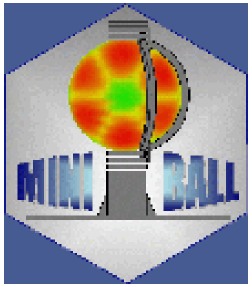
- One- and two-neutron transfer reactions at REX-ISOLDE … valuable tool to study exotic nuclei

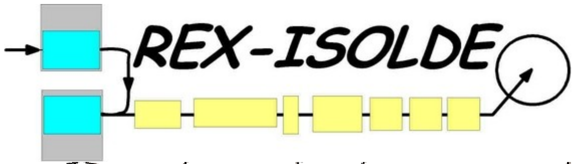
- Versatile set-up: T-REX & MINIBALL
- Particle - γ-ray coincidences often needed to identify populated states!!!

- Deuterium und Tritium targets
- Experiments performed with exotic Be to Zn beams

- First results published

… bright perspectives for transfer reactions at HIE-ISOLDE





Announcement: Spettrometer workshop

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Workshop on

Spectrometer for HIE-ISOLDE

March 10-11, 2011 at Lund

… further informations will be available soon

Organising Committee:
Joakim Cederkäll
Yorick Blumenfeld
Thorsten Kröll
Juha Uusitalo