Transfer reactions

into the

Island of Inversion

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University of Guelph

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bmb+f - Förderschwerpunkt
Hadronen - und Kernphysik
Großgeräte der physikalischen Grundlagenforschung

Outline

- Island of Inversion
- Transfer reactions (in inverse kinematics)
- T-Rex setup @ REX-ISOLDE
- d (^{30}Mg, p) ^{31}Mg experiment
- Summary

Outline
Island of Inversion
Nuclear shell structure away from stability
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Status of ^{31}Mg
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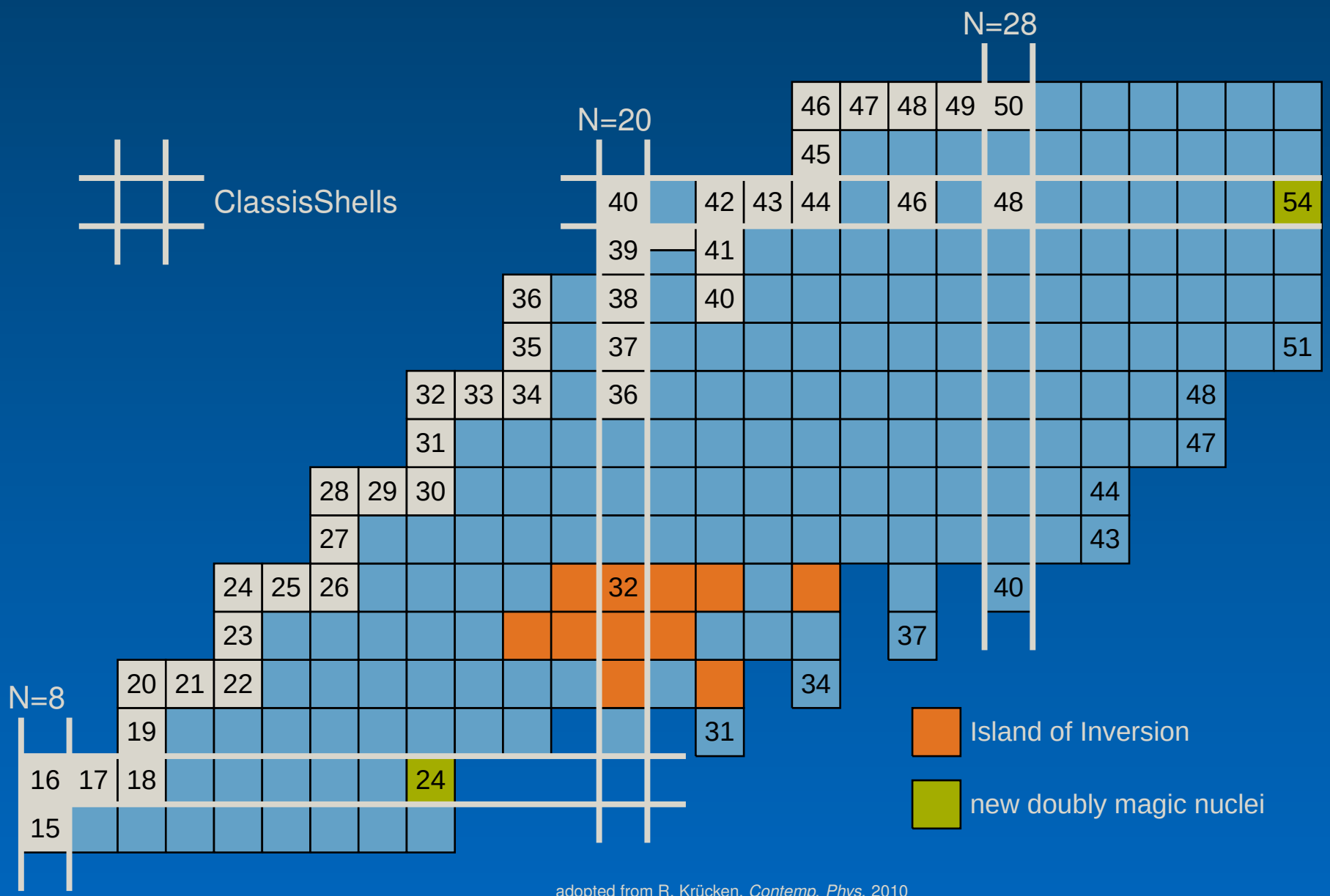
Nuclear shell structure away from stability

Technische Universität München

How do the magic numbers change when going away from stability?



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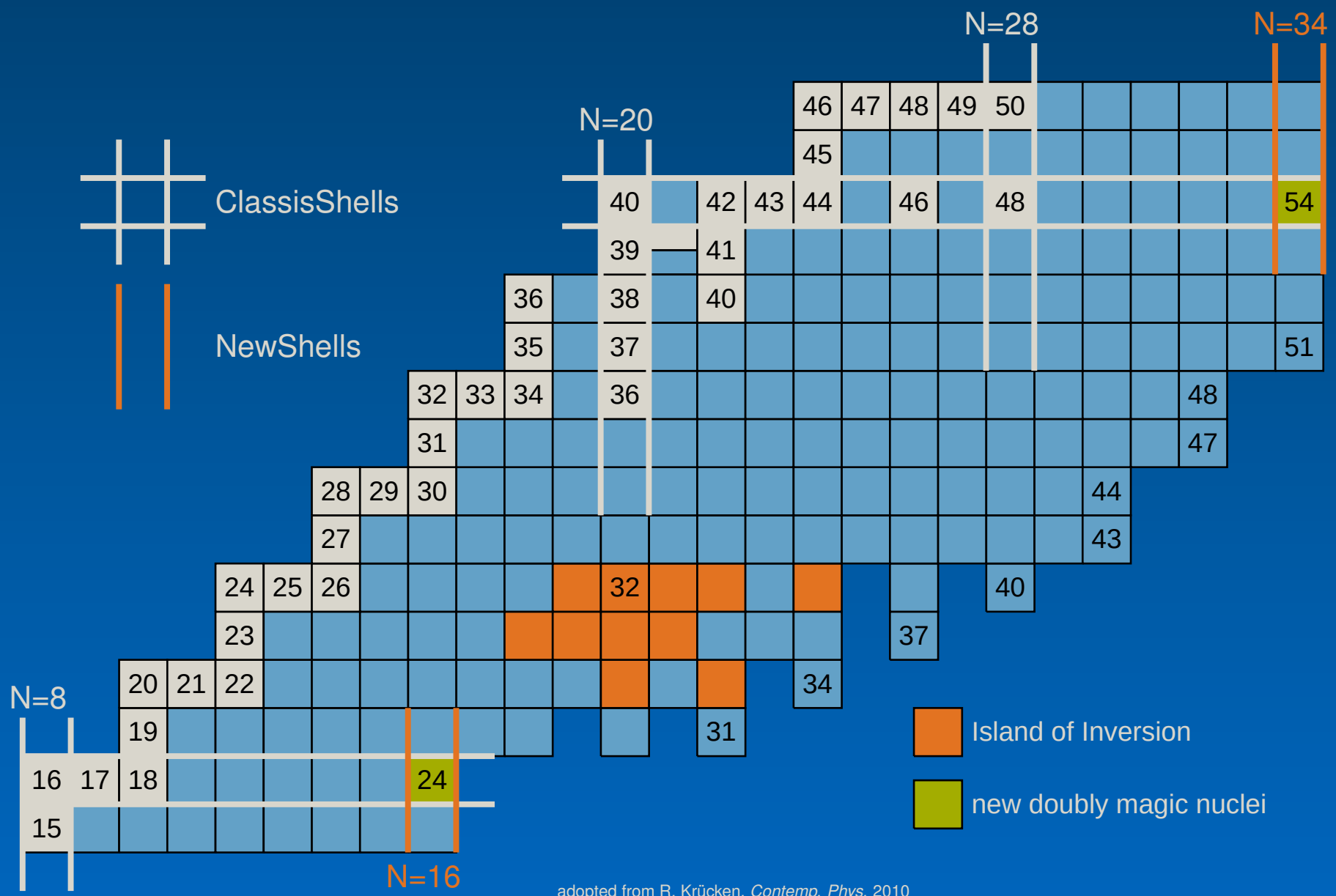

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monopole part of residual interaction

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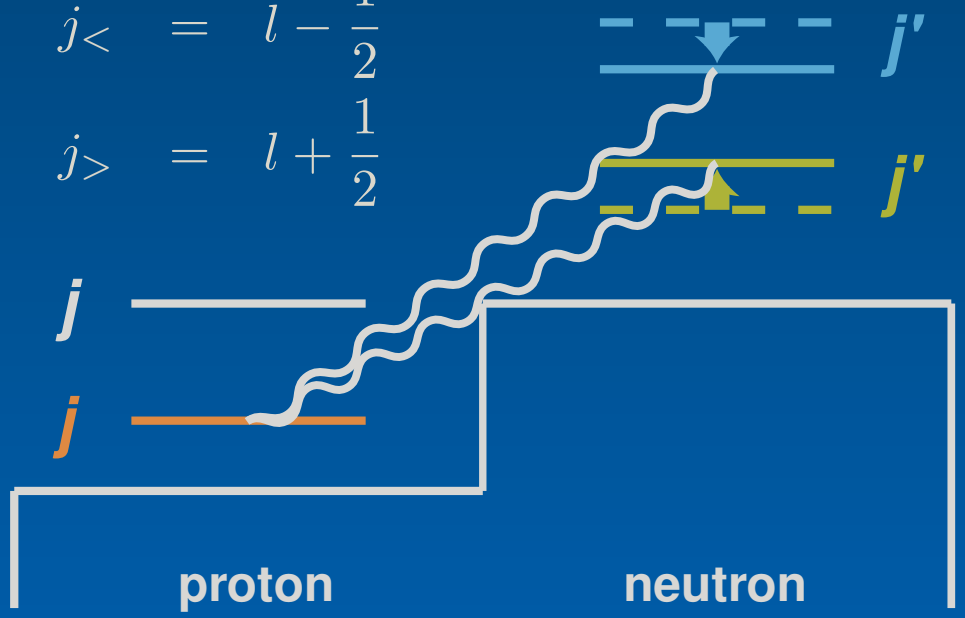

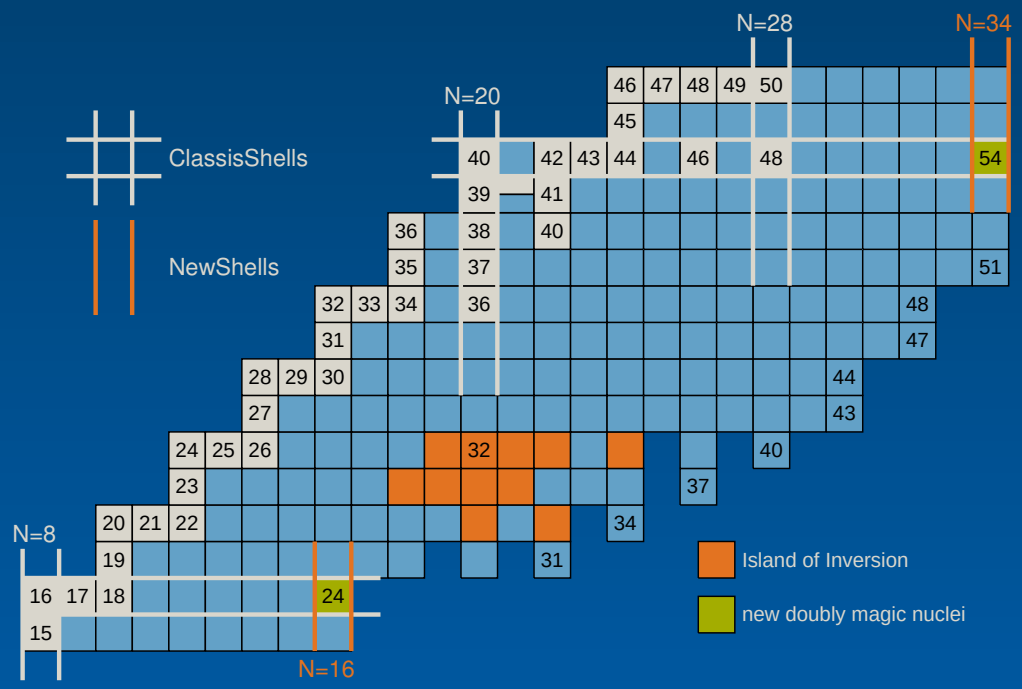

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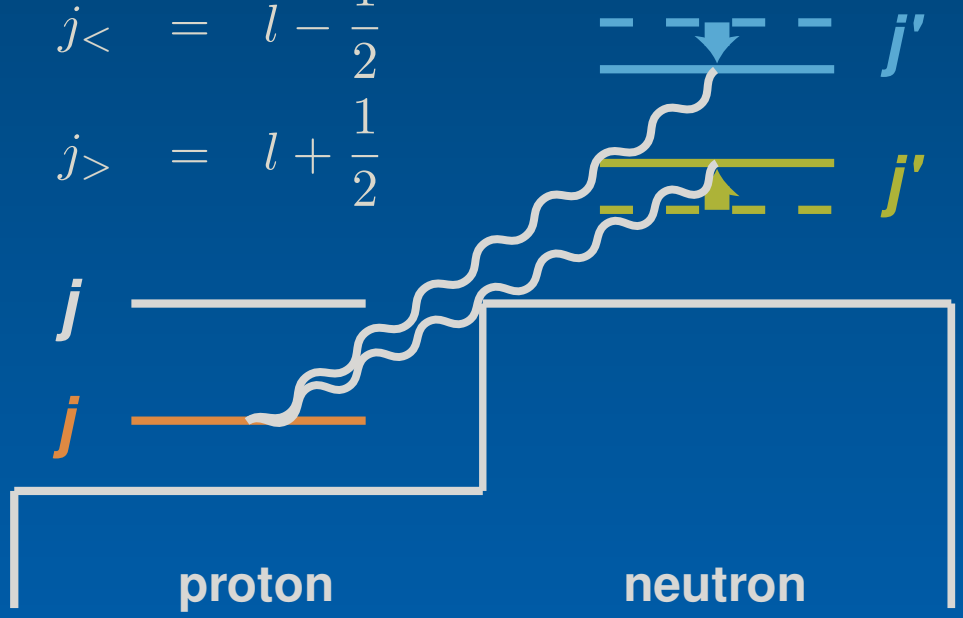

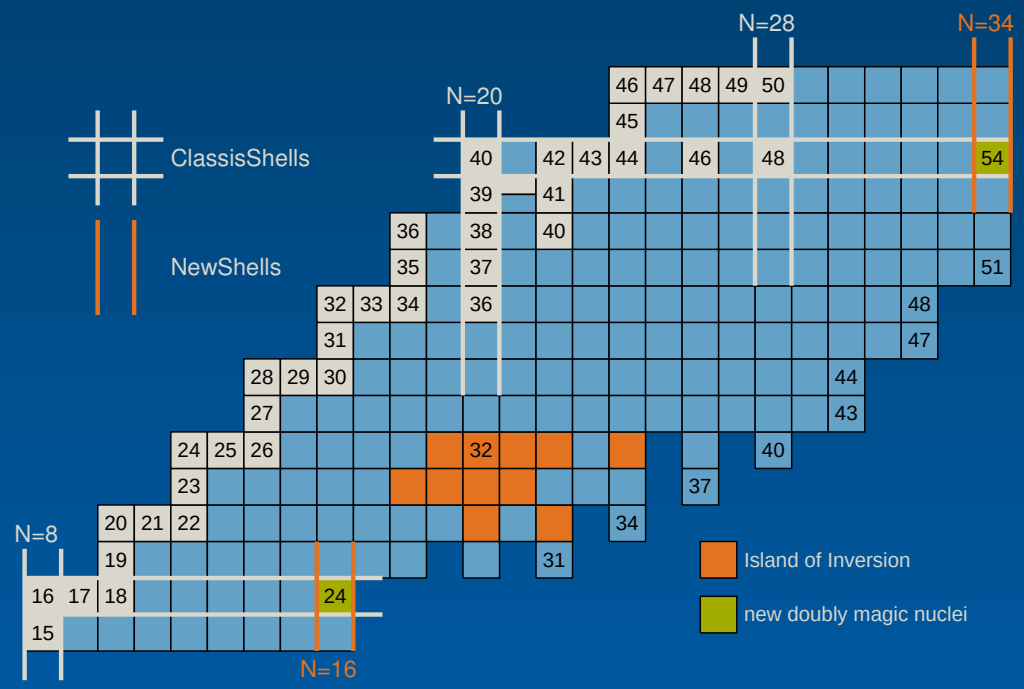

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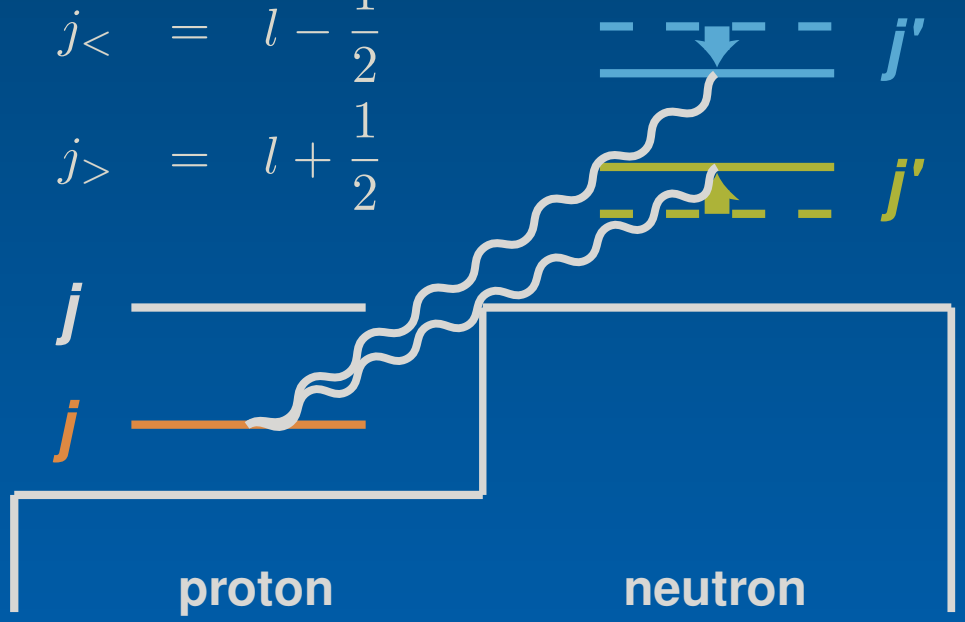
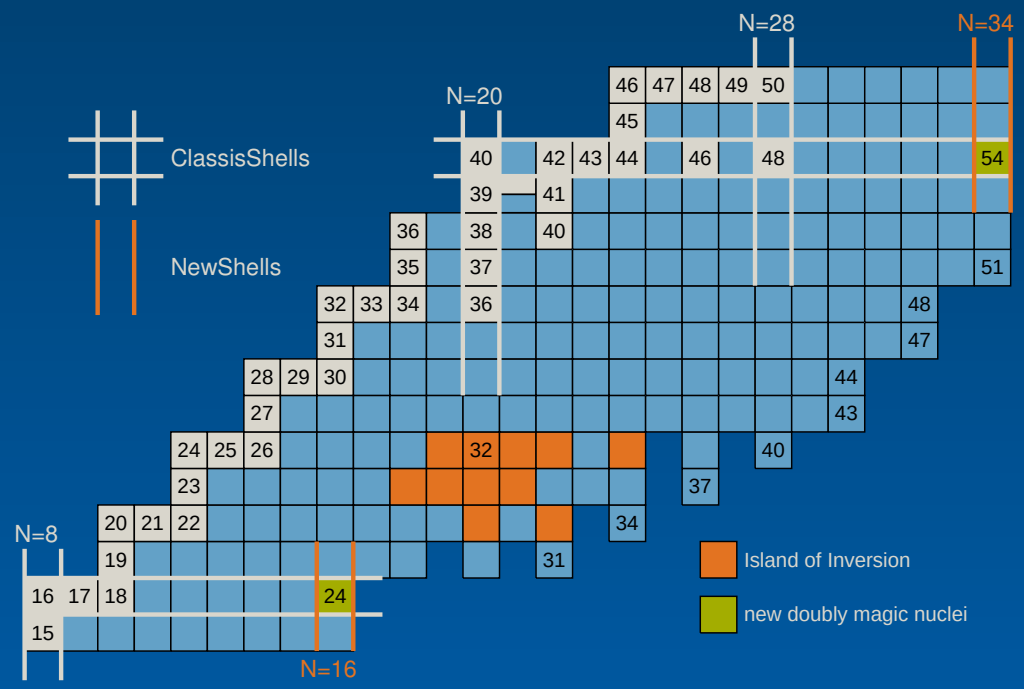
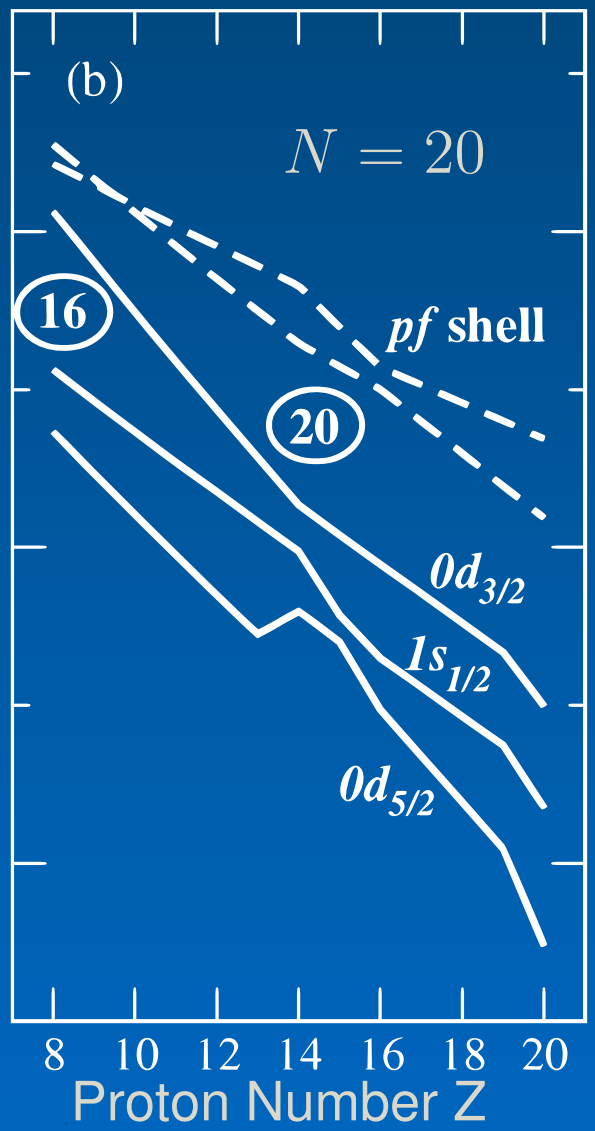


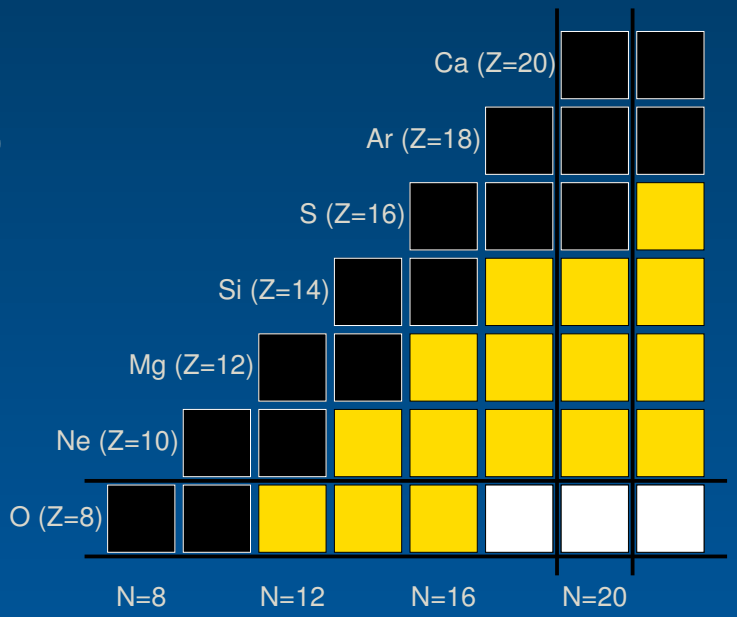


- stable nuclei: $N \gtrsim Z \Rightarrow$ $\pi j_>$ occupied $\longrightarrow$ lowering of $\nu j_<$
- neutron rich nuclei with same $N \Rightarrow$ $\pi j_>$ not occupied $\longrightarrow$ no lowering of $\nu j_<$

Island of Inversion

Frontiers and challenges of nuclear shell model
T. Otsuka *et al.*, Euro. Phys. Journal A **15**, 151 (2002)





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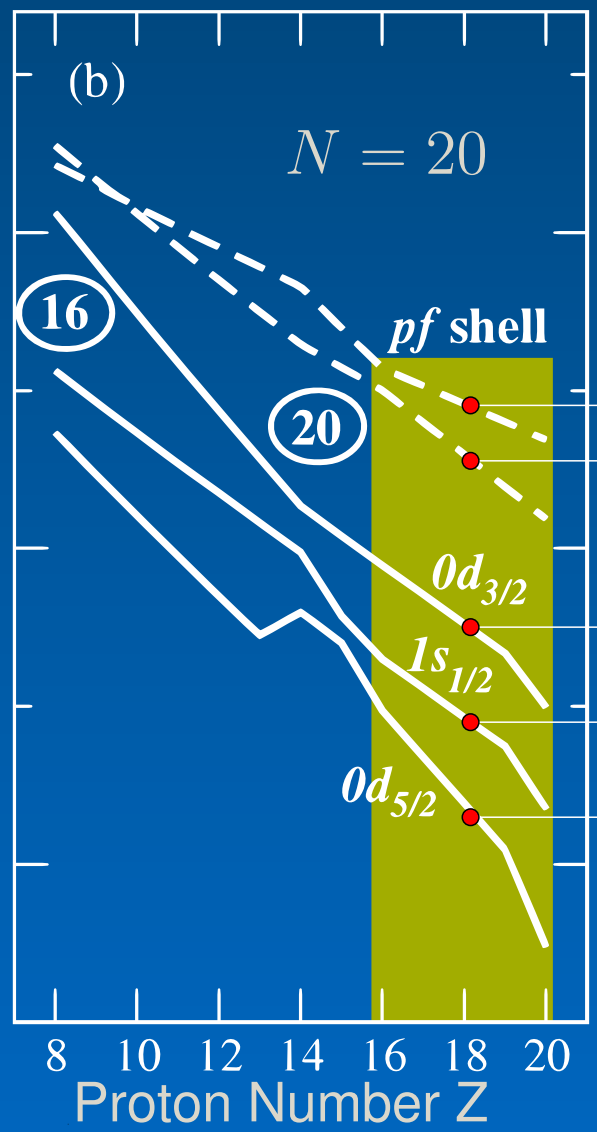

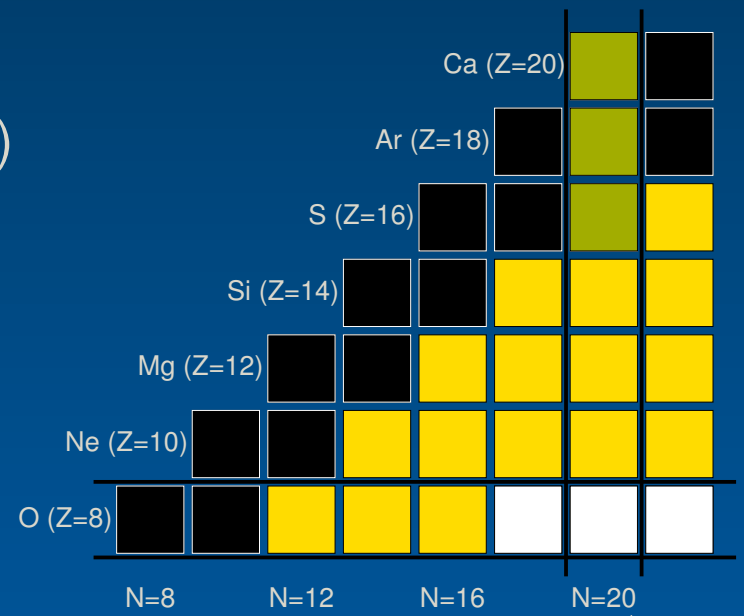

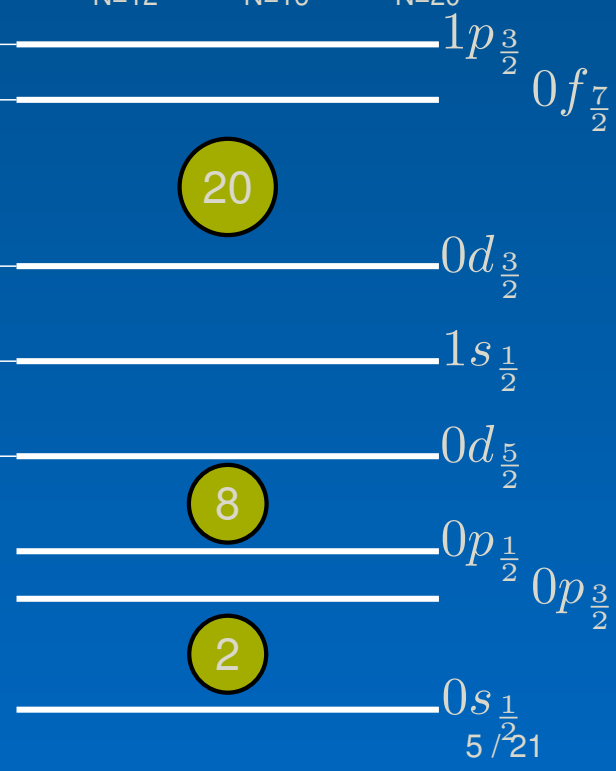

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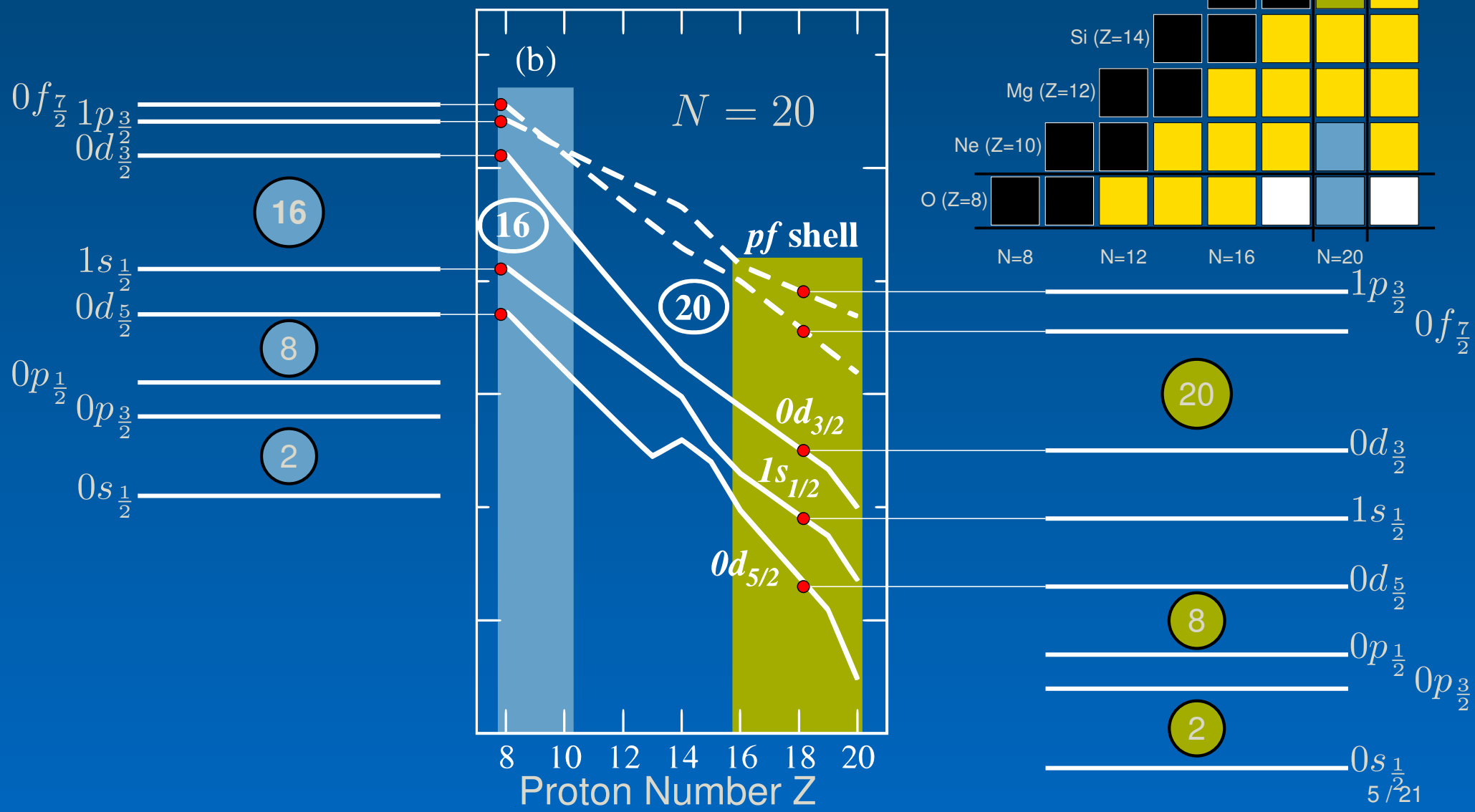

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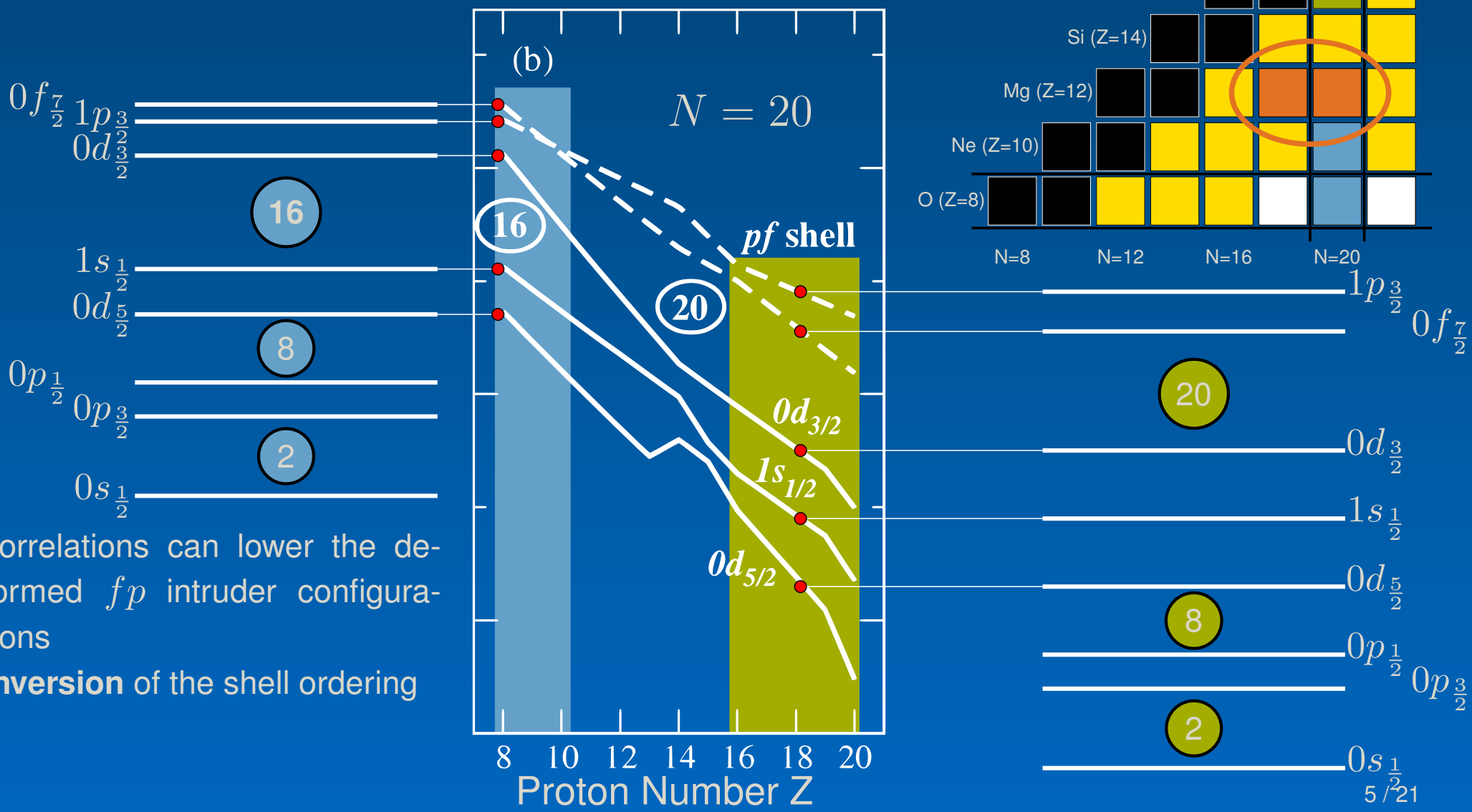


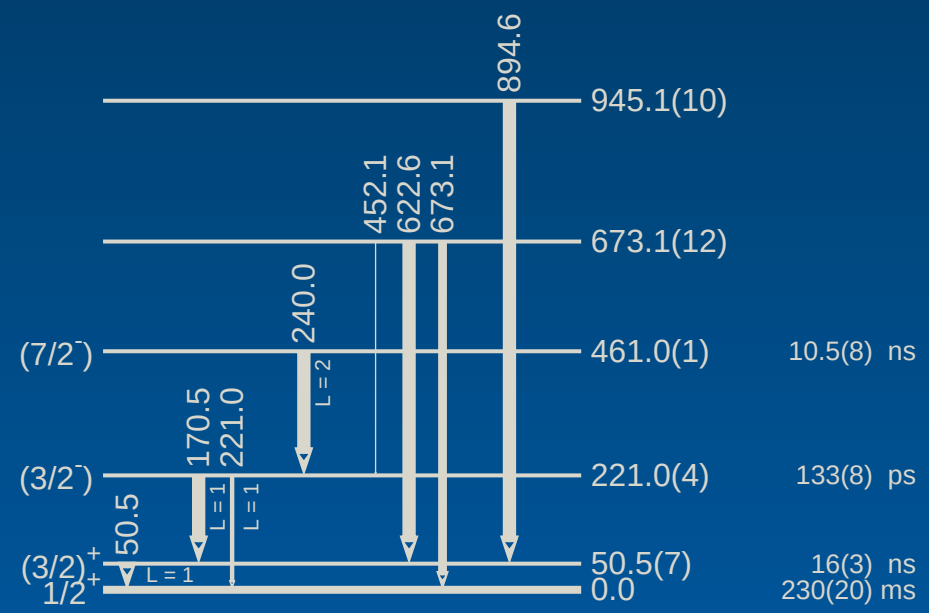
correlations can lower the deformed fp intruder configurations

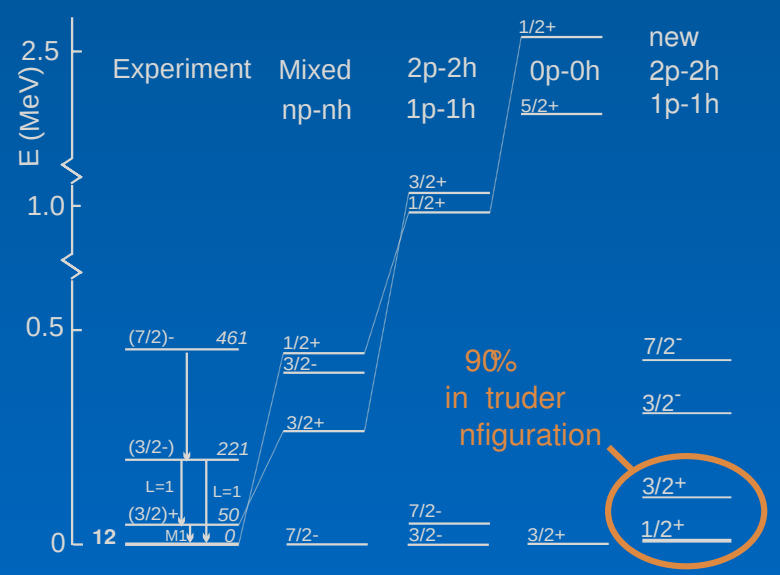
inversion of the shell ordering

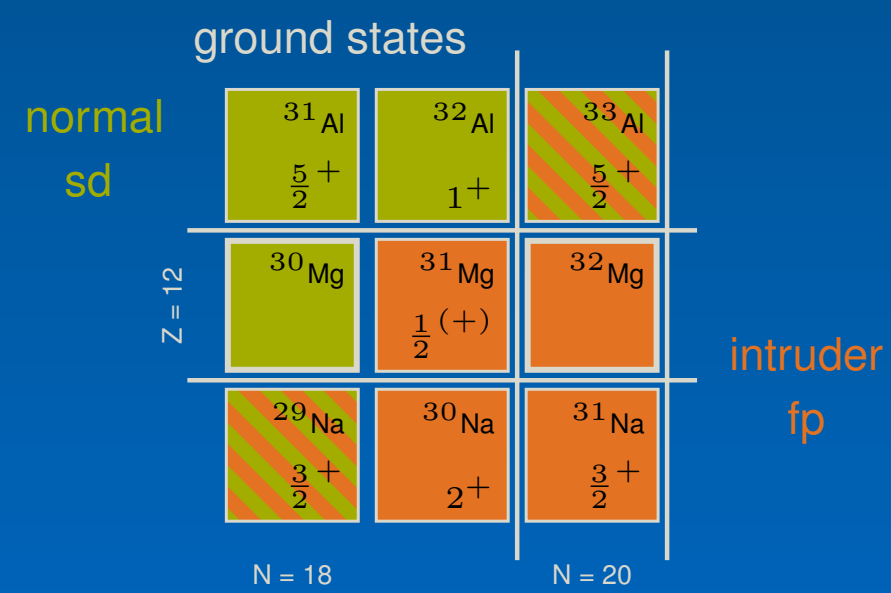
Status of ^{31}Mg

Many experiments using differents techniques have been used to explore the Island of Inversion, e.g.:

- β-decay experiments yielded first information about γ-ray multipolarities and lifetimes
- β-NMR study discovered the $1/2^{(+)}$ ground state







mostly g-factor measurements

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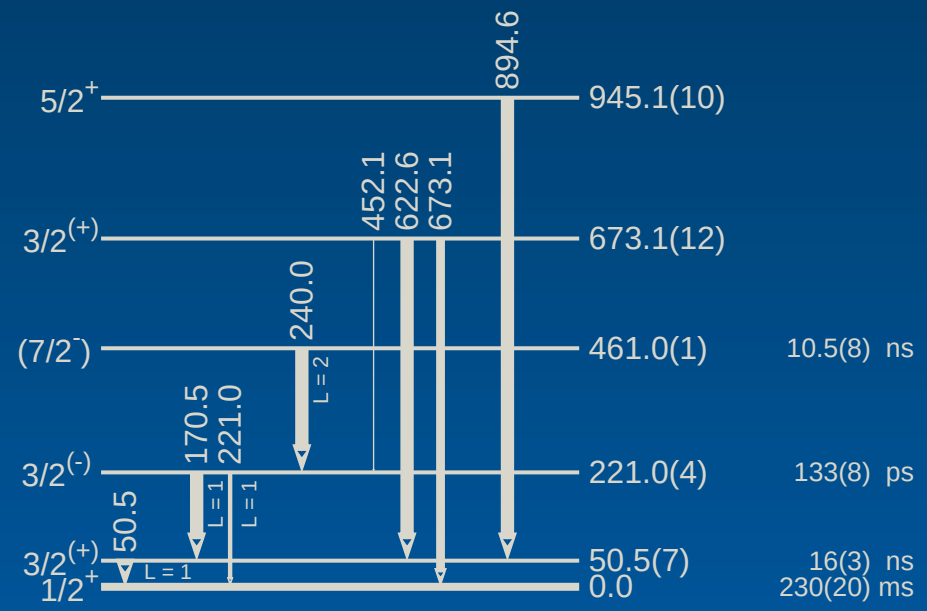
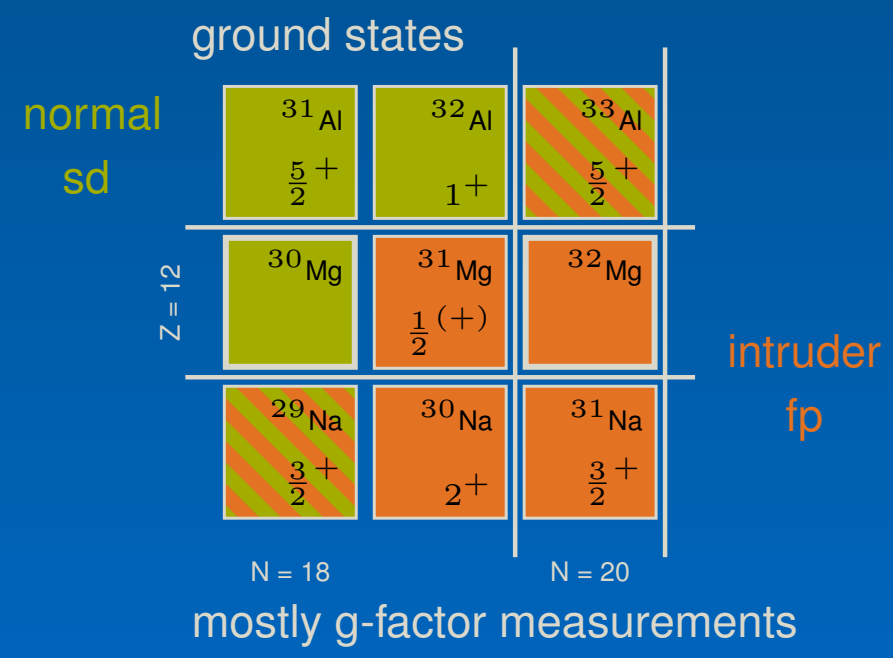
- β-decay experiments yielded first information about γ-ray multipolarities and lifetimes
- β-NMR study discovered the 1/2$^{(+)}$ ground state
- proton-knockout showed $J = 3/2$ spin for the first two excited states
- Coulomb excitation gave further information about transition strengths





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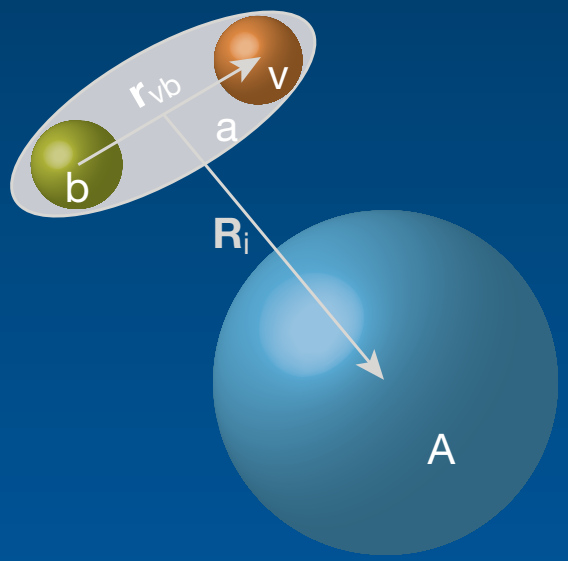
Transfer Reactions and DWBA



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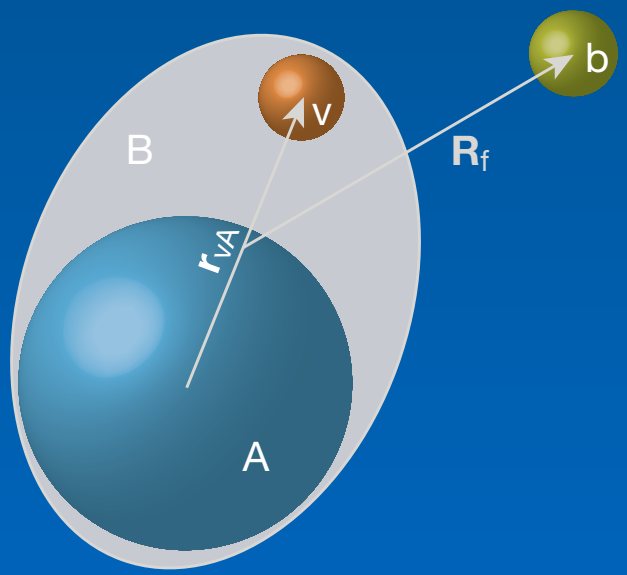

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The DWBA theory replaces the exact solution of the three-body problem with a distorted wave multiplied with a corresponding bound state.The input needed for the DWBA are

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- the core-core interaction between b and A, and
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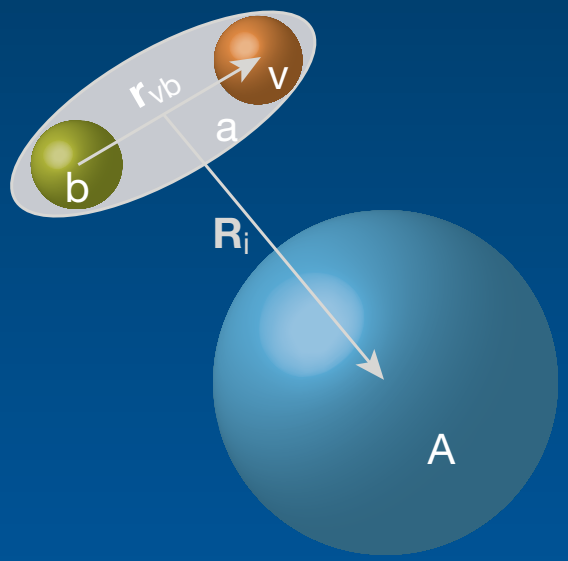

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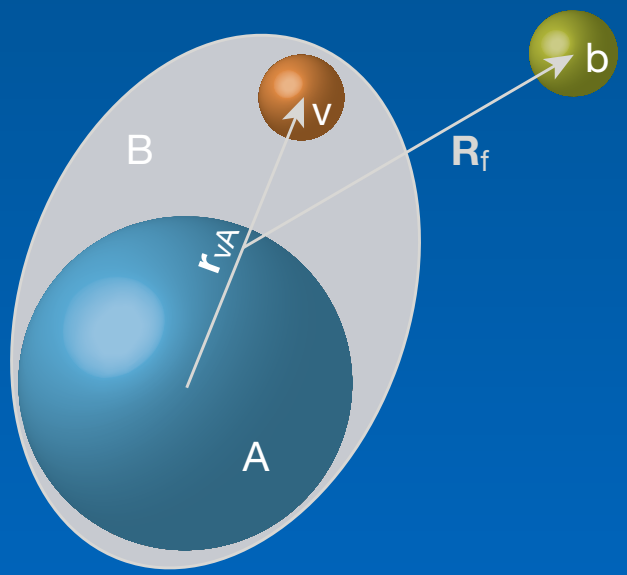

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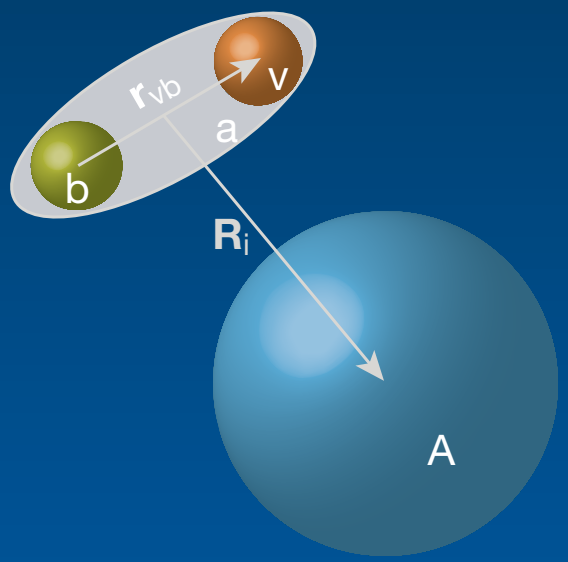

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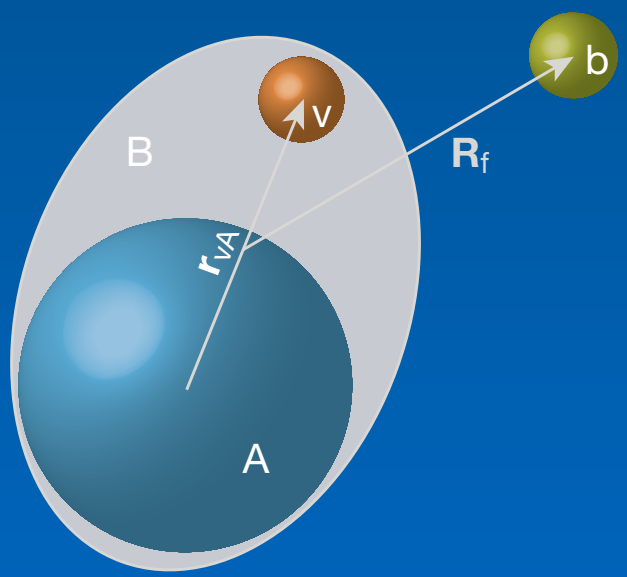

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  S: overlap of real wave function with pure single-particle wave function

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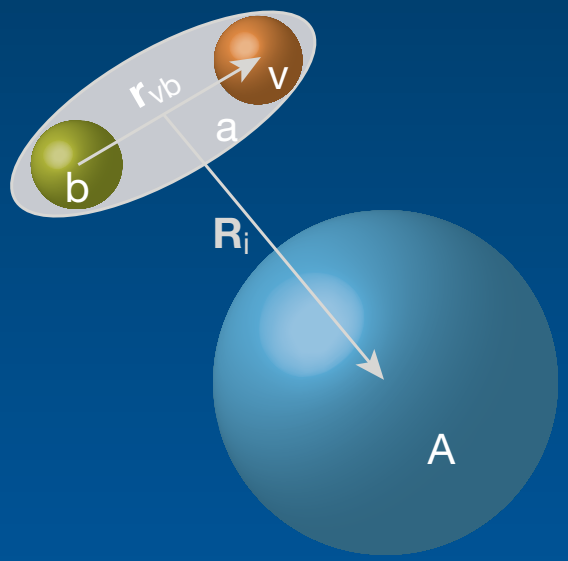

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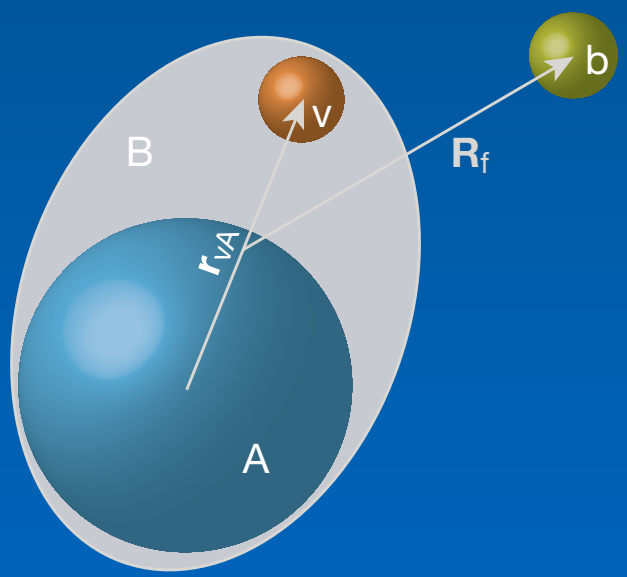

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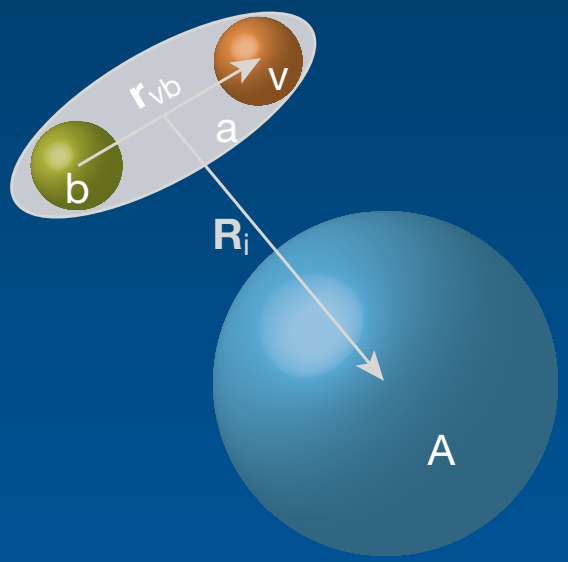

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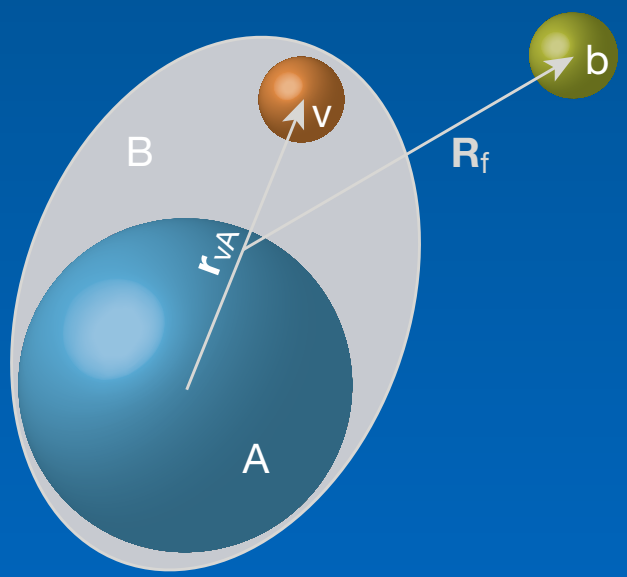

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$\Rightarrow$typical energies are around 5–10 MeV/u

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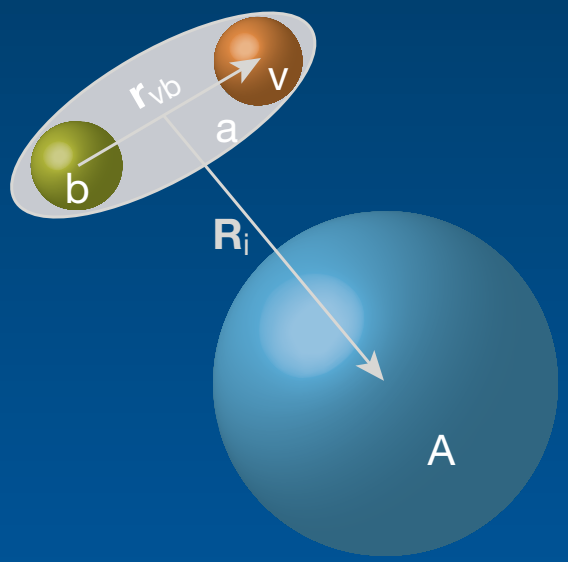

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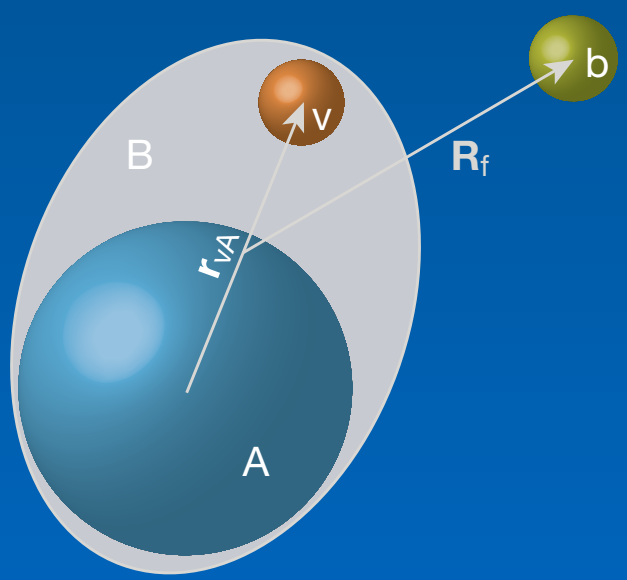

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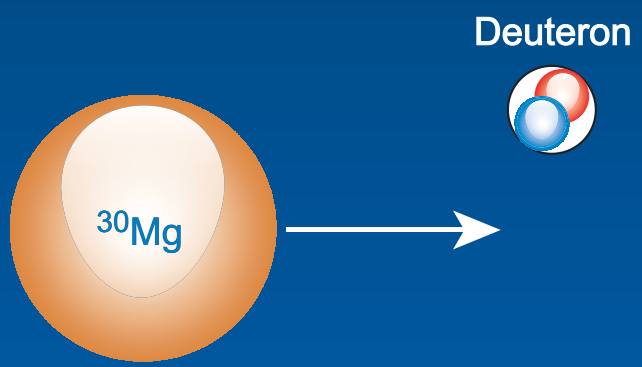
low energies allow for background from compound reactions

Transfer Experiments with RIBs

radioactive ion beam impinges on target with deuterons (deuterated poly-ethylene)



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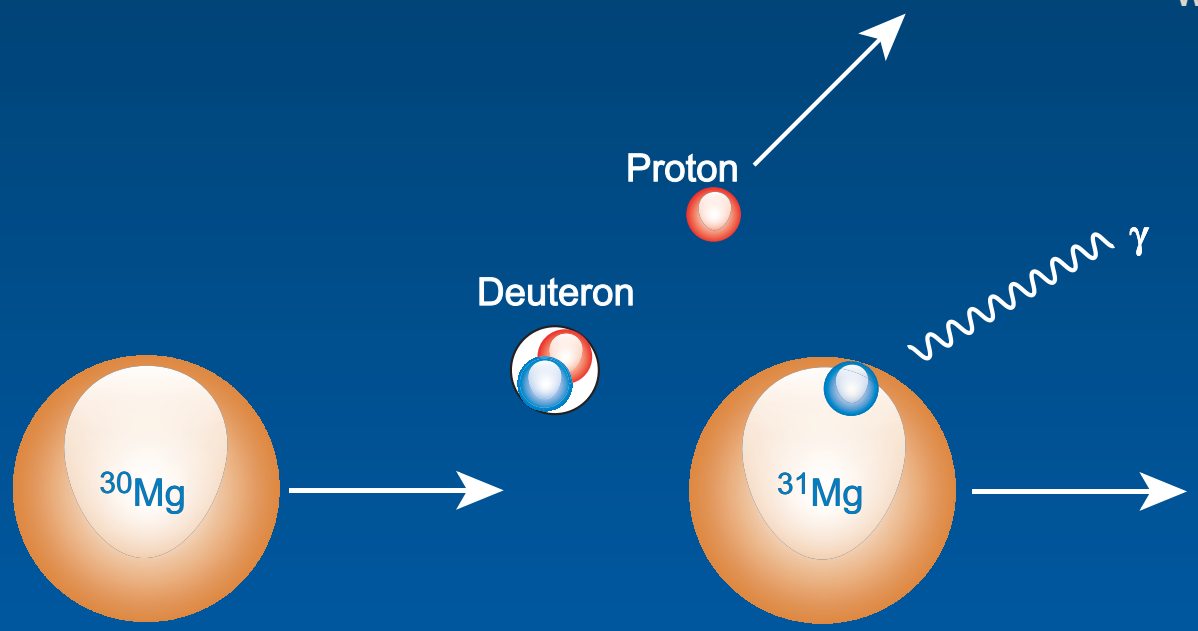

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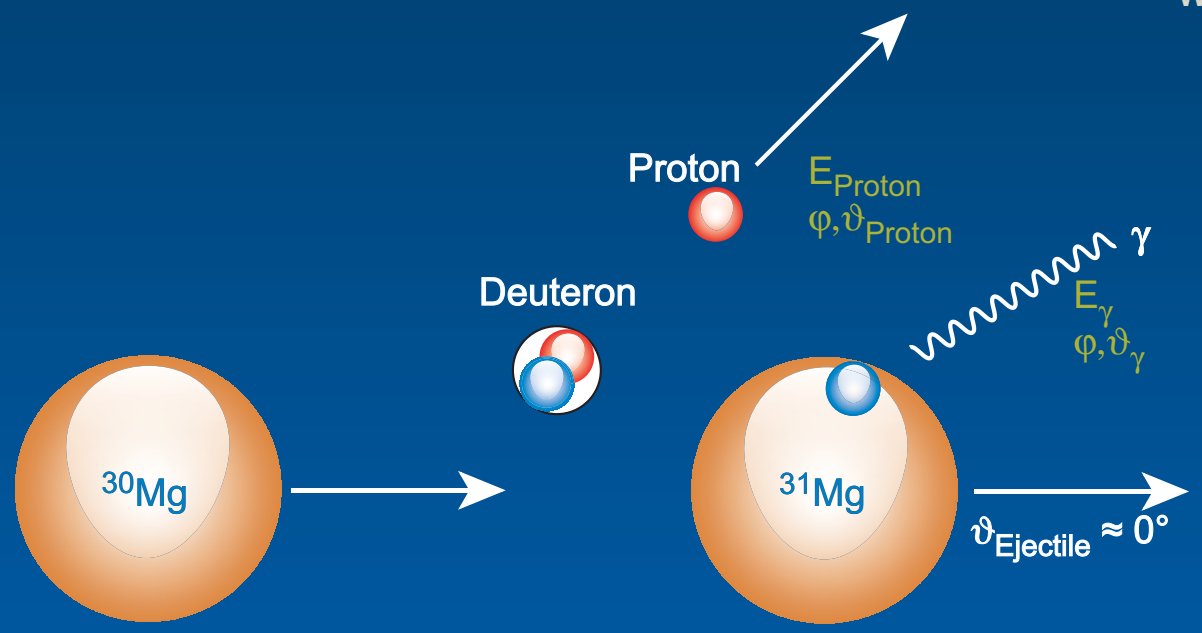

radioactive ion beam impinges on target with deuterons (deuterated poly-ethylene)

- excitation energies
  $\Rightarrow$ single particle energies

comparing with DWBA calculations (FRESCO code)

- particle angular distributions
  $\Rightarrow$ orbital momenta l
- cross sections
  ($\Rightarrow$ transfer cross section scaling factors S)

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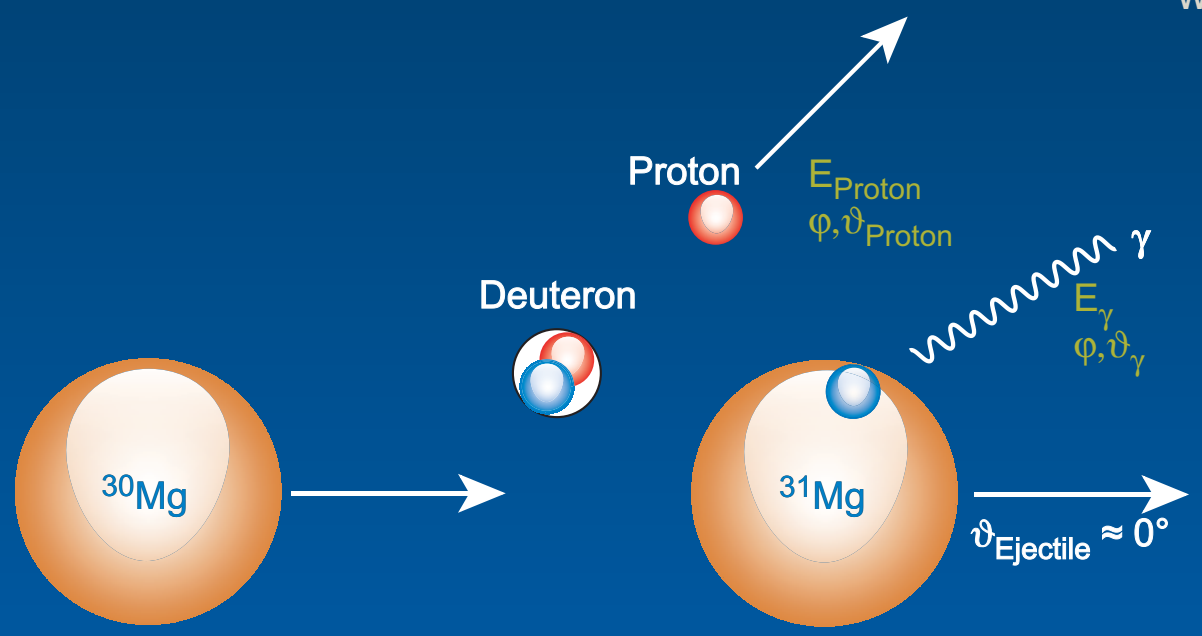

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differences in inverse kinematics:

- lower beam intensities (typical 10^{4-6} instead of 10^{10-12} particles/s)
- thicker target necessary $\Rightarrow$ higher energy losses in target
- lower E_{cm} $\Rightarrow$ no extraction of spectroscopic factors possible
- $\Delta E^* = 1$ MeV $\Rightarrow \Delta E_{lab}(p)$ @ 180° $\approx$ 300 keV
- $E_{lab}(p)$ @ 180° can be very low (500 keV)

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REX-ISOLDE
REX
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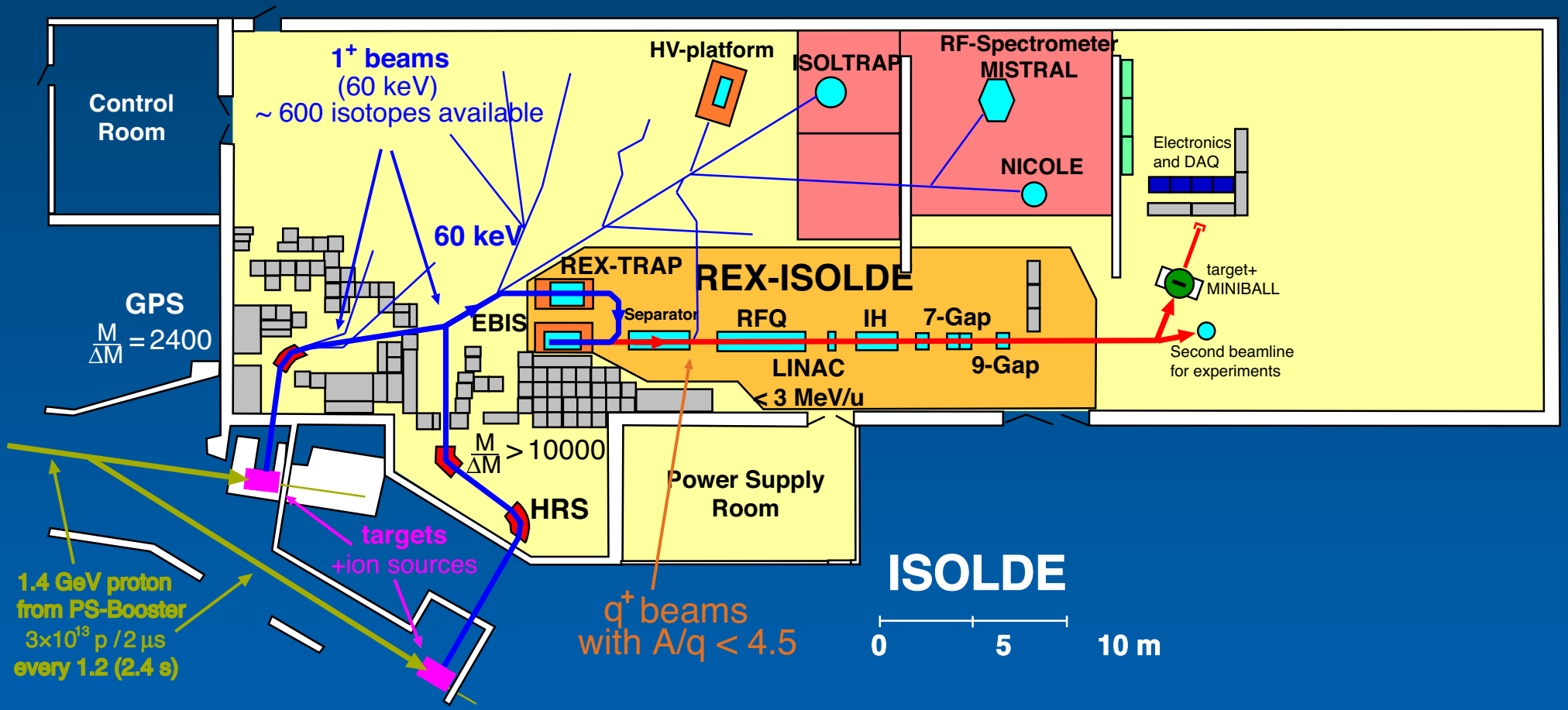
T-REX @ REX-ISOLDE

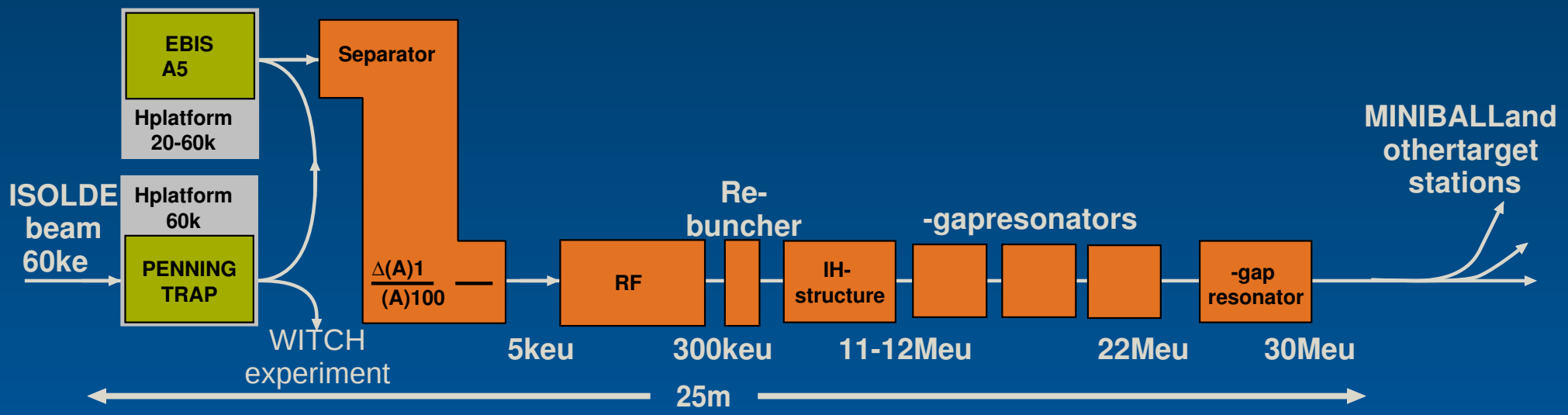
REX-ISOLDE

beam energy: 2.86 MeV/u = 85.8 MeV



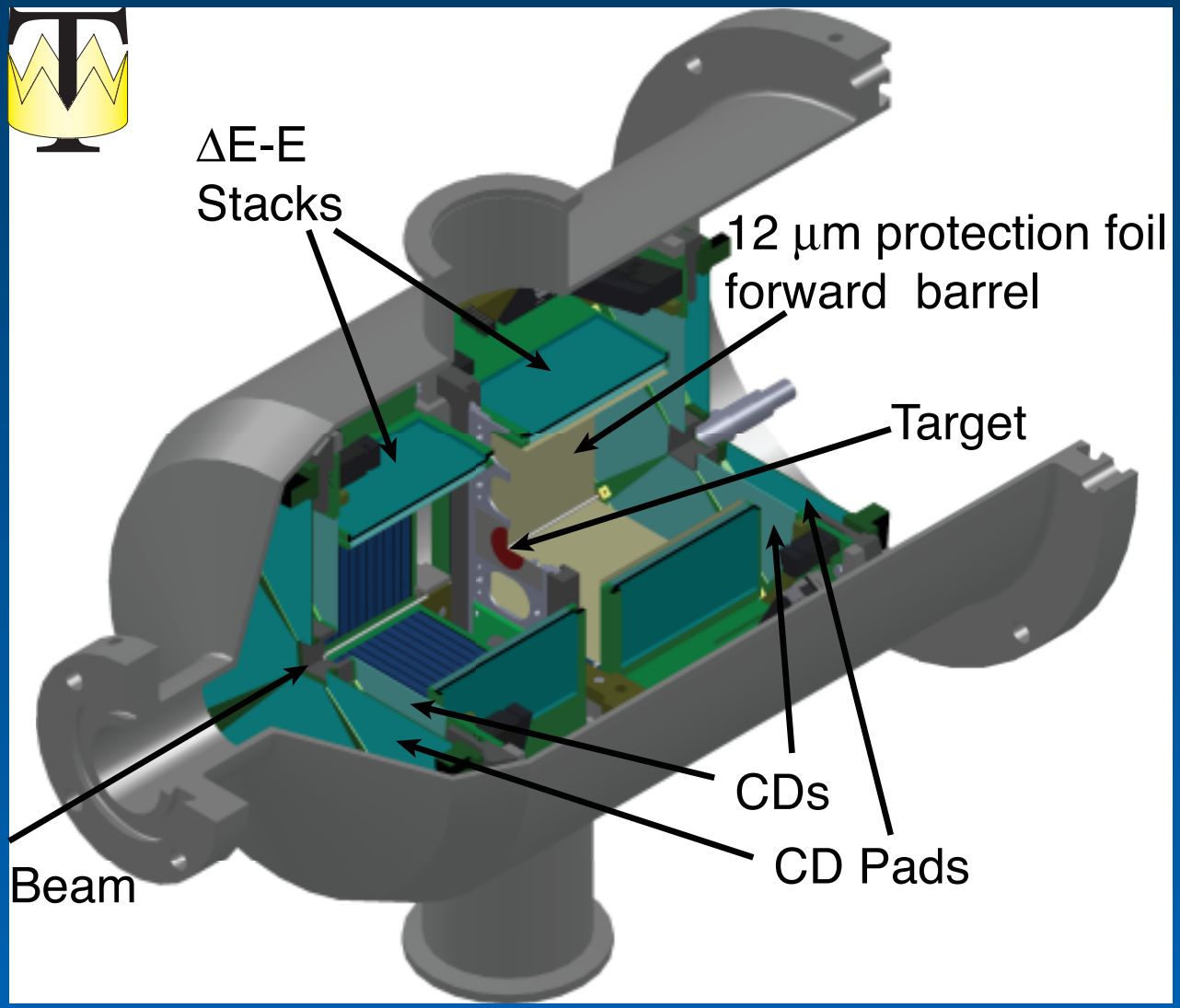
- fragmentation/fission/spallation of UCx-target by 1.4 GeV protons
- ionisation by Resonance Ionization Laser Ion Source (RILIS)
- mass-separation in General Purpose Separator (GPS)

REX



- collecting, cooling and bunching of 60 keV 1^+ ions in REX-TRAP
- charge breeding in EBIS to $A/q < 4.5$
- A/q separation
- acceleration to < 3 MeV/u
- upgrade to HIE-ISOLDE: up to 5.5 MeV/u (2013) and 10 MeV/u later

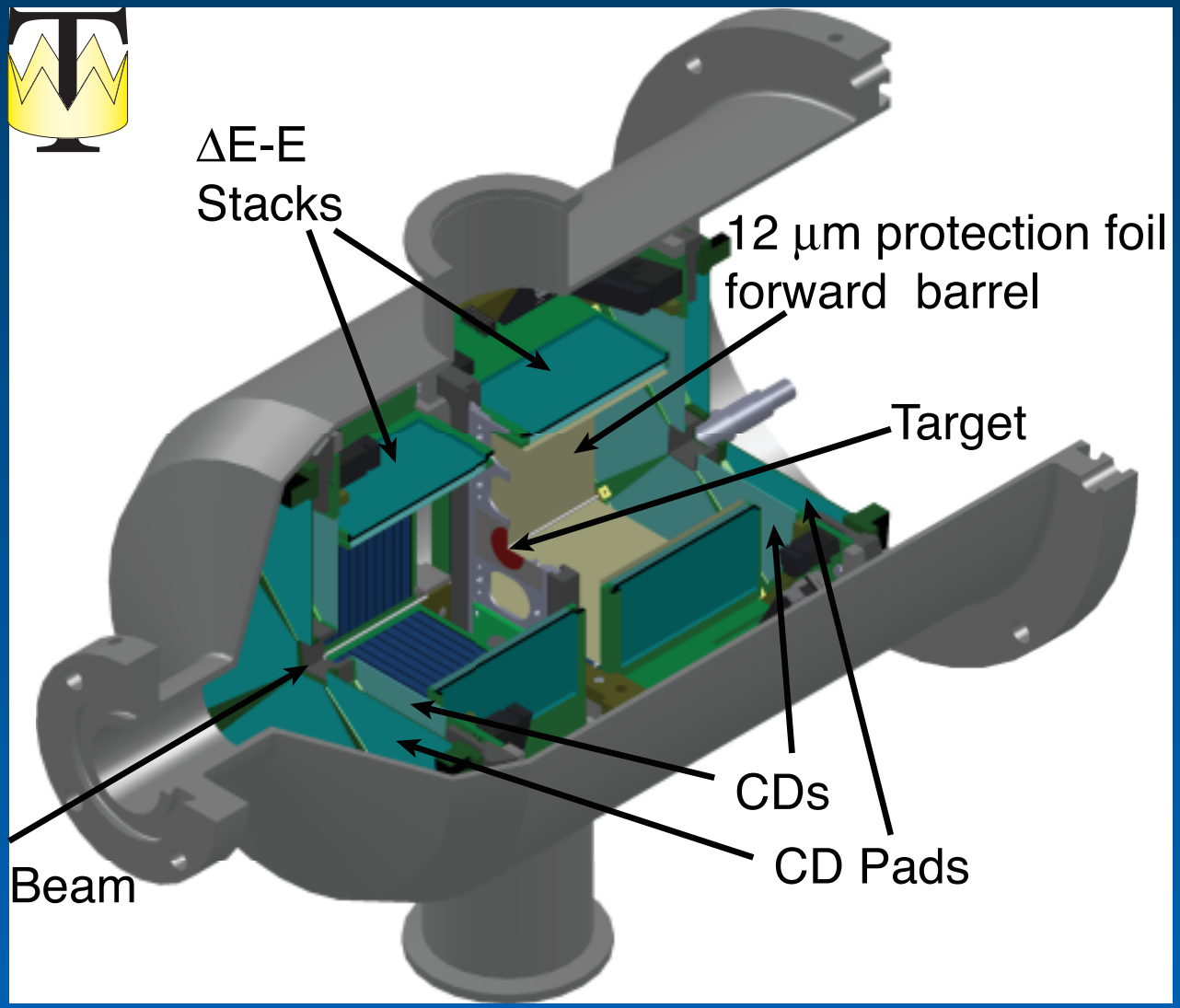
T-REX



barrel silicon detector stacks:

- ΔE: 140 µm position sensitive resistive strip detectors
- E: 1 mm pad detectors
- ϑ_{lab}: 28–78, 102–152°
  $\Delta\vartheta \approx$ 2–6°
- $\Delta\Omega$: 56 %

T-REX



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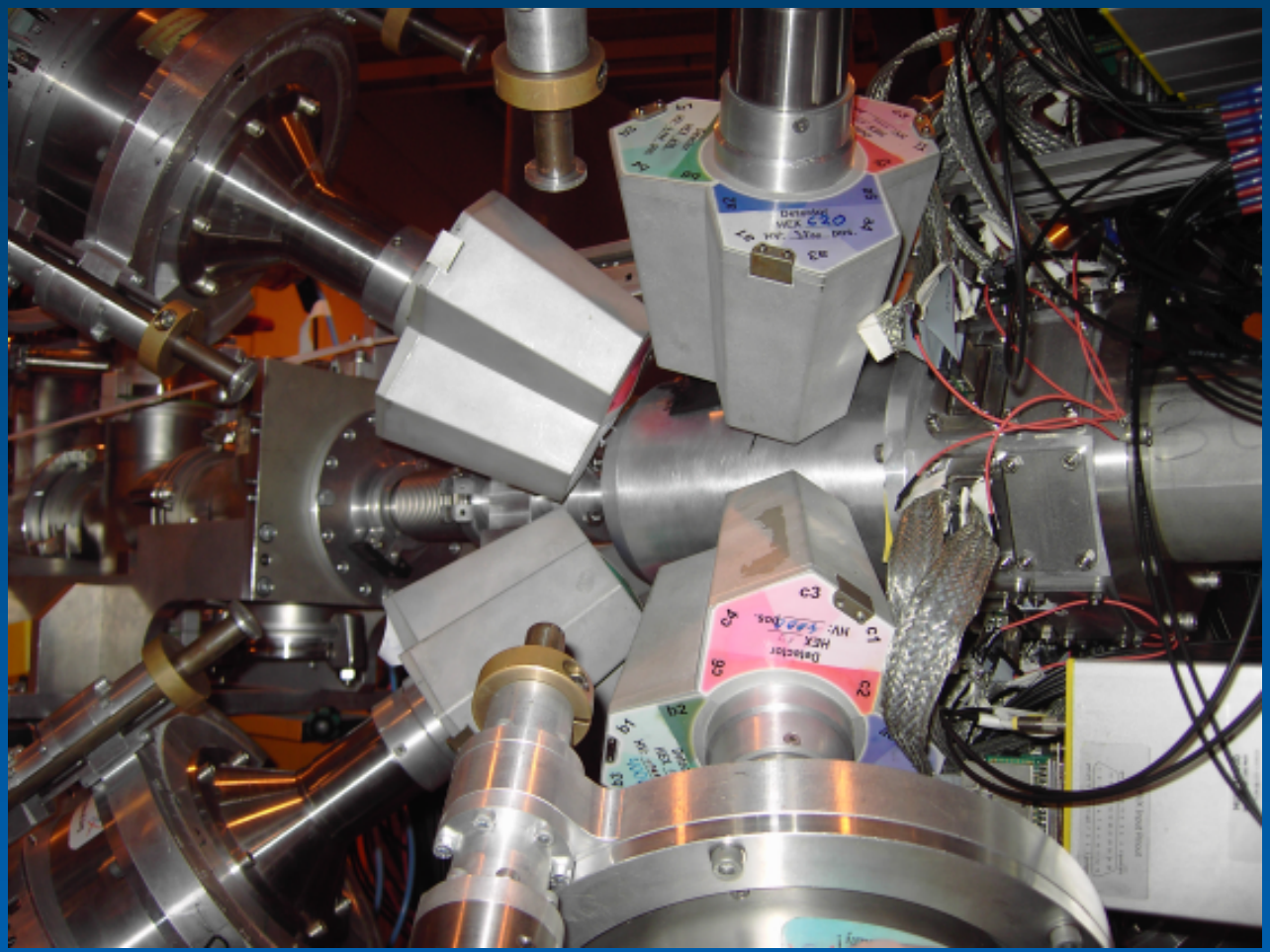
CD silicon detector stacks:

- forward ΔE - E: 500/1500 µm
- backward ΔE - E: 140/500 µm
- ϑ_{lab}: 8–28, 152–172°
  $\Delta\vartheta \approx$ 2°
- $\Delta\Omega$: 10 %
  $\Rightarrow \Delta\Omega_{tot} = 66\,\%$

T-REX



barrel silicon detector stacks:

- ΔE: 140 µm position sensitive resistive strip detectors
- E: 1 mm pad detectors
- ϑ_{lab}: 28–78, 102–152°
  $\Delta\vartheta \approx$ 2–6°
- $\Delta\Omega$: 56 %

CD silicon detector stacks:

- forward ΔE - E: 500/1500 µm
- backward ΔE - E: 140/500 µm
- ϑ_{lab}: 8–28, 152–172°
  $\Delta\vartheta \approx$ 2°
- $\Delta\Omega$: 10 %
  $\Rightarrow \Delta\Omega_{tot} = 66\,\%$

Miniball γ-spectrometer:

- 24 6-fold segmented HPGe crystals in 8 triple cluster
  $\varepsilon_{ph}(1332\,\text{keV}) = 5.0(3)\,\%$ (with addback)

Outline
Island of Inversion
Transfer Reactions
T-REX @ REX-ISOLDE
d (^{30}Mg, p) ^{31}Mg
d (^{30}Mg, d) ^{30}Mg
γ-Spectrum from d (^{30}Mg, p) ^{31}Mg
Angular Distributions of ^{31}Mg
^{31}Mg in the Nilsson Model
Summary

d (^{30}Mg, p) ^{31}Mg

d (^{30}Mg, d) ^{30}Mg

Experiment in 2008:

- $E_{\mathrm{beam}} = 2.85\,\mathrm{MeV/u}$
- 1 mg/cm^2 deut. PE
- 25 hours of data

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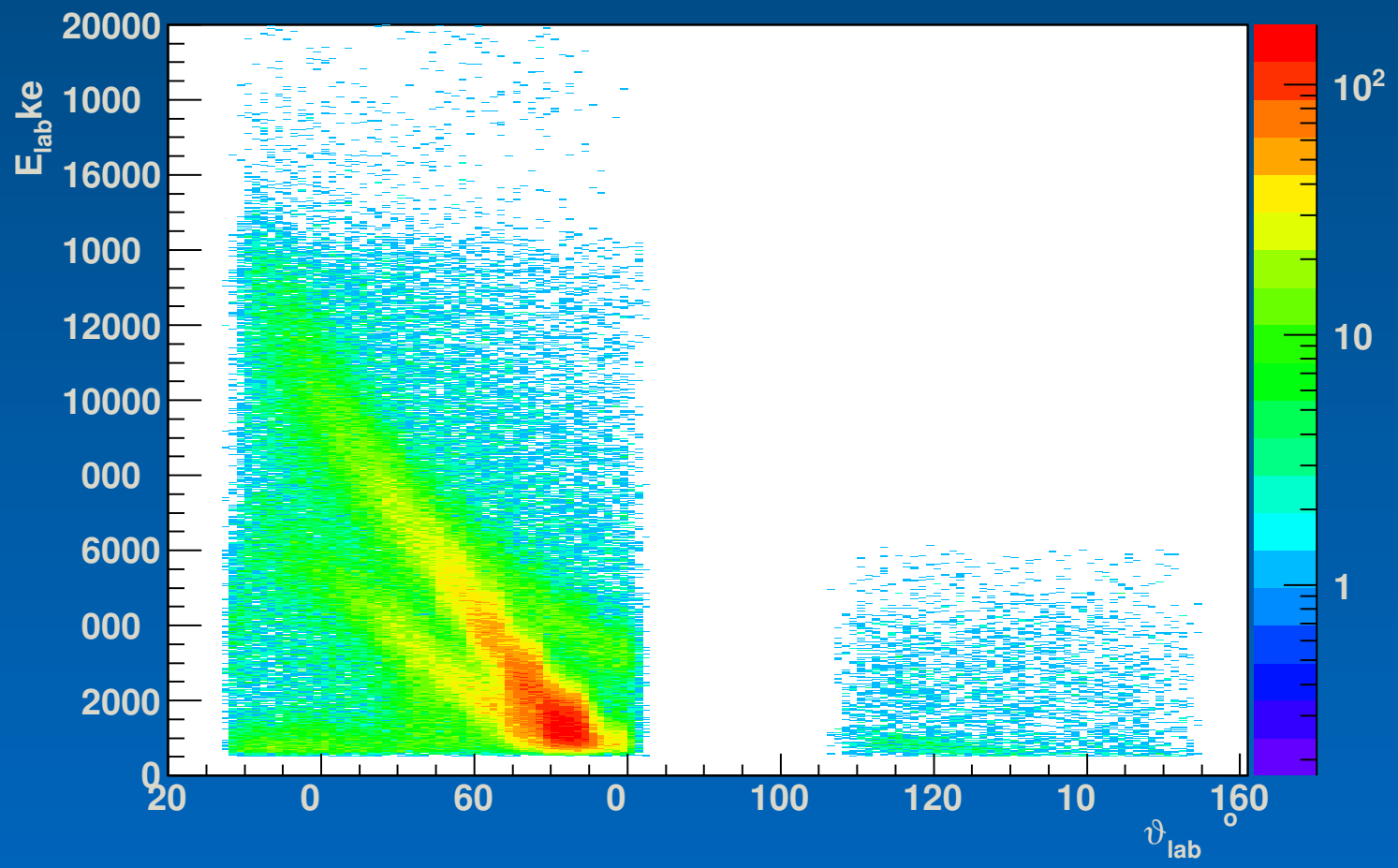

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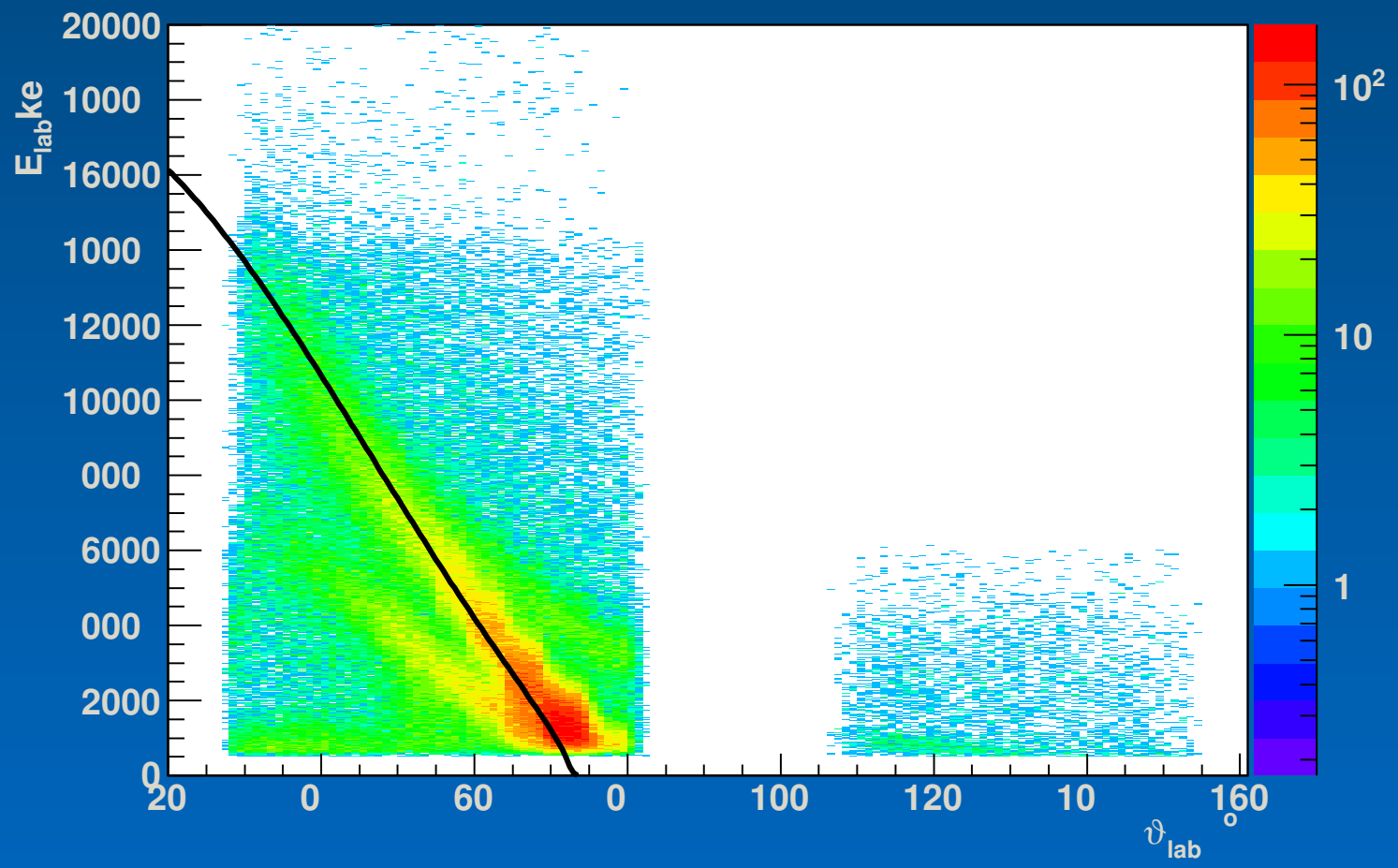

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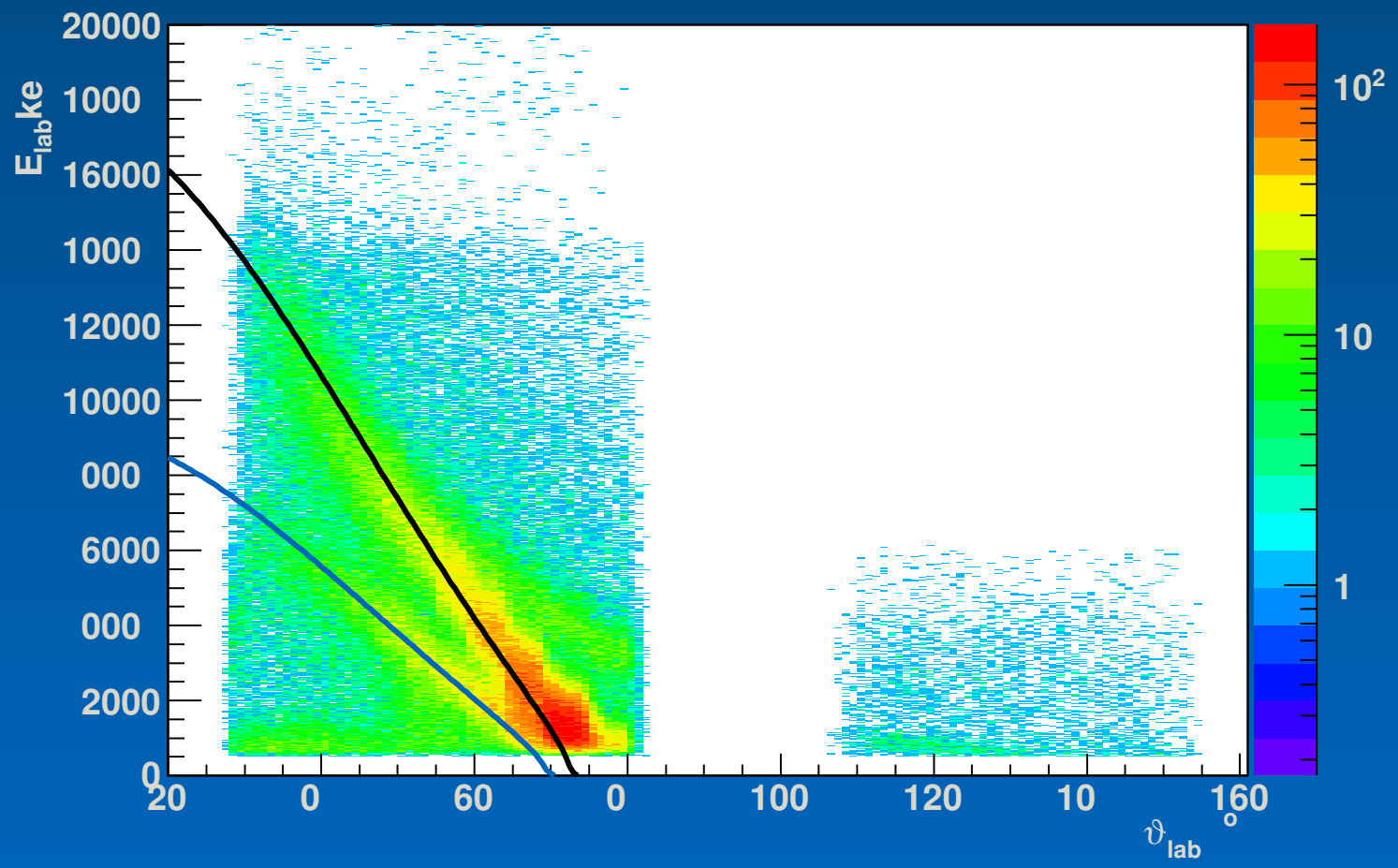

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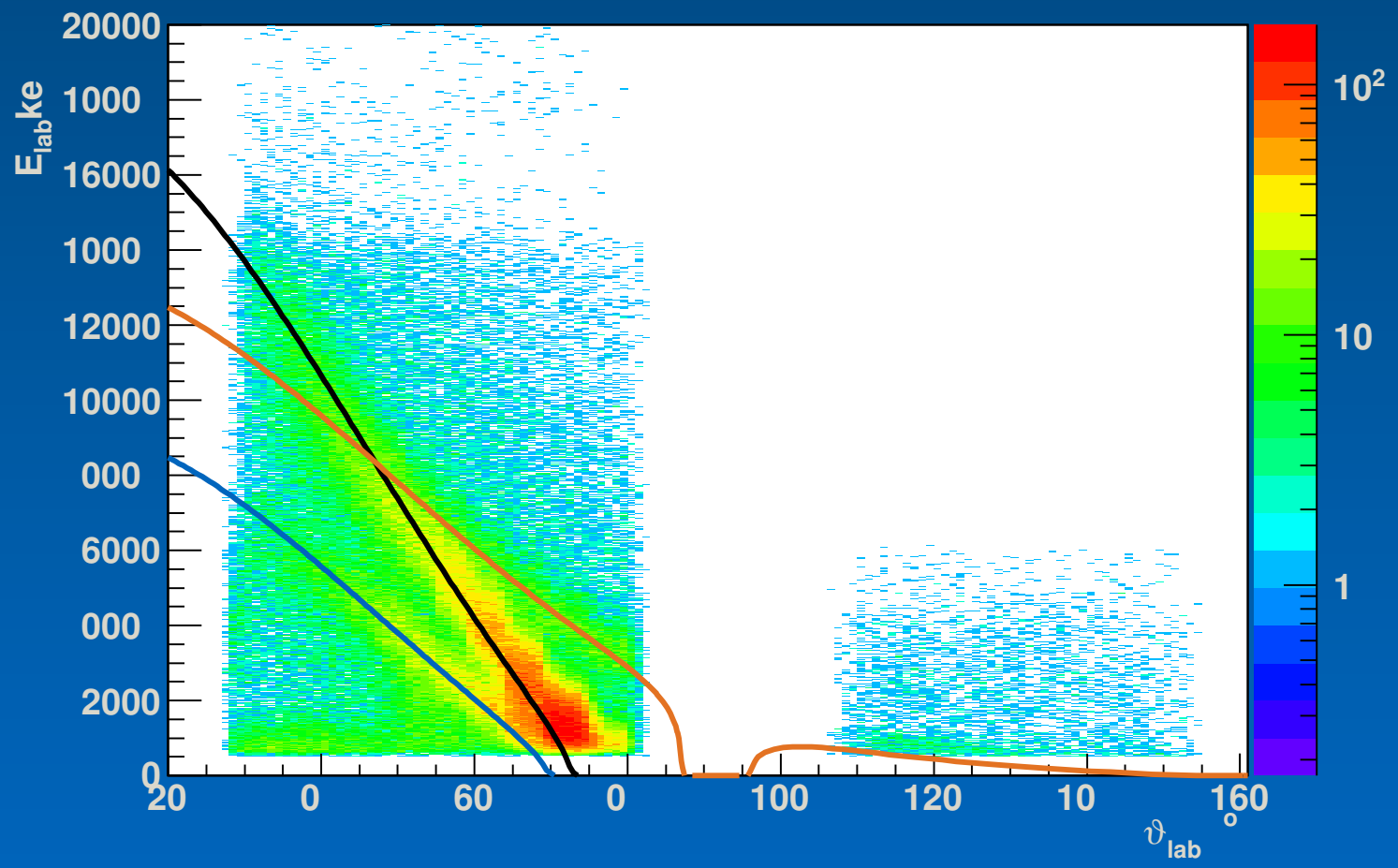

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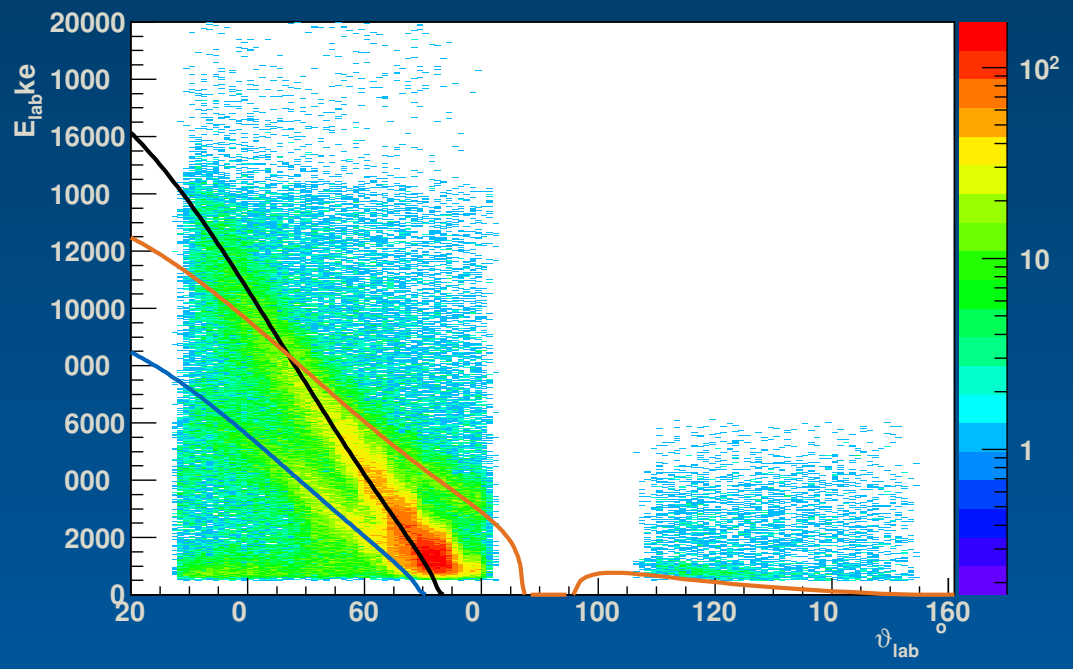

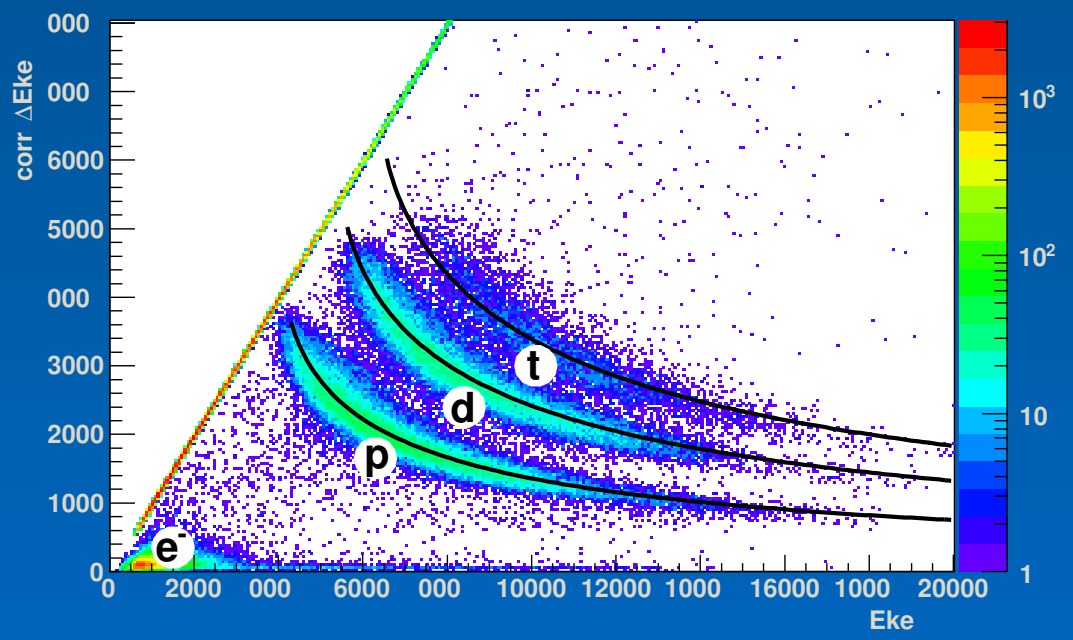

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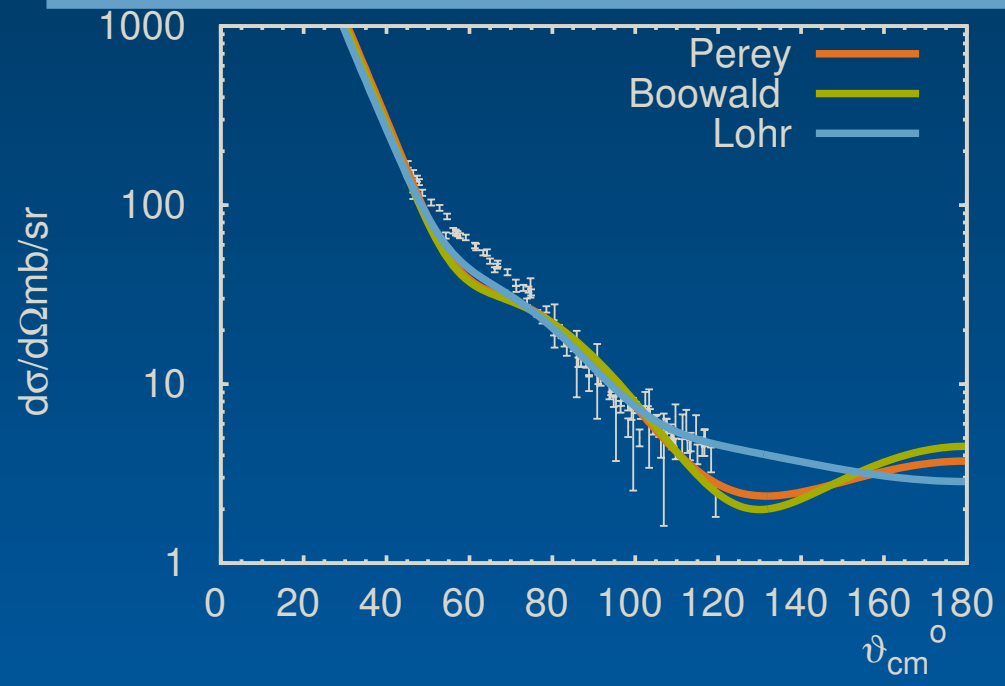


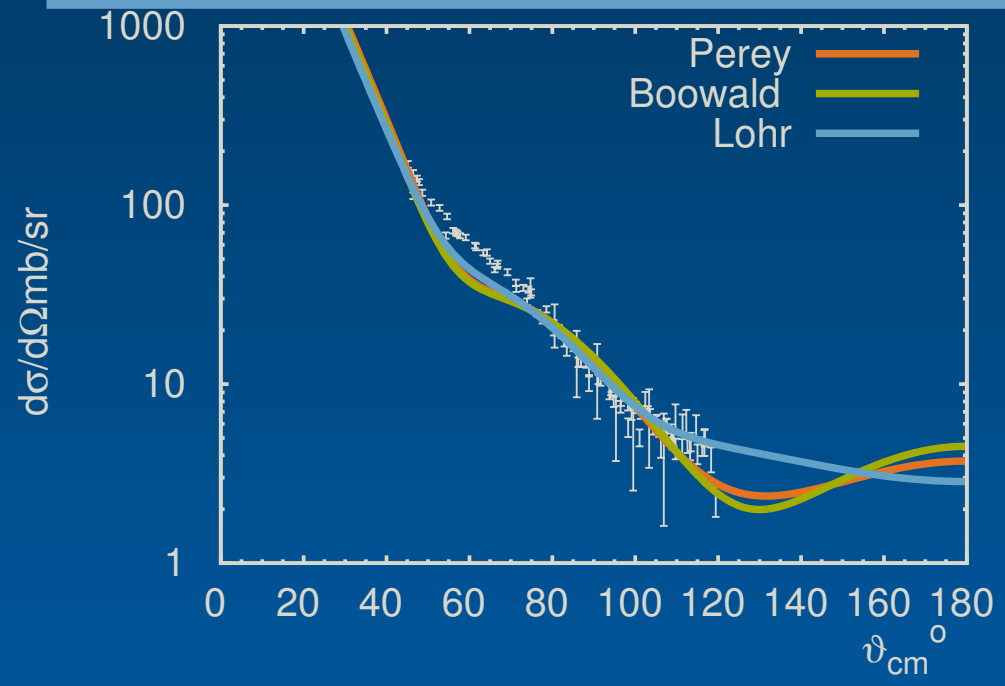
Experiment in 2008:

- $E_{\mathrm{beam}} = 2.85\,\mathrm{MeV/u}$
- 1 mg/cm^2 deut. PE
- 25 hours of data

global parameters:

fitted to stable isotopes
scaled for isospin and energy
stable ⇒isospin and mass are strongly coupled
deuteron energies at and above 10 MeV

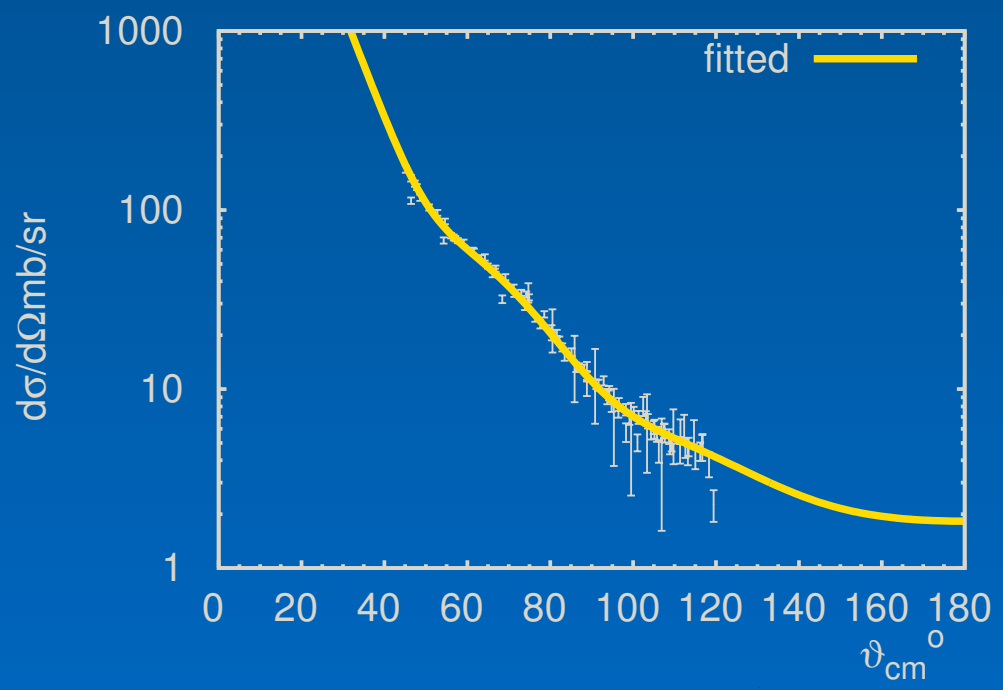
d (^{30}Mg, d) ^{30}Mg



Experiment in 2008:

- $E_{\mathrm{beam}} = 2.85\,\mathrm{MeV/u}$
- 1 mg/cm^2 deut. PE
- 25 hours of data
- luminosity is 443(86)/mb

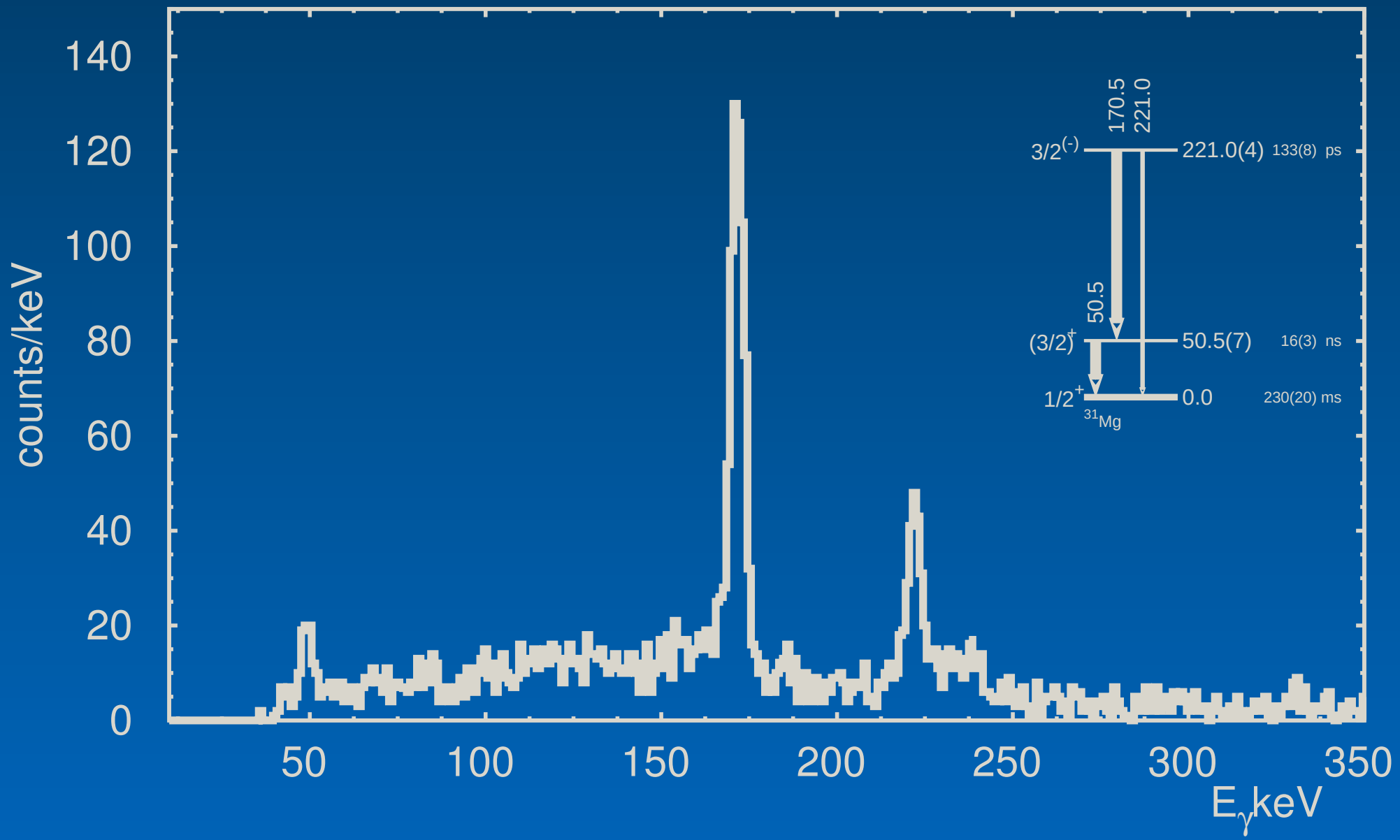
$\Rightarrow 6.5(12) \times 10^4$ ^{30}Mg/s



fitted global parameters:

fitted only radii of real and imaginary woods-saxon and the diffuseness of the real woods-saxon

γ-Spectrum from d (^{30}Mg, p) ^{31}Mg



Cut on coincident protons, Doppler corrected with $\vartheta(^{31}\mathrm{Mg}) = 0°$

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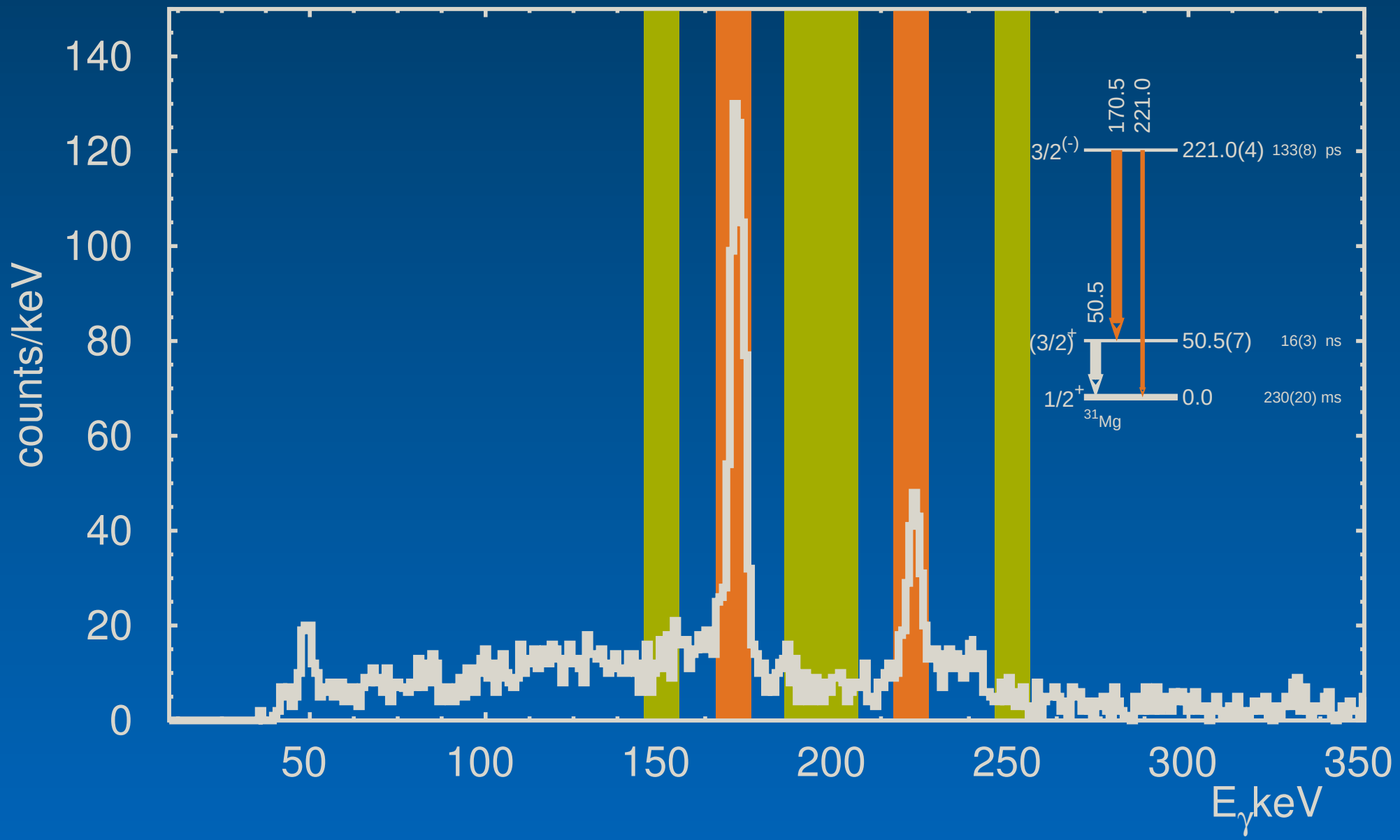

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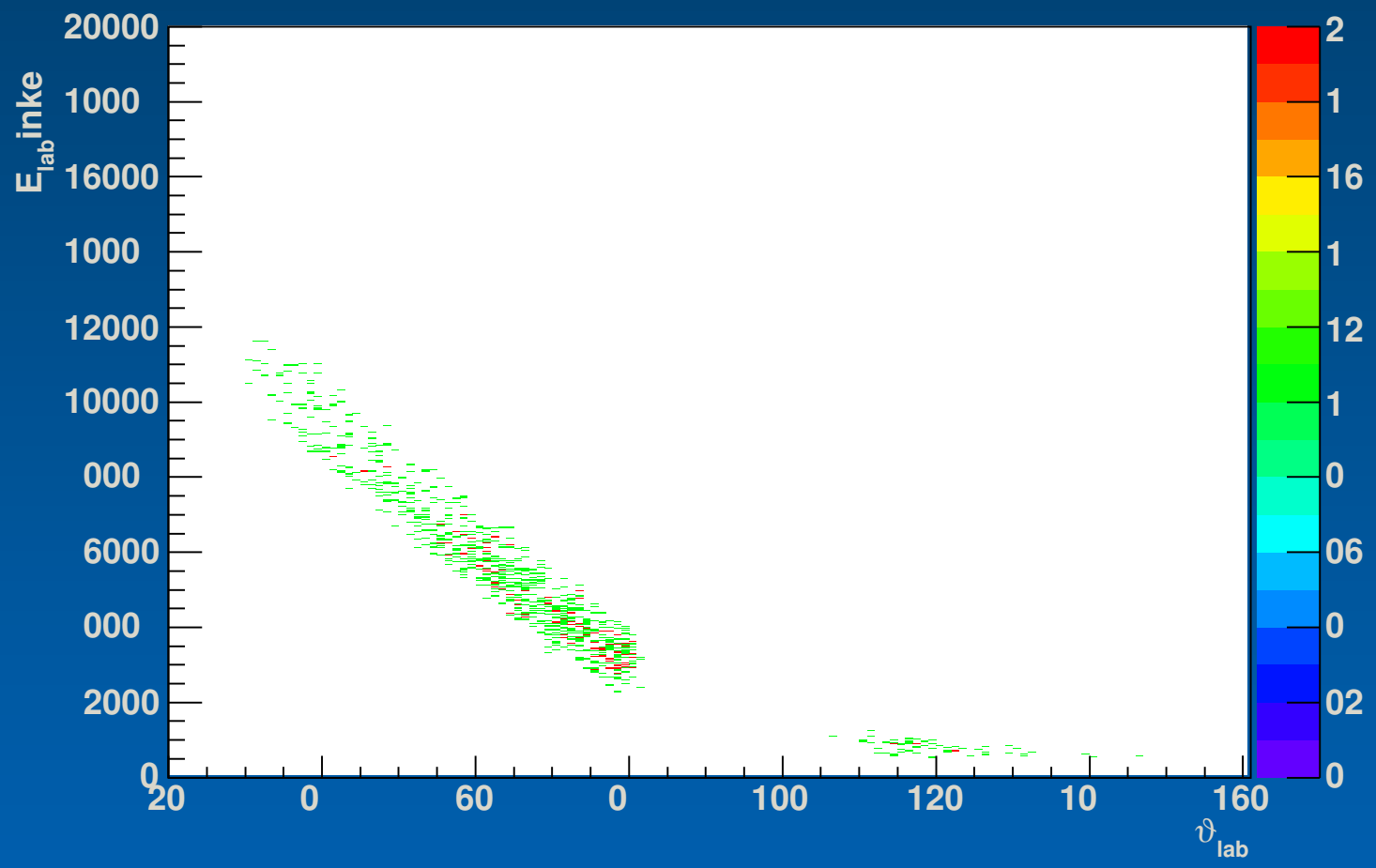
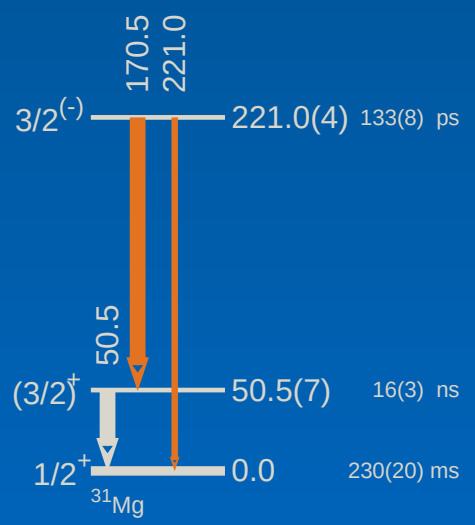
Angular Distributions of ^{31}Mg

Technische Universität München





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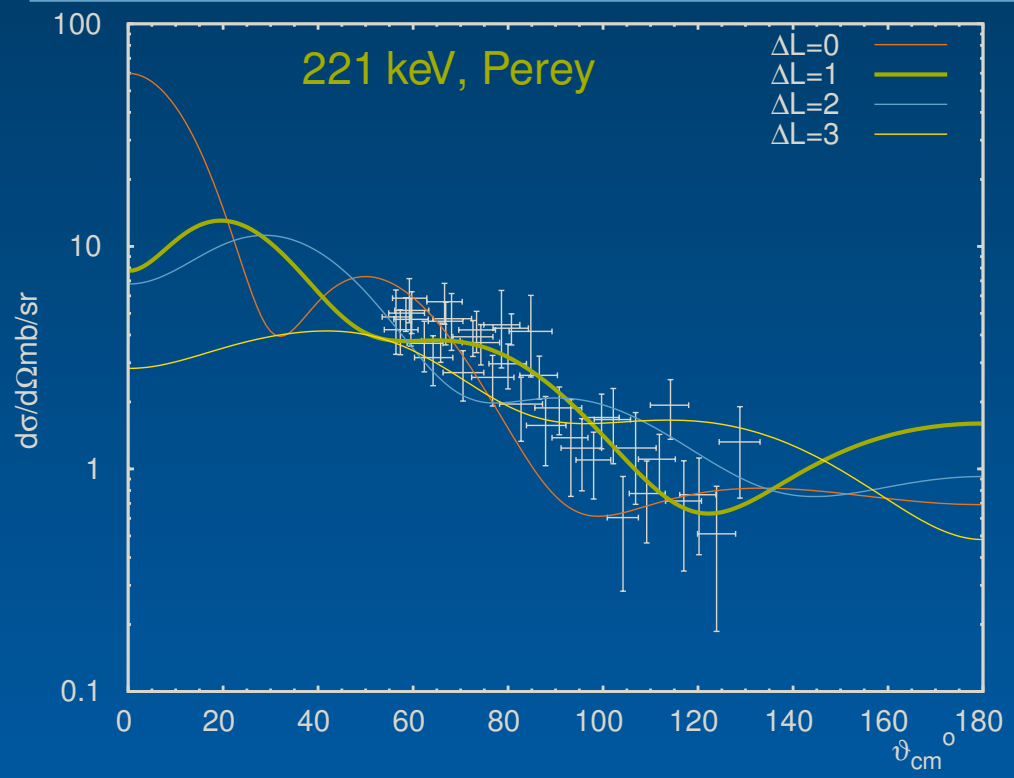
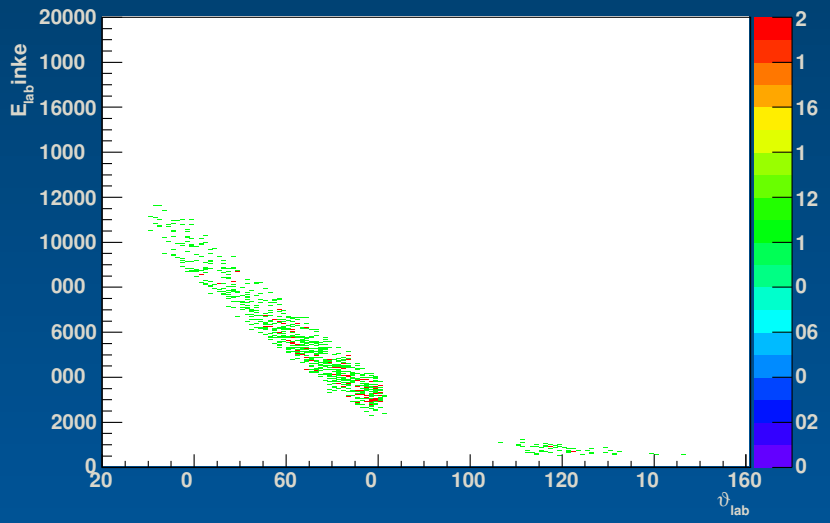
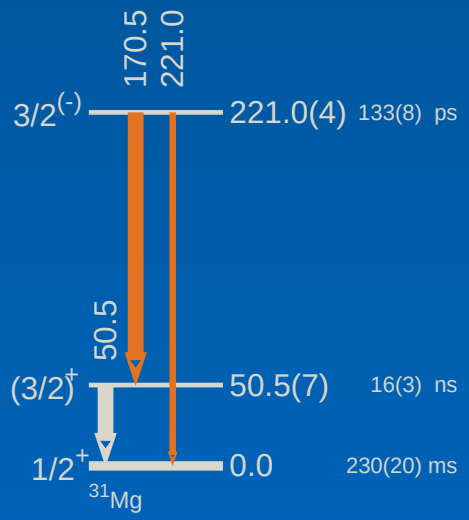




- 221 keV state: $\Delta l = 1$ with $S_{\Delta l=1} = 0.04$–0.08



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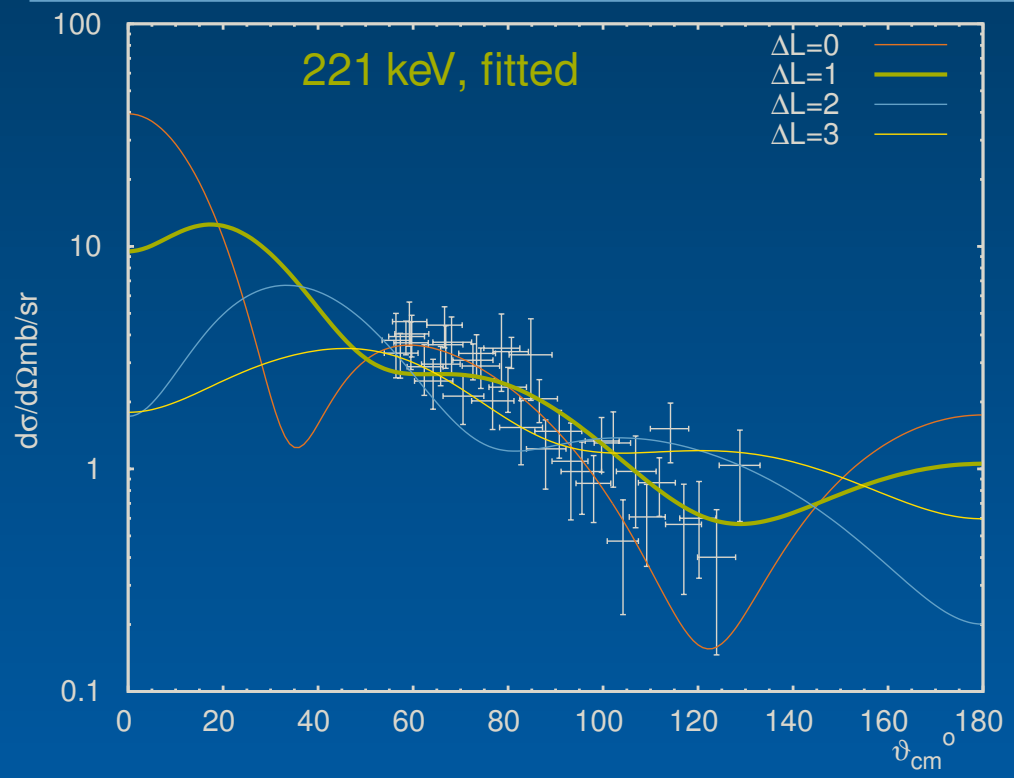
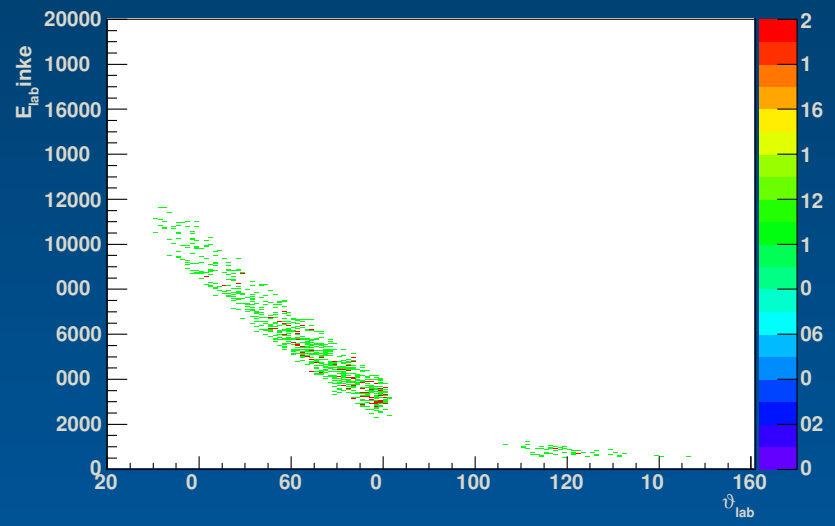
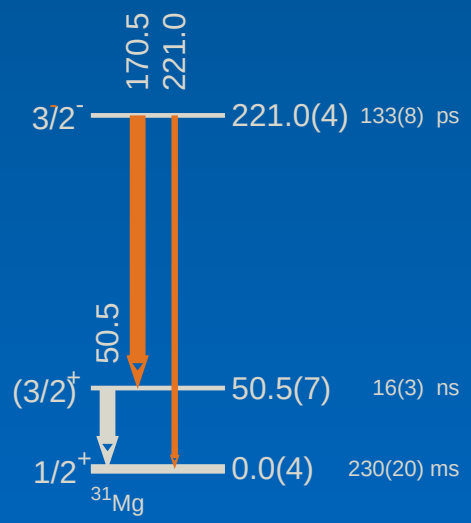




- 221 keV state: $\Delta l = 1$ with $S_{\Delta l=1} = 0.04$–0.08
- $\Delta l = 0, 2, 3$ do not reproduce shape of angular distribution
  $\Rightarrow$for the first time measurement of the negative parity of the 221 keV state



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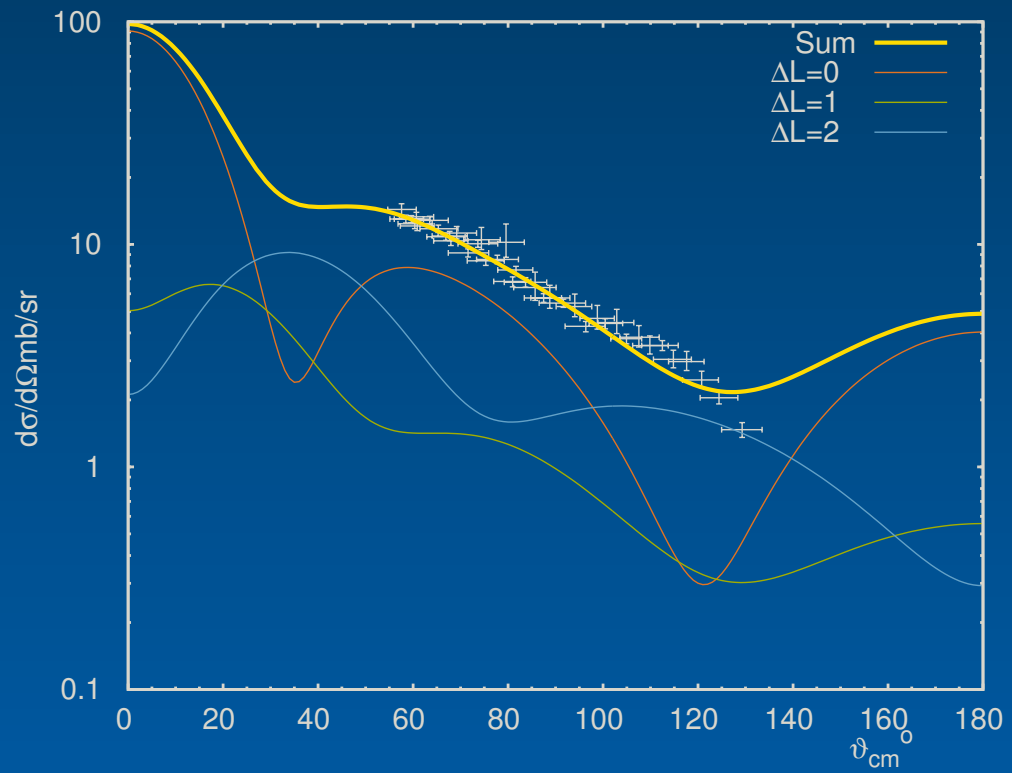

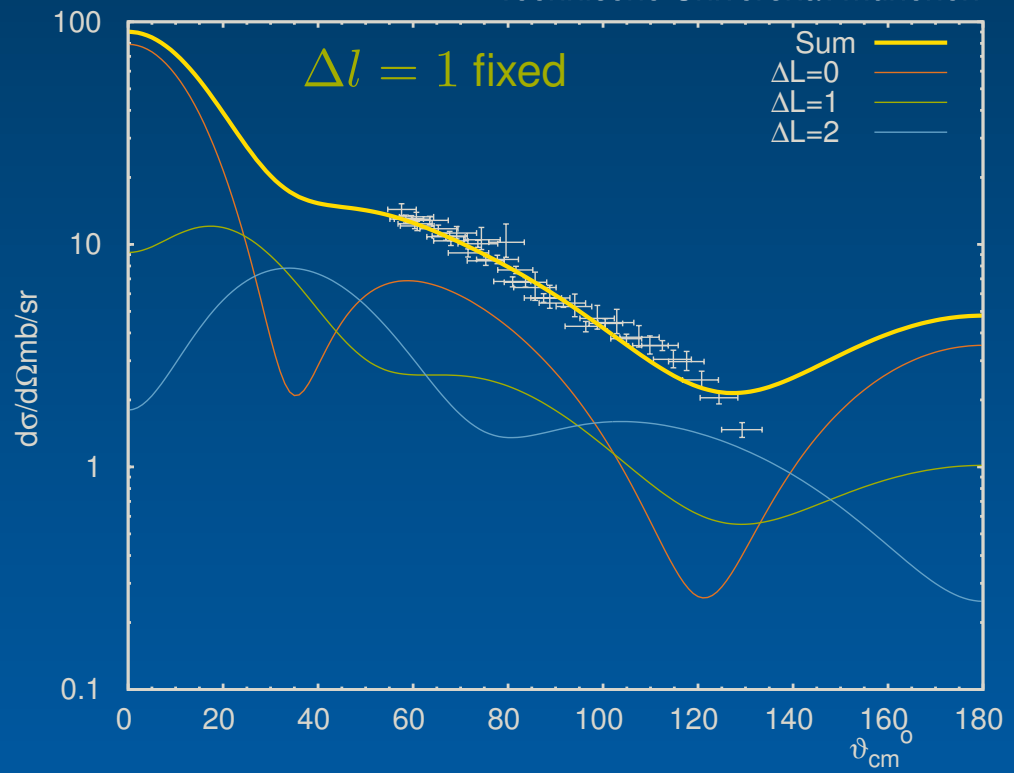

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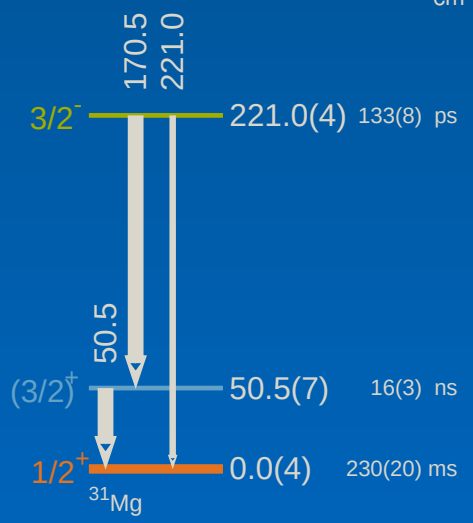
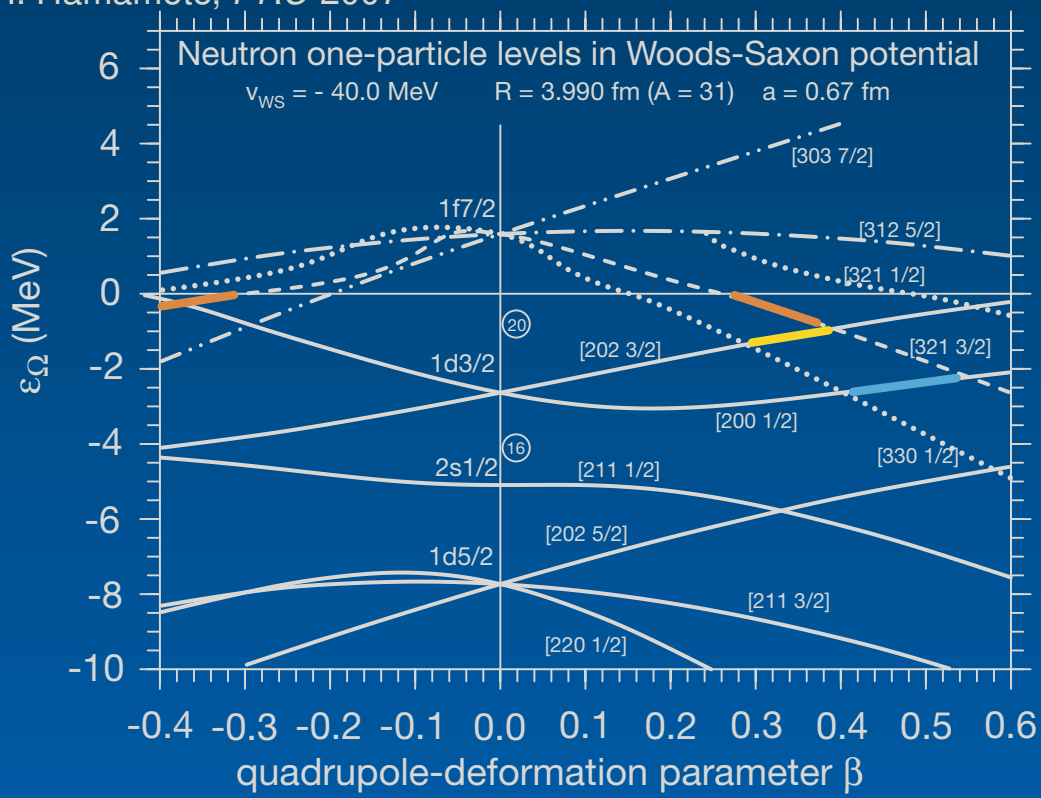
- all protons from transfer reactions with $\Delta l = 1$ contribution fixed:
  $S_{\Delta l=0}/S_{\Delta l=1} = 4.1(9)$
  $S_{\Delta l=2}/S_{\Delta l=1} = 5.0(18)$



^{31}Mg in the Nilsson Model

I. Hamamoto, *PRC* 2007



two neutrons in the $K^\pi[Nn_z\Lambda] = 1/2^-[330]$ level $(2p-2h)$

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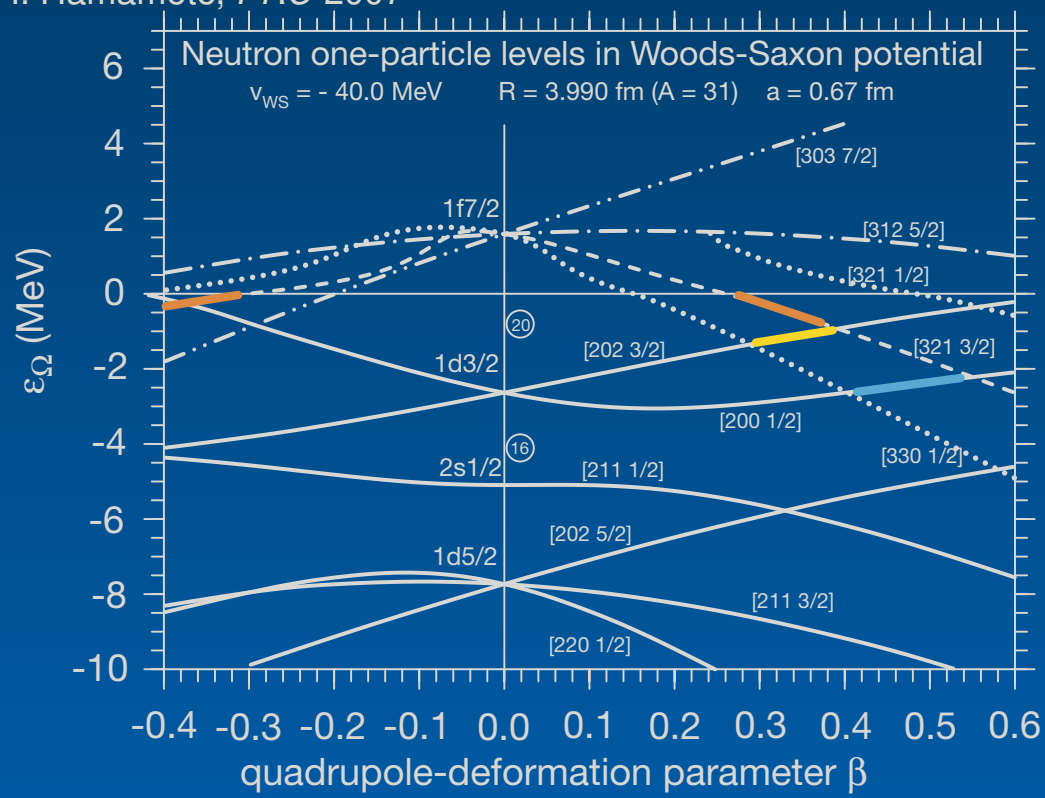

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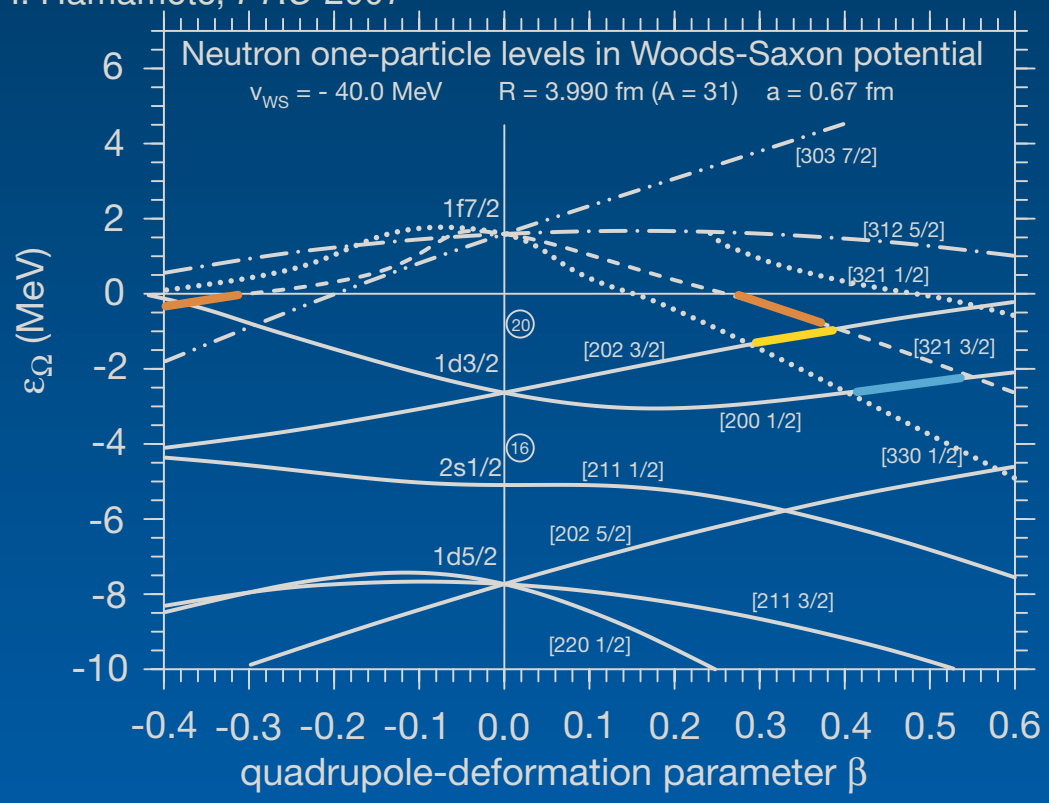

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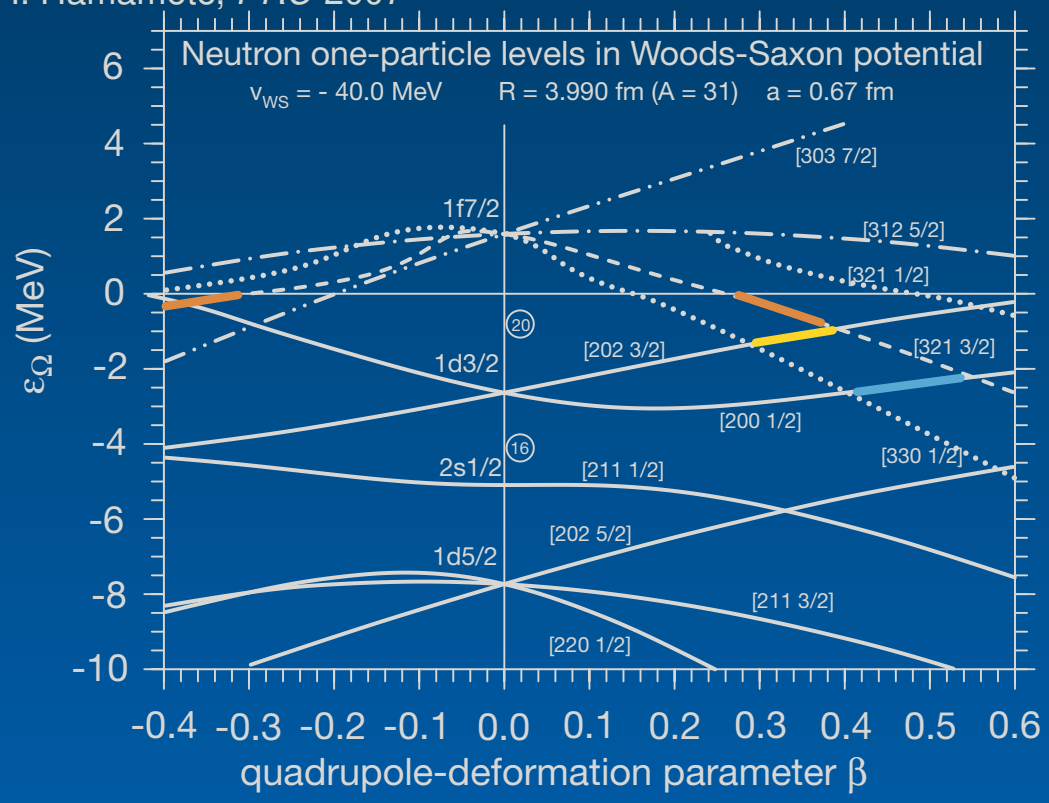

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^{31}Mg in the Nilsson Model

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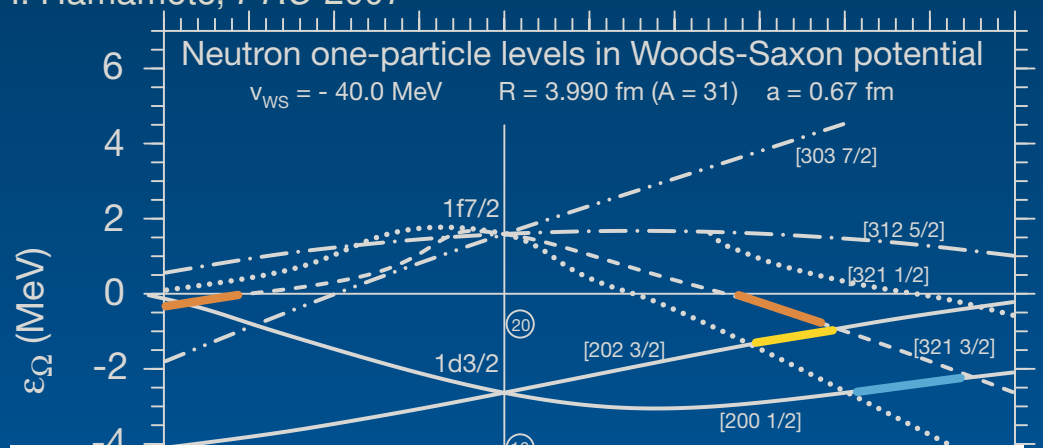

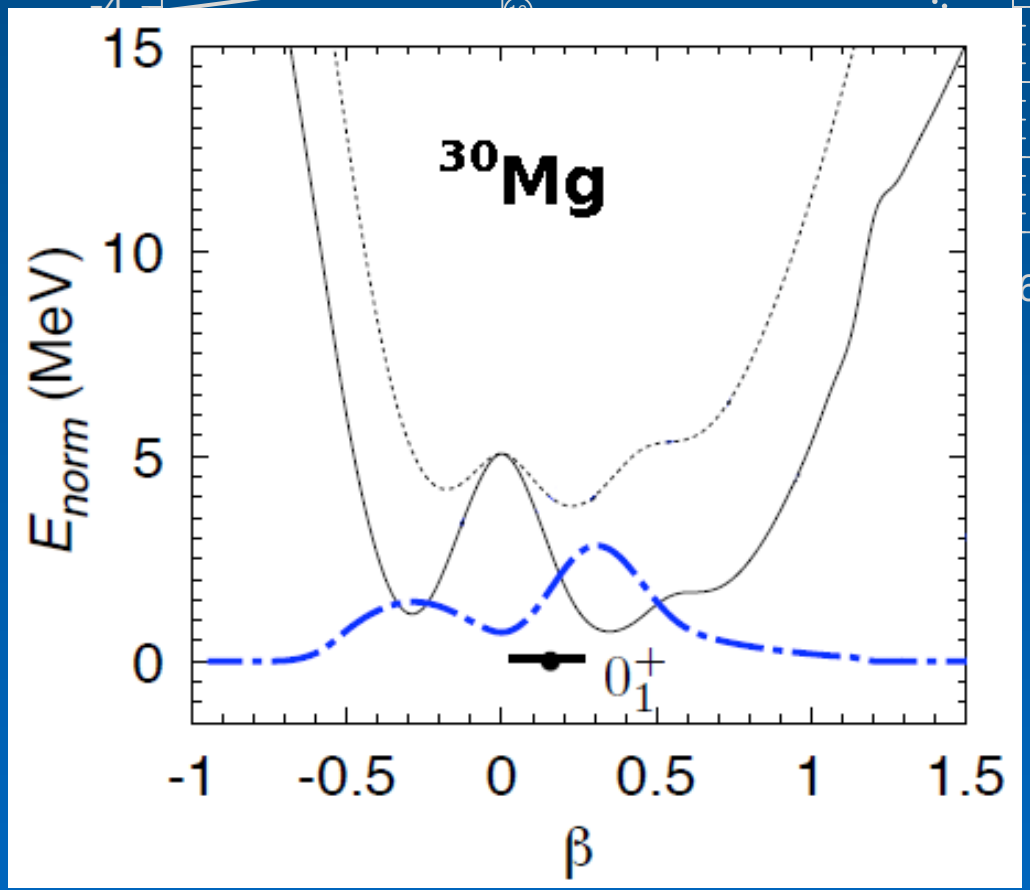

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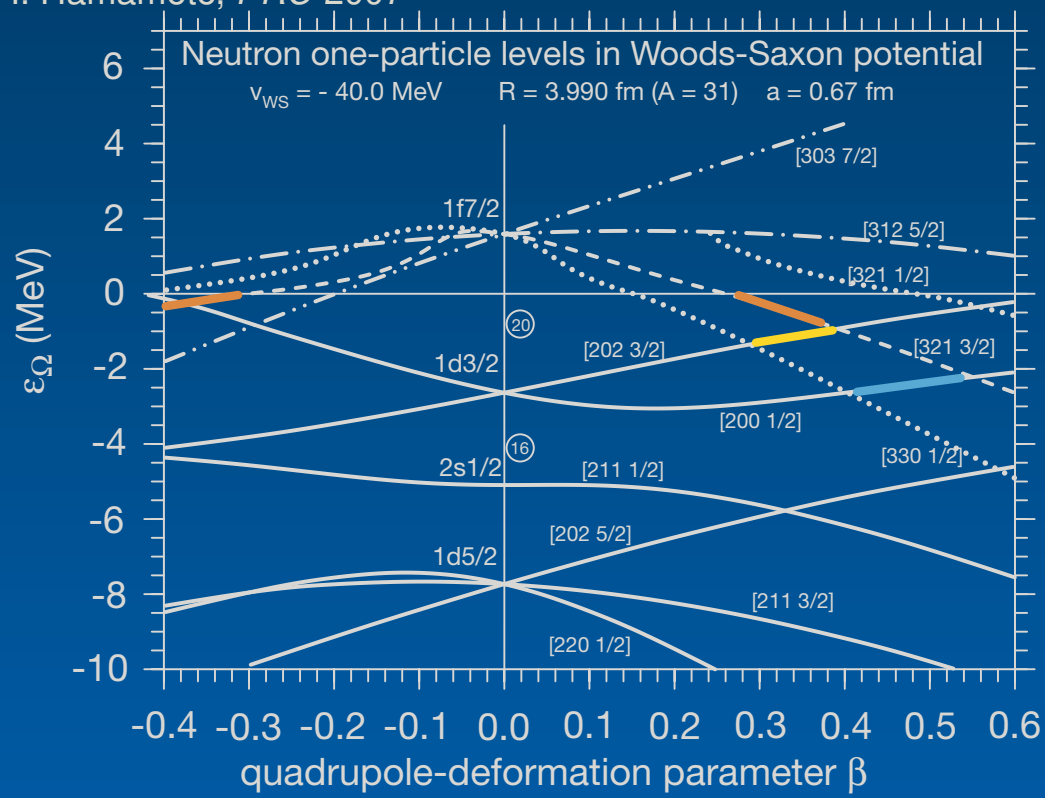
T. Rodriguez and J. Egido, priv. comm.

^{31}Mg in the Nilsson Model

I. Hamamoto, *PRC* 2007



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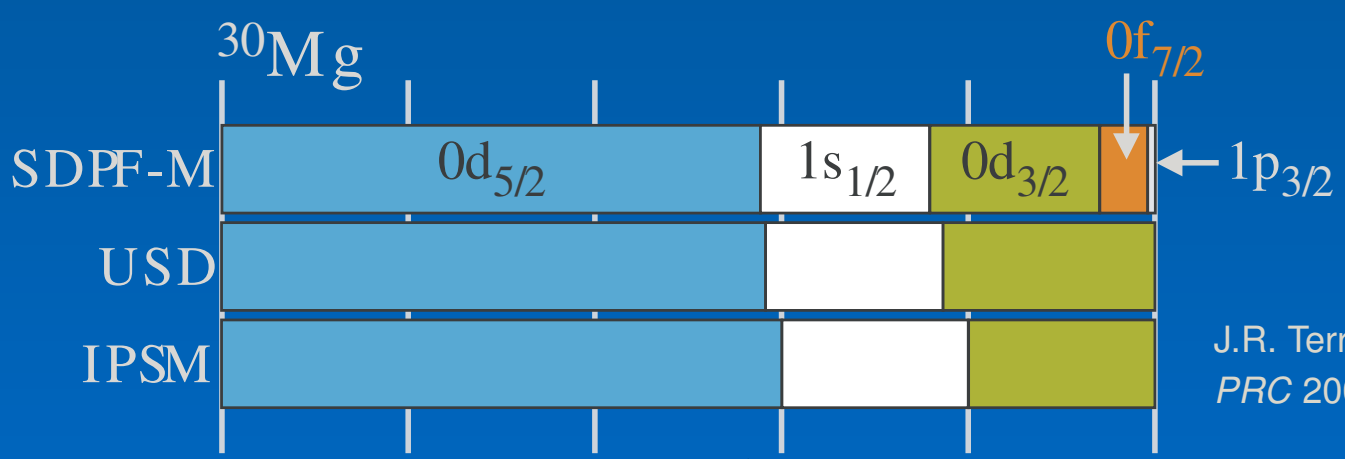

J.R. Terry *et al.*, *PRC* 2008

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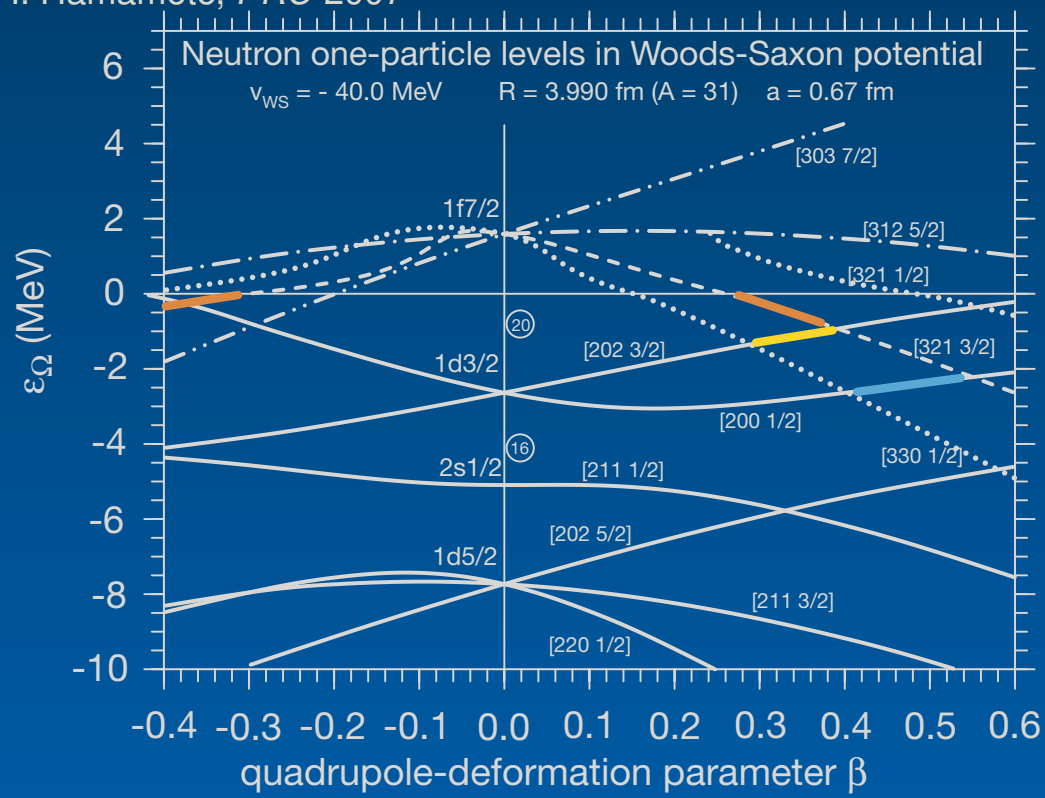
I. Hamamoto, *PRC* 2007



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two different effects can explain the lower observed cross section for the second excited state

- smaller contribution from $2p3/2$ to $3/2^-[321]$ Nilsson orbital
- smaller contribution to oblate configurations in ground state of ^{30}Mg

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Summary & Outlook
MINIBALL REX-ISOLDE Collaboration

Summary

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- transfer reactions are an excellent tool to study single particle properties, inverse kinematics pose some challenges

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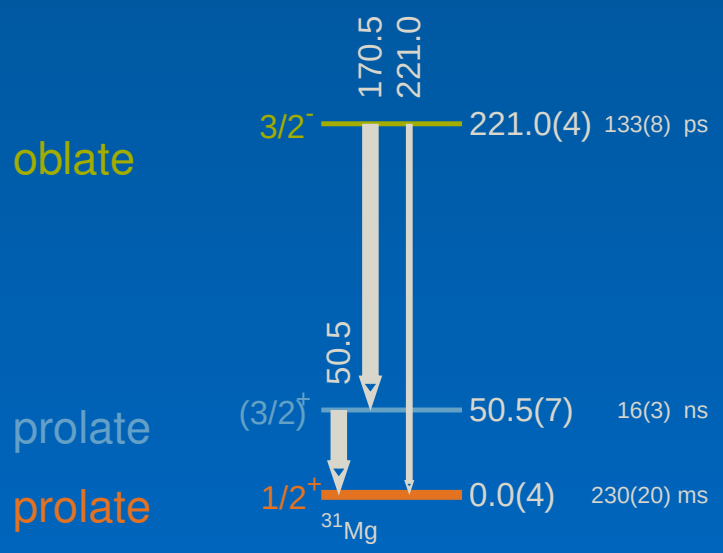
Summary

- transfer reactions are an excellent tool to study single particle properties, inverse kinematics pose some challenges
- d (^{30}Mg, p) ^{31}Mg was the first one neutron transfer experiment with T-REX at REX-ISOLDE
- identified the second excited state in ^{31}Mg at 221 keV for the first time as $l = 1$
- ratio between transfer cross section scaling factors implicates oblate deformation for the second excited state while the ground and first excited state are prolate deformed

$$S_{gs}/S_{221\,\text{keV}} = 4.1(9)$$
$$S_{50\,\text{keV}}/S_{221\,\text{keV}} = 5.0(18)$$



Summary & Outlook

start of a program for transfer reactions at REX-ISOLDE:

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- ^{11}Be: (d,t), (d,d) and (d,p), 2009/10, — J. Johanson et al. (Aarhus Universitet, Denmark)
- d(^{66}Ni,^{67}Ni)p: $N = 40$ subshell closure, 2009, — J. Diriken et al. (KU Leuven, Belgium)
- d(^{78}Zn,^{79}Zn)p: $N = 50$ shell gap near ^{78}Ni, 2010, — R. Orlandi et al. (University of Madrid)
- t(^{44}Ar,^{46}Ar)p: deformation and shape coexistence, 2010, — K. Nowak et al. (TU München)
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CERN approved upgrade to HIE-ISOLDE:

- higher beam energies will be available $\Rightarrow$ transfer reactions with higher masses possible
- a future 0°-spectrometer (EMMA type) would allow direct measurement of the nuclei of interest

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- ^{11}Be: (d,t), (d,d) and (d,p), 2009/10, — J. Johanson et al. (Aarhus Universitet, Denmark)
- d(^{66}Ni,^{67}Ni)p: $N = 40$ subshell closure, 2009, — J. Diriken et al. (KU Leuven, Belgium)
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CERN approved upgrade to HIE-ISOLDE:

- higher beam energies will be available $\Rightarrow$ transfer reactions with higher masses possible
- a future 0°-spectrometer (EMMA type) would allow direct measurement of the nuclei of interest

d(^{30}Mg,^{31}Mg)p data:

- check effect of particle-γ correlation
- use ADWA instead of DWBA

MINIBALL REX-ISOLDE Collaboration

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Thanks for your attention!