Ядрено-структурни експерименти с радиоактивни снопове. Ядрени моменти и вероятности за преход.

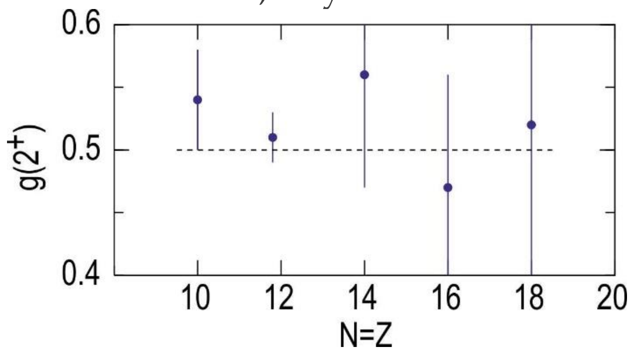
Георги Георгиев, CSNSM, Орсе

- Physics motivation
  - *Why do we need high-precision measurements of nuclear moment?*
  - *Transition probability studies for nuclei far from stability – why?*
- Time Dependent Recoil In Vacuum (TDRIV) on H-like ions
  - *Experimental approach for stable ions. What are the peculiarities for RIB studies?*
  - *g factor of ^{24}Mg – revisited.* ***Prove of principle and physics results***
- Coulomb excitation studies in the A~100 region
  - *Sudden onset of deformation at N=60. What is the contribution of the proton orbitals – odd-mass Rb nuclei*
  - *Experimental results on $^{97\text{-}99}$Rb – below and above N=60*
- Conclusions and perspectives

Physics motivation

- Nuclear moments and transition probabilities – extremely sensitive probes towards the structure of the nuclei:
  - g factors – considered as fingerprints of the single-particle properties
  - **transition probabilities** – sensitivity towards the **collective properties** of the nuclei

- g factors in self-conjugated nuclei
  - expected to be equal to 0.5
  - shell-model calculations – a sizeable departure from g=0.5 (up to 10%) for 2^+ states in ^{20}Ne – ^{36}Ar (W. A. Richter, S. Mkhize, and B. A. Brown, Phys. Rev. C 78, 064302 (2008))
  - experimental values – "consistent" with g=0.5



- transition probabilities
  - giving an insight to the transitional matrix elements
  - indications for structure modifications, e.g. single-particle-like towards collective properties

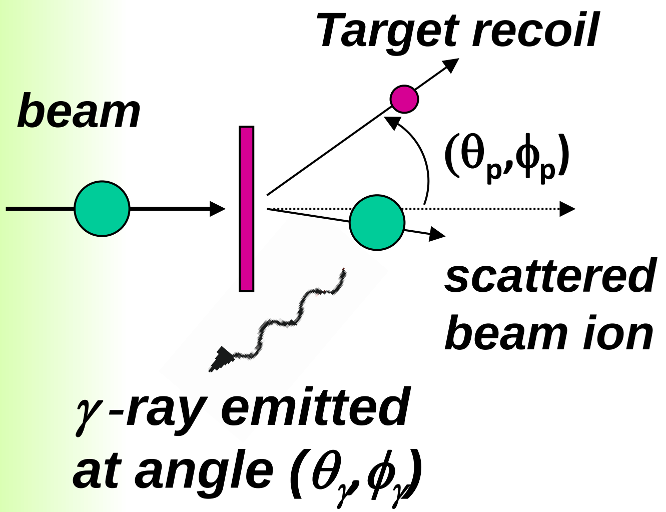
Time Dependent Recoil In Vacuum on H-like ions

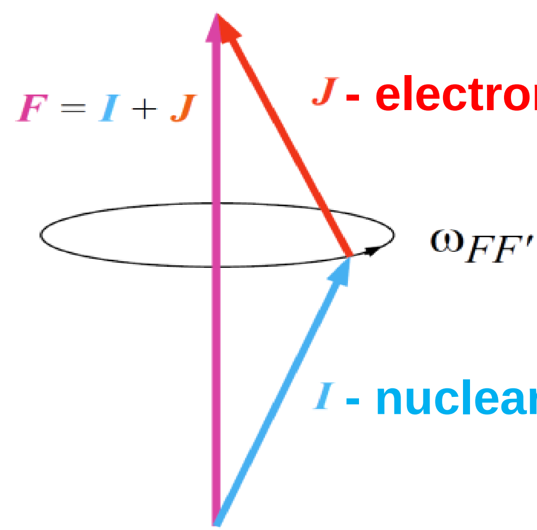
…

The RIB approach

Electron-nuclear spin interaction in vacuum

$$B_{ns} = 16.7\frac{Z^3}{n^3}\left[1 + (Z/84)^{2.5}\right]\ \mathbf{[T]}$$





$$W(\theta_p,\theta_\gamma) = \sum_{k,q}\sqrt{2k+1}\,\rho_{kq}(\theta_p)G_k F_k Q_k D^{k*}_{q0}(\phi_\gamma - \phi_p,\theta_\gamma,0)$$

$$G_k(t) = \sum_{F,F'} C_{FF'}\exp(-\omega_{FF'}t)$$

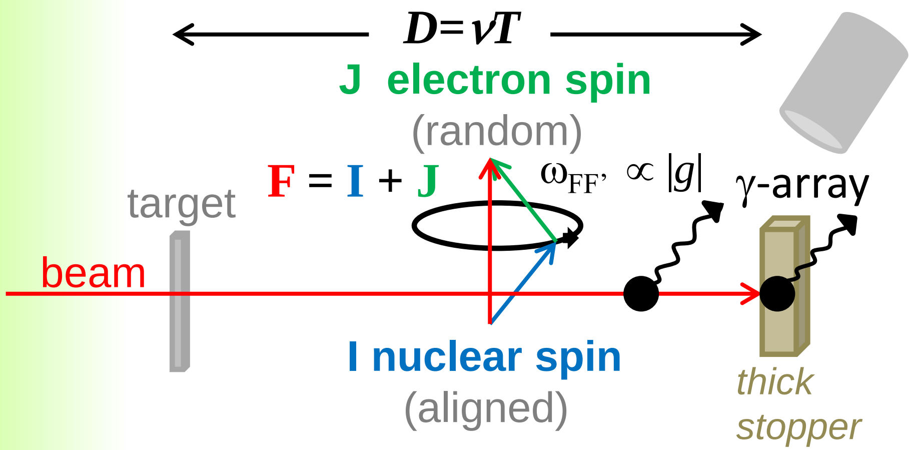
$$(0 \le |G_k| \le 1)$$

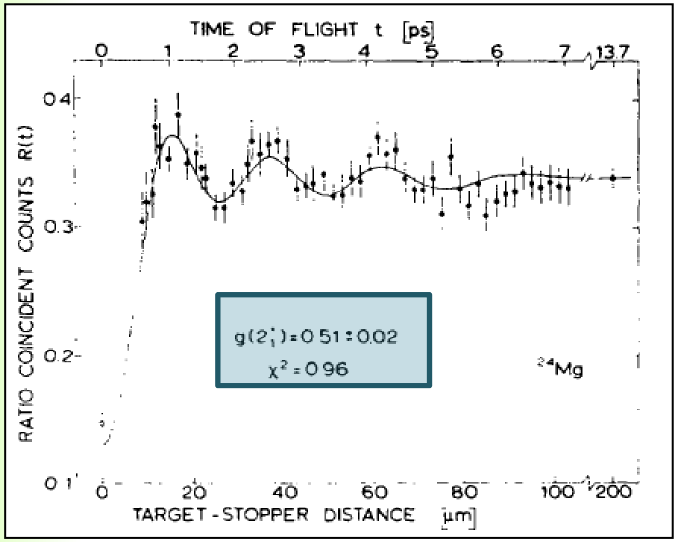
attenuation coefficients – a measure for the electron – nuclear spin interaction

$$\omega_{FF'} = \{F(F+1) - F'(F'+1)\}\frac{\mu_N B}{2\hbar J}g$$

interaction frequency - depends on I and J – **single frequency for J=1/2**

Time Dependent Recoil In Vacuum (stable beams)

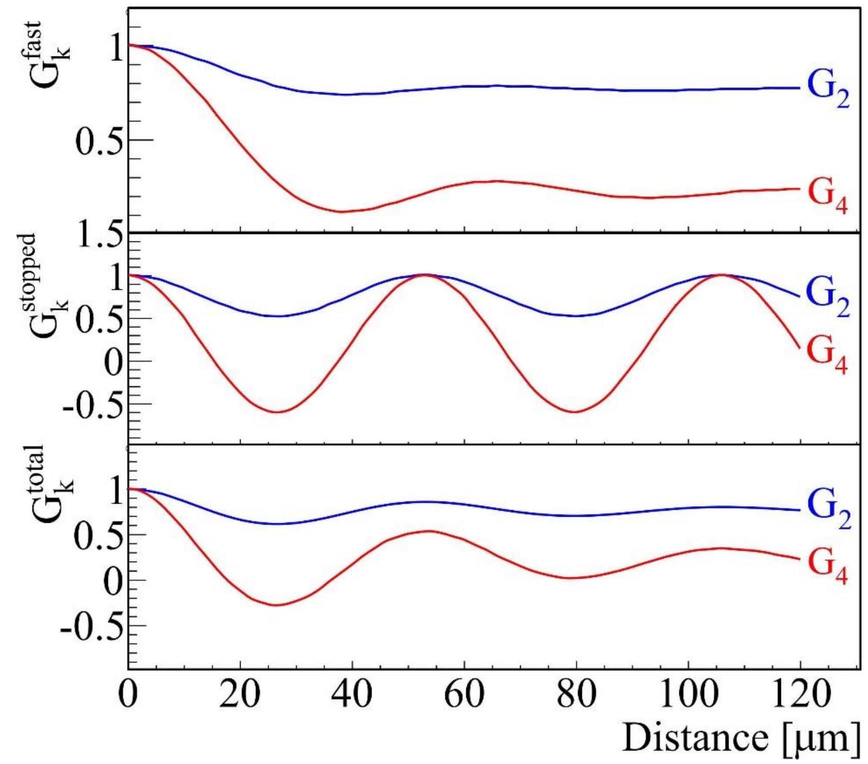




R.F. Horstman *et al.*, Nucl. Phys. **A248**, 291 (1975)

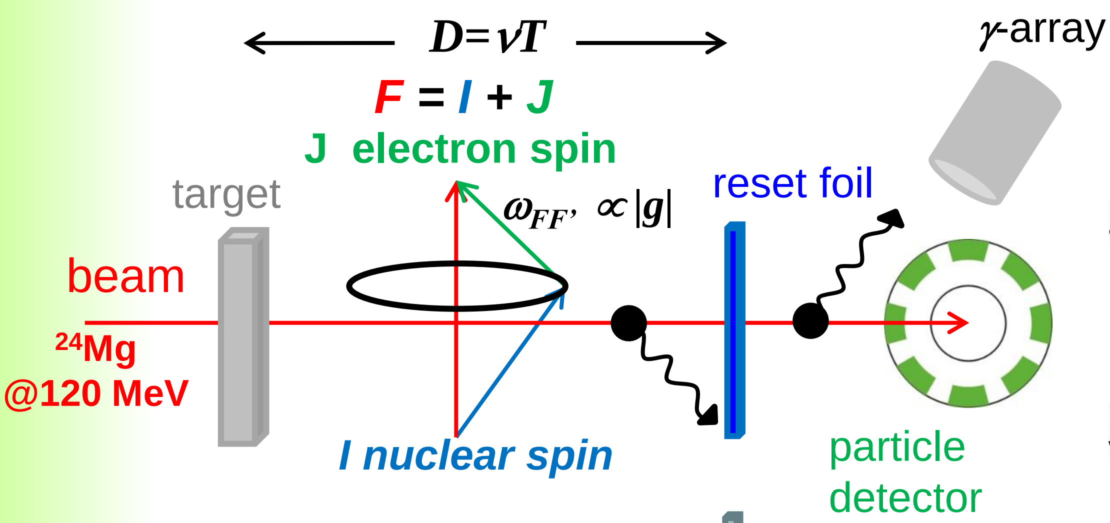
H-like ions

attenuation factor



- ***magnetic field*** *for H-like ions – can be calculated from first principles!*
- *pure H-like charge state could not be achieved (~15 %)*

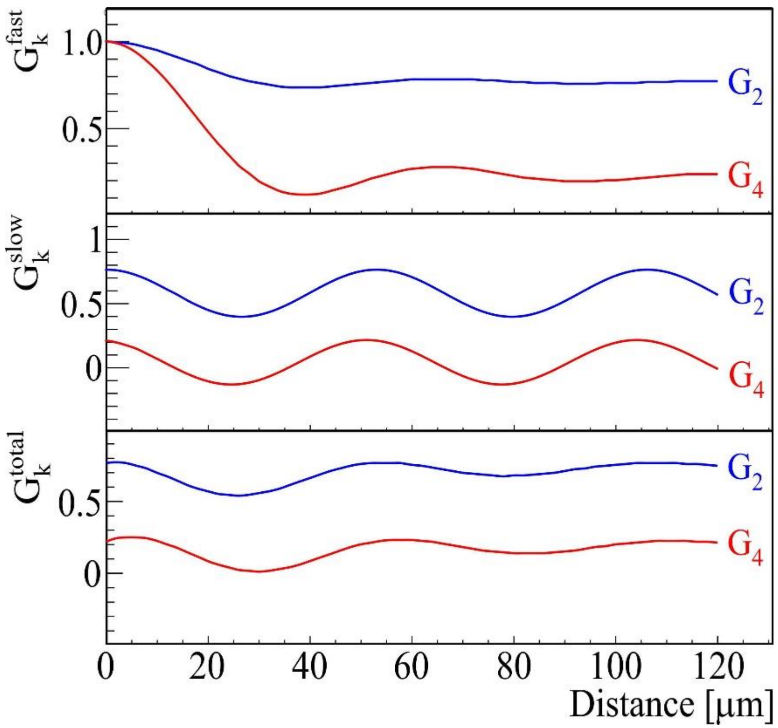
TDRIV – radioactive beam geometry



$$\overline{G_k(T)} = \int_0^T G_k(t)\lambda e^{-\lambda t}\,dt$$

$$G_k(T)\,G_k(\infty)$$

$$G_k(\infty) = \int G_k(t)\lambda e^{-\lambda t}\,dt$$

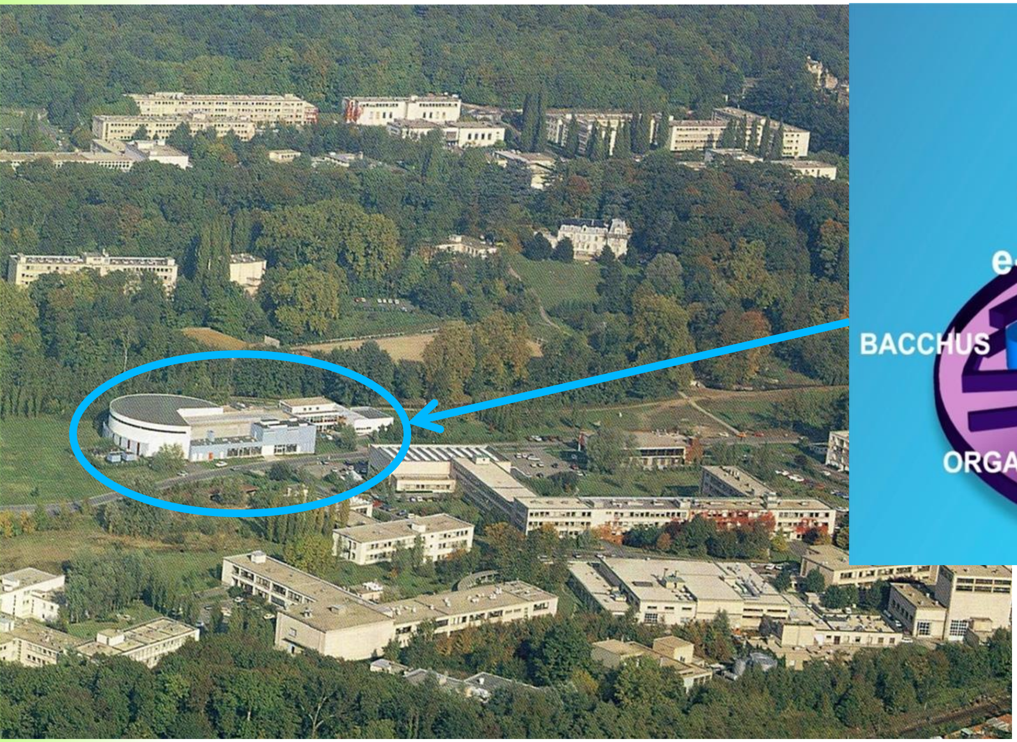


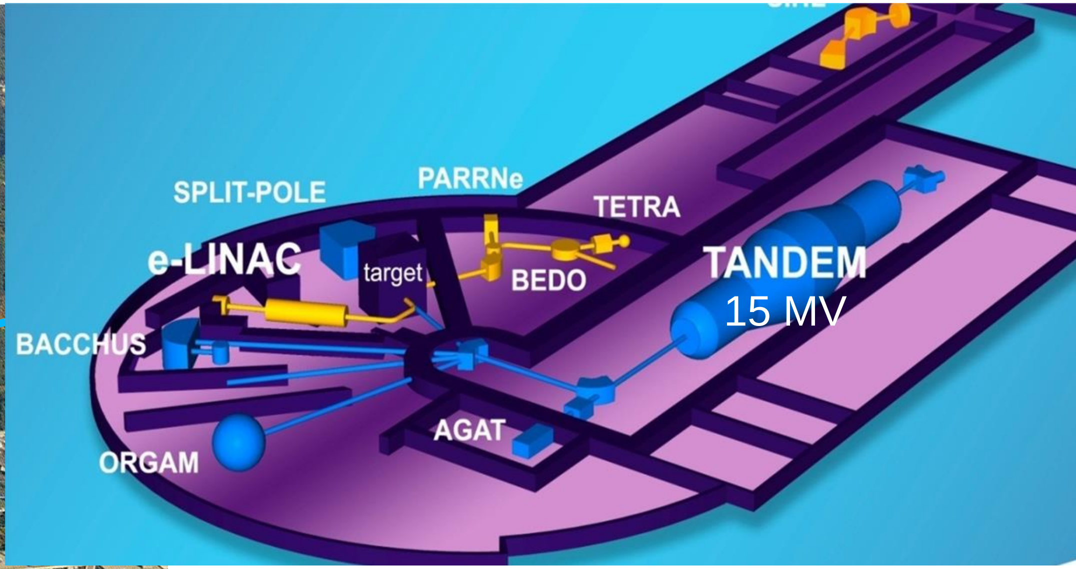
A.E. Stuchbery et al., Phys. Rev. C71, 047302 (2005).

The same oscillation frequency can be found even after the reset foil

(with some damping of the amplitude due to the hard-core attenuation)

The ALTO facility in Orsay

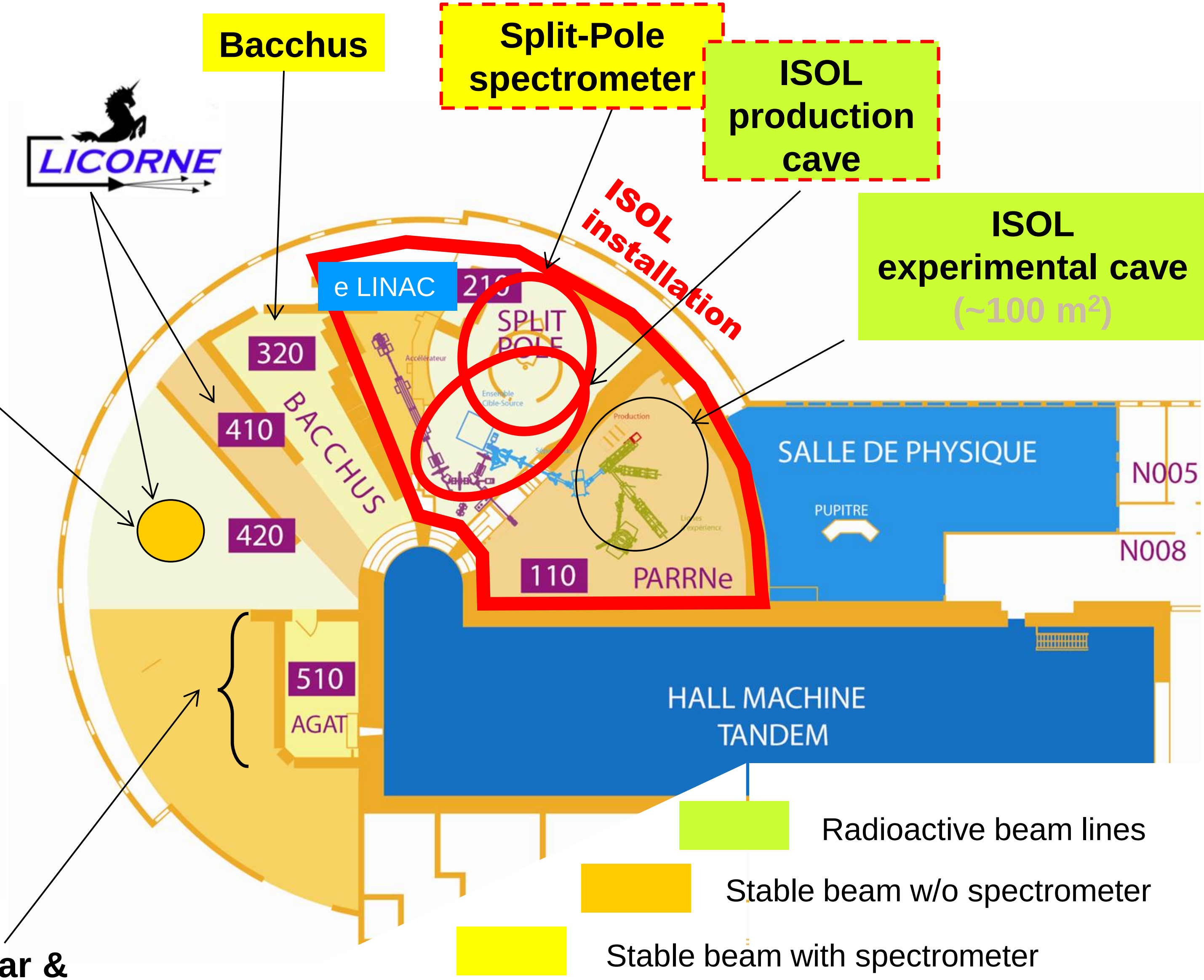




	2011	2012	2013	2014	2015
Users	~120	~240	200	135	246
Beam-time	1752 h	3600 h	2712 h	2232 h	3816 h
	219 UT	450 UT	339 UT	279 UT	477 UT

ALTO – experimental areas

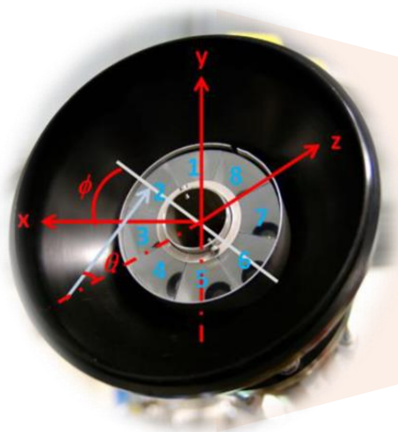
γ-spectroscopy

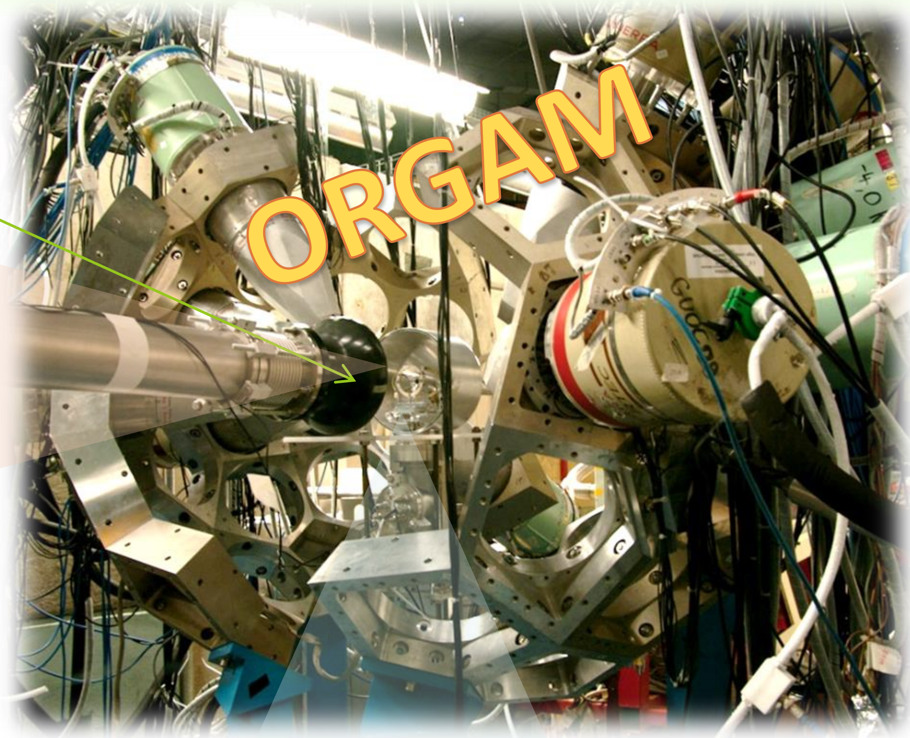


cluster, molecular & droplets beams

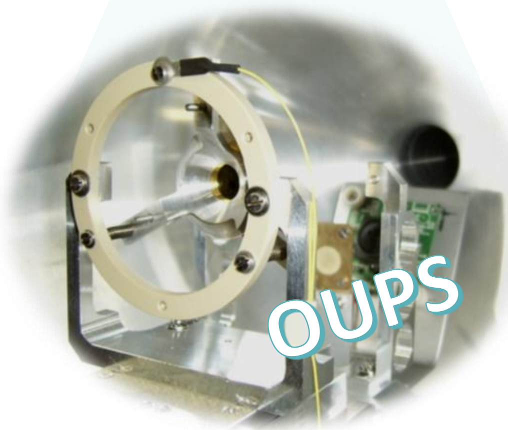
TDRIV experimental setup @ ALTO

Plastic scintillator





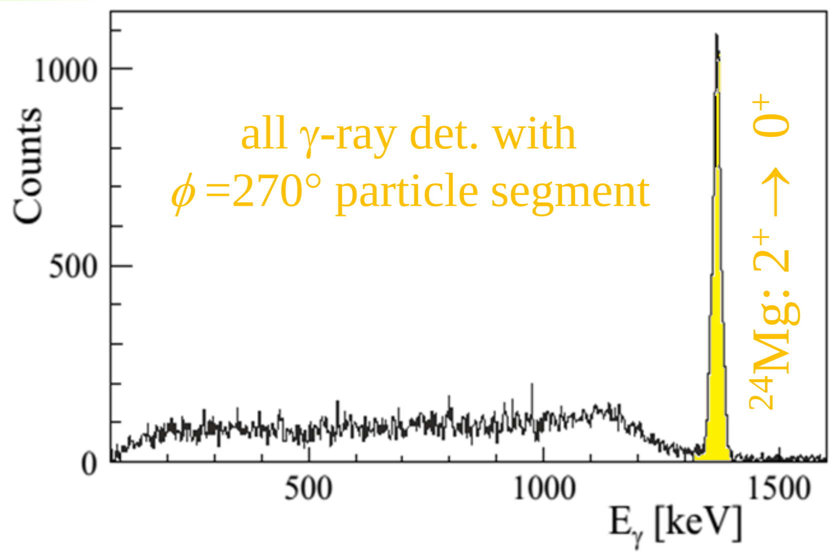
beam: ^{24}Mg @120 MeV (5 MeV/u)
target: 2.4 mg/cm^2 ^{93}Nb
reset Foil: 1.7 mg/cm^2 ^{197}Au

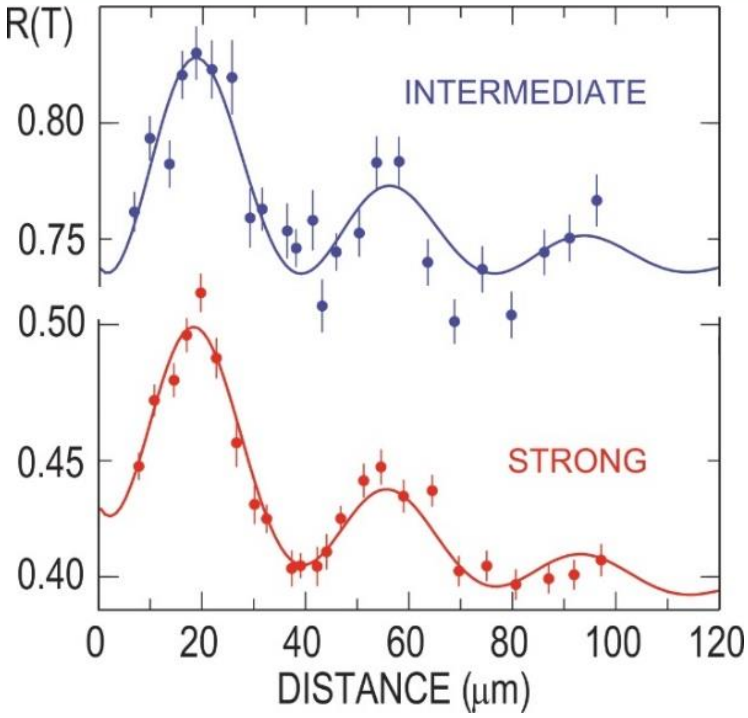


Orsay Universal Plunger System

- ✓13 HPGe @ θ= 46.5°, 72.1°, 85.8°, 94.2°, 108.0°, 133.6°, 157.6°
- ✓8-fold segmented annular detector
- ✓Orsay Universal Plunger System (OUPS)

Experimental results





Previous measurement:

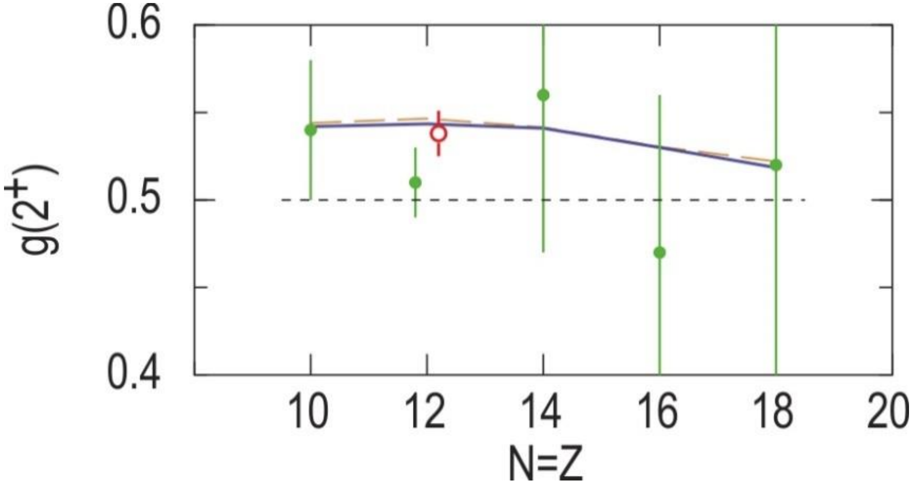
$|g(2^+)| = 0.51\ (2)$

R.F. Horstman et al., NPA 248, 291 (1975)

Our result:

$|g(2^+)| = 0.538$ **(13)**

A. Kusoglu et al. PRL 114, 062501 (2015)



Transition Probability Studies with Radioactive Ion Beams

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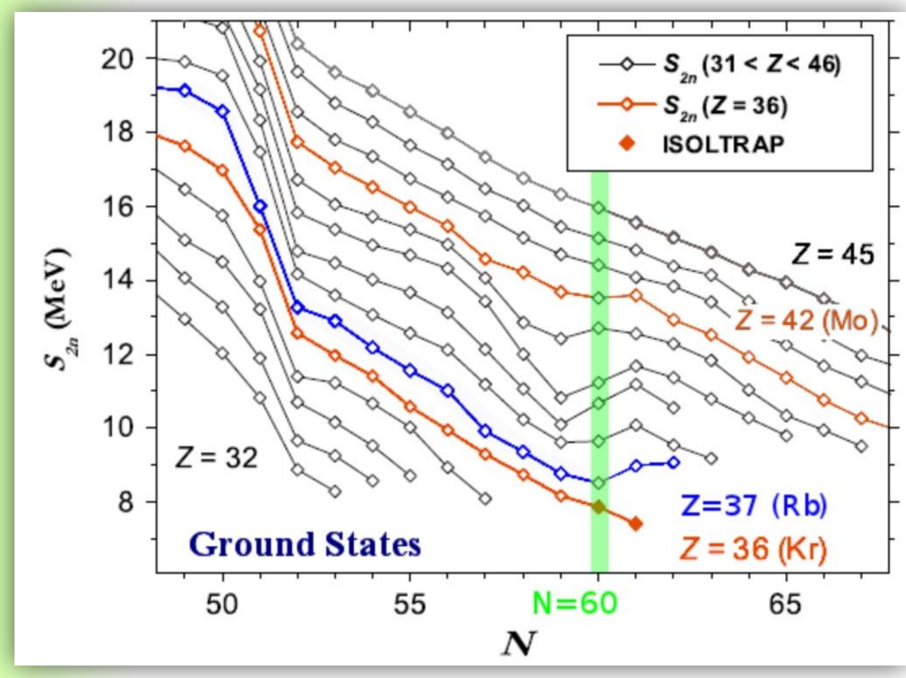
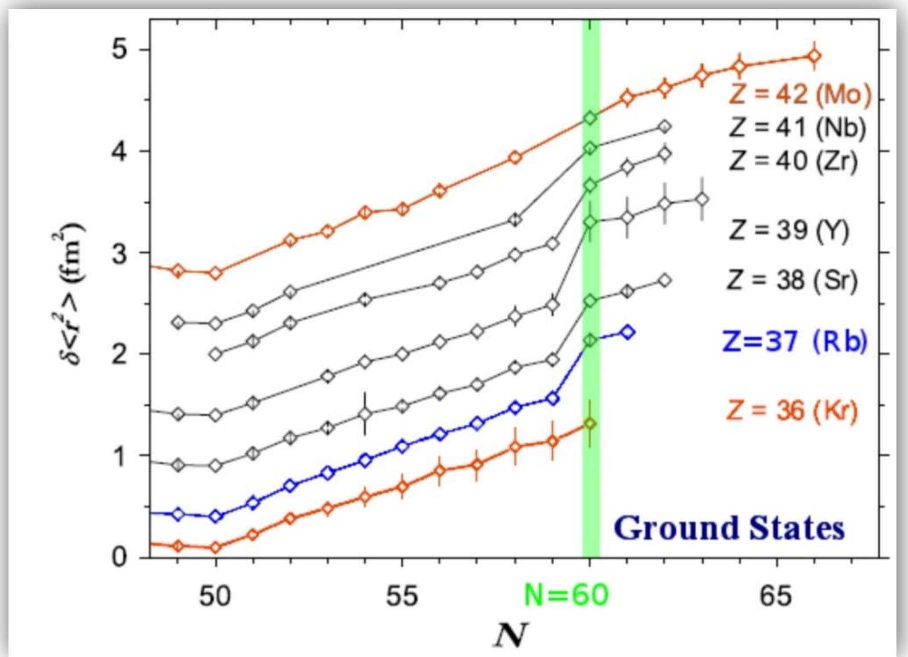
Coulomb excitation of $^{93-99}$Rb at ISOLDE, CERN

G. Georgiev

Sudden onset of deformation at N=60





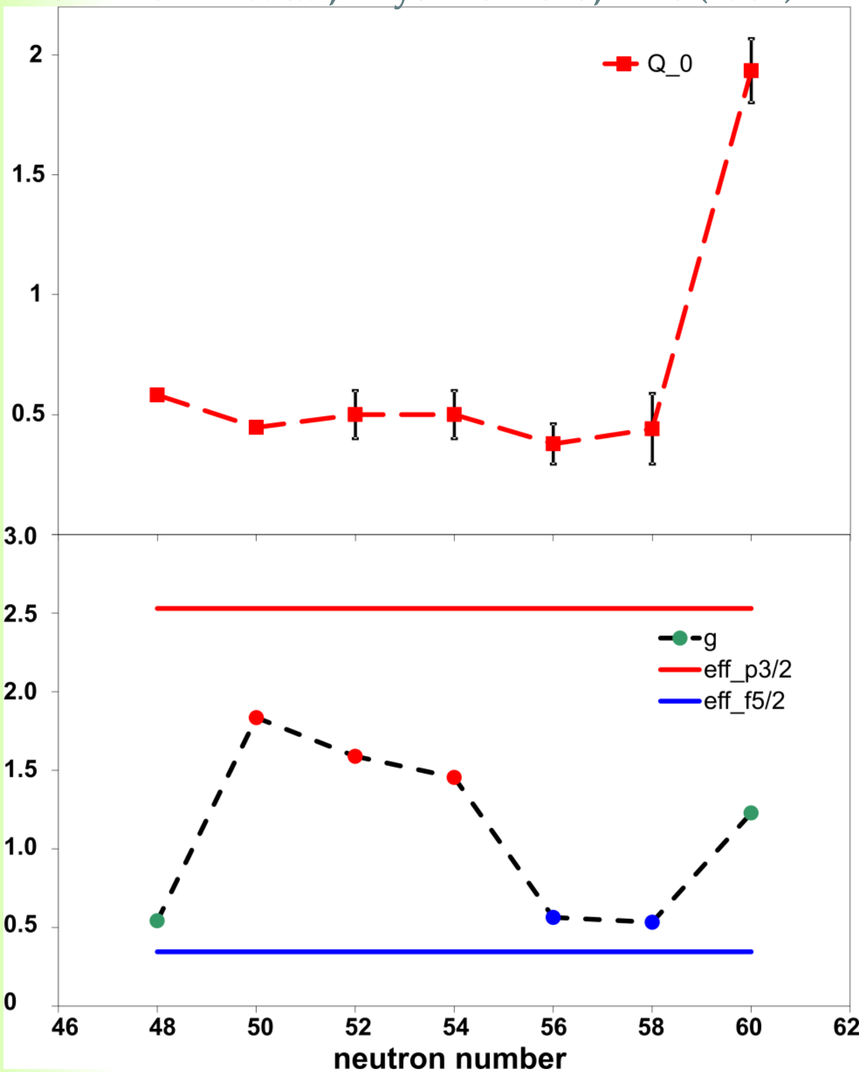
S. Naimi *et al.*, PRL 105, 032502 (2010)

- region of sudden onset of deformation between Z=36 (Kr) and Z=42 (Mo)
- charge radii – sudden increase at N=60 from Rb on

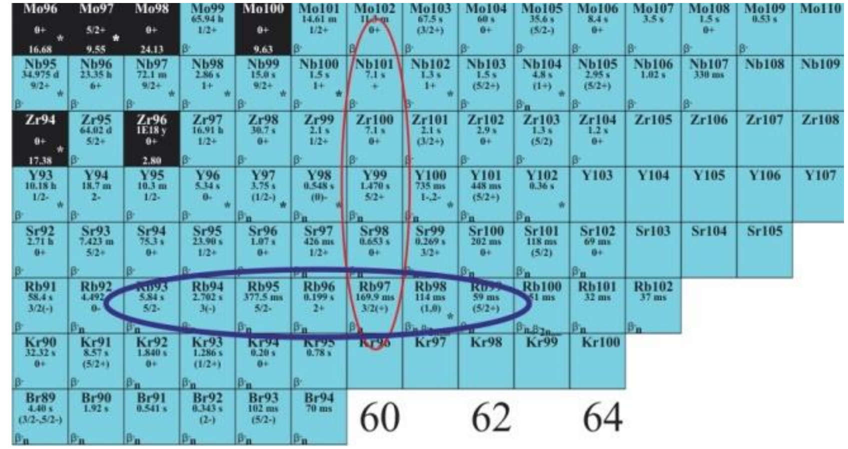
  → points to a specific importance of the π–ν interaction

What about Rb’s?

C. Thibault *et al.*, Phys. Rev. C23, 2720 (1981)



$\pi 3/2^-[312]$, $\pi 3/2^-[301]$, $\pi 3/2^+[431]$

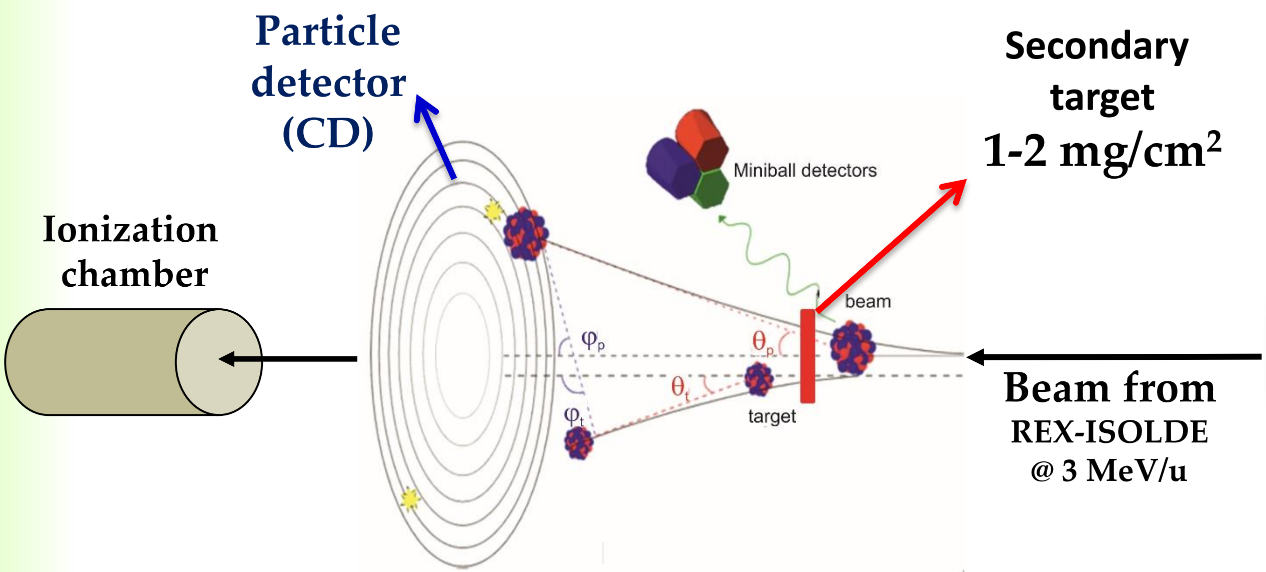


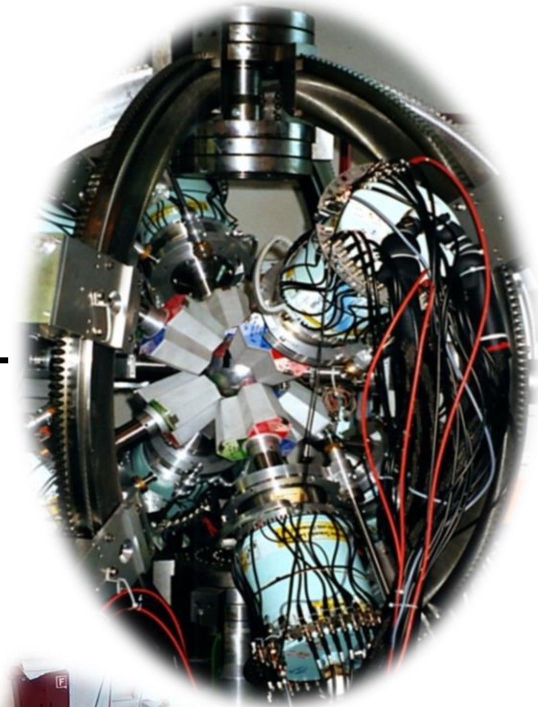
Ground-state nuclear moment measurements of ^{97}Rb

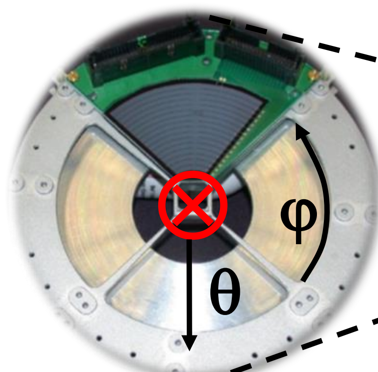
K	I^π	Q_s [eb]	μ [μ_N]	Orbital
3/2	$3/2^-$	0.6	1.9	$\pi\frac{3}{2}^-[301]$
3/2	$3/2^+$	0.6	1.99	$\pi\frac{3}{2}^+[431]$
3/2	$3/2^-$	0.6	0.7	$\pi\frac{3}{2}^-[312]$
Experimental Values		0.6	1.84	-

- ✓ **Sudden onset of deformation at ^{97}Rb**
- ✓ **Ground-state magnetic moment measurement – favors $\pi 3/2^+[431]$ but does not exclude $\pi 3/2^-[301]$**

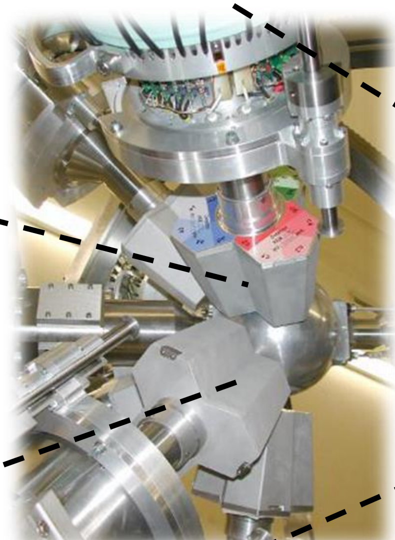
Coulex with Miniball @ ISOLDE



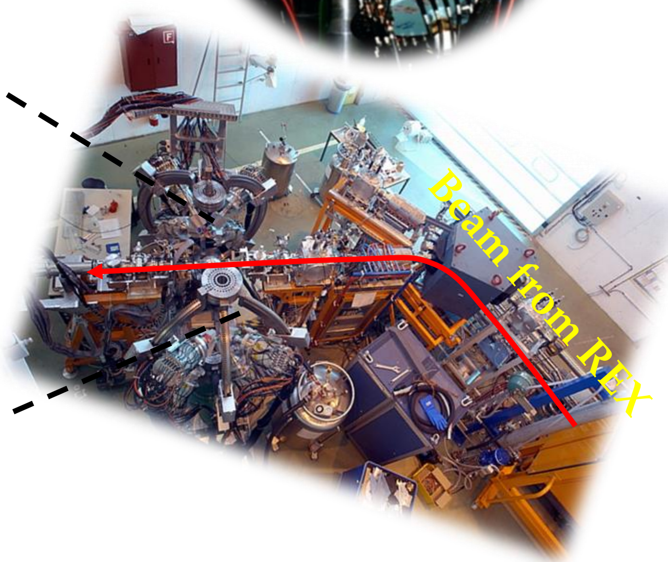




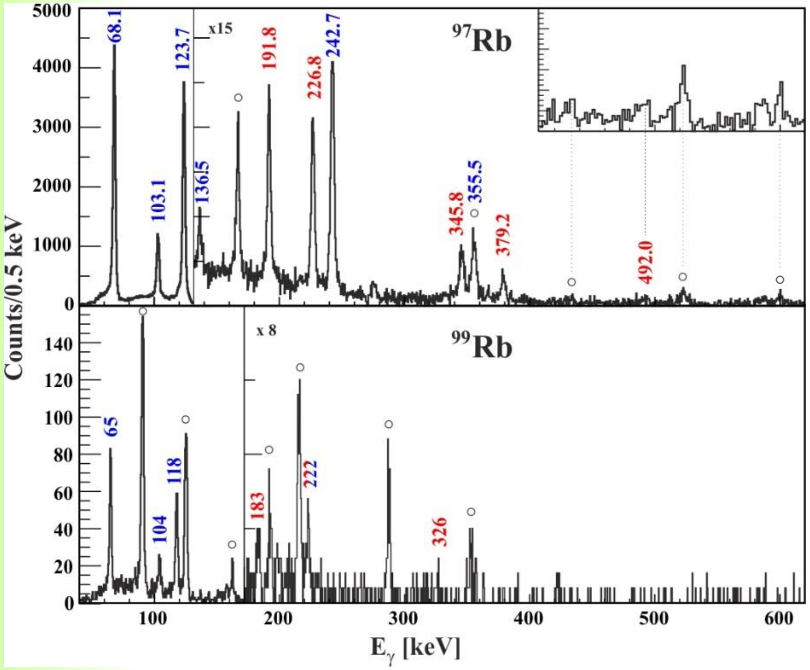
CD detector
(16° – 53°)



Vacuum chamber &
Miniball detectors

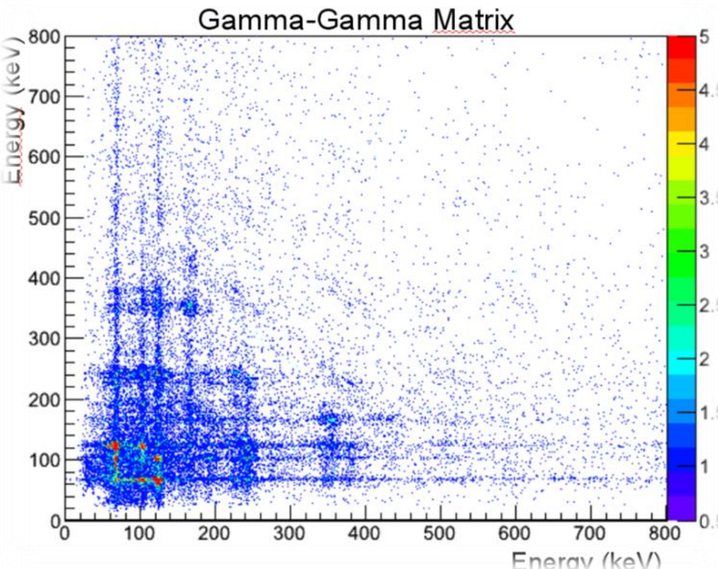


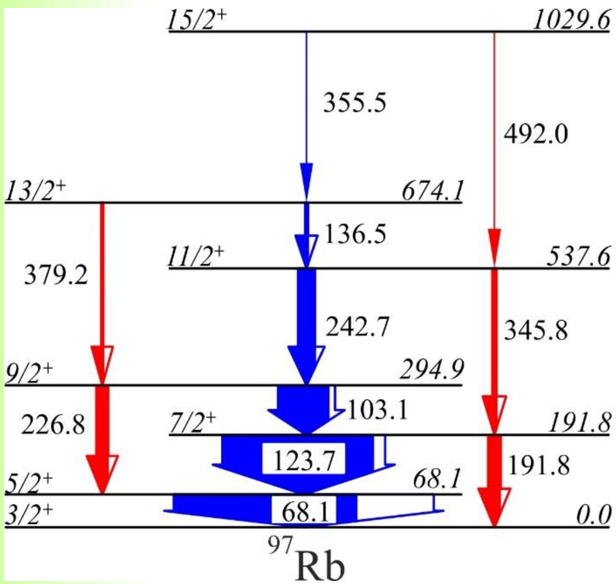
Coulex of ^{97}Rb and ^{99}Rb

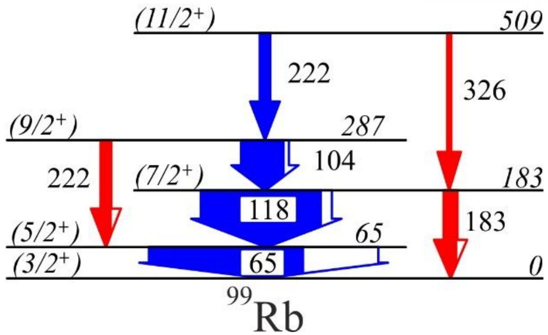


Isotopes	$T_{1/2}$	Intensities
^{93}Rb	5.8s	6 10^6pps
^{95}Rb	377ms	1 10^6pps
^{97}Rb	170ms	4 10^5pps
^{99}Rb	50ms	few 10^3pps

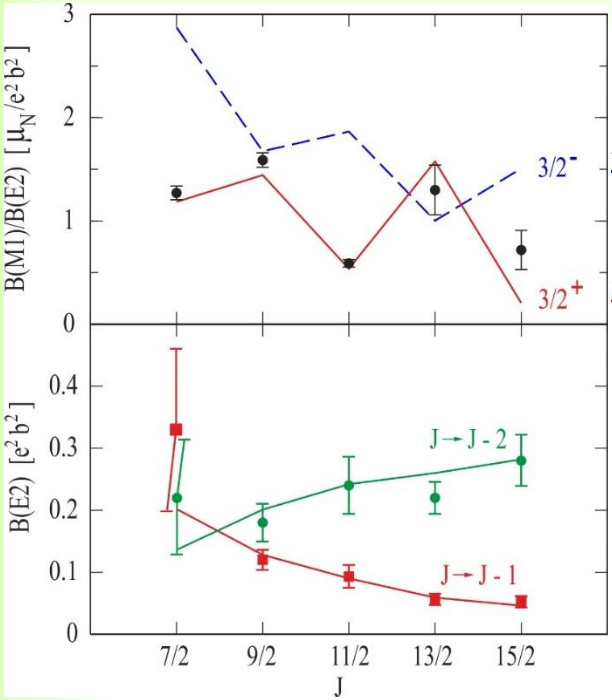
NO previously known excited states or transitions!







What the theory sais?

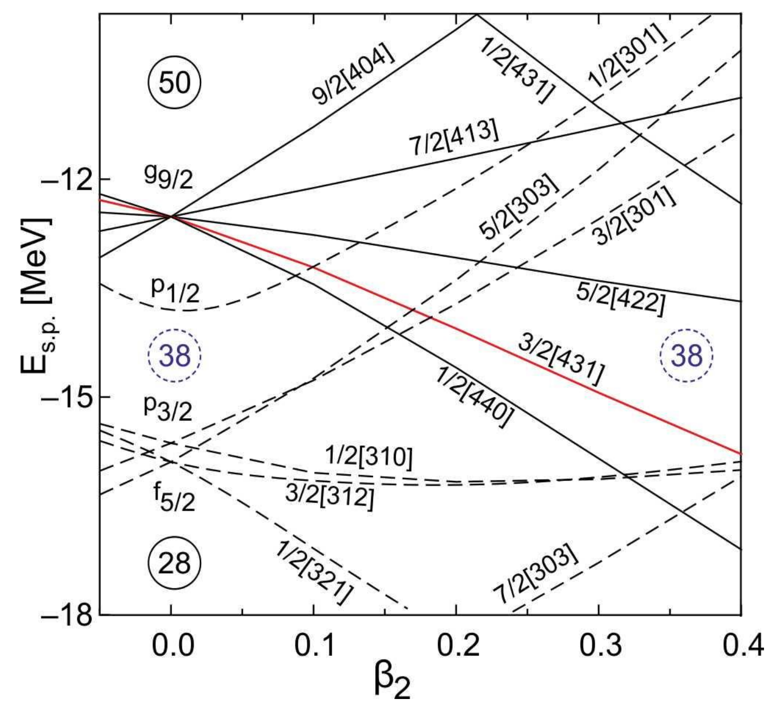


B(M1)/B(E2) values *(from exp. intensities)*

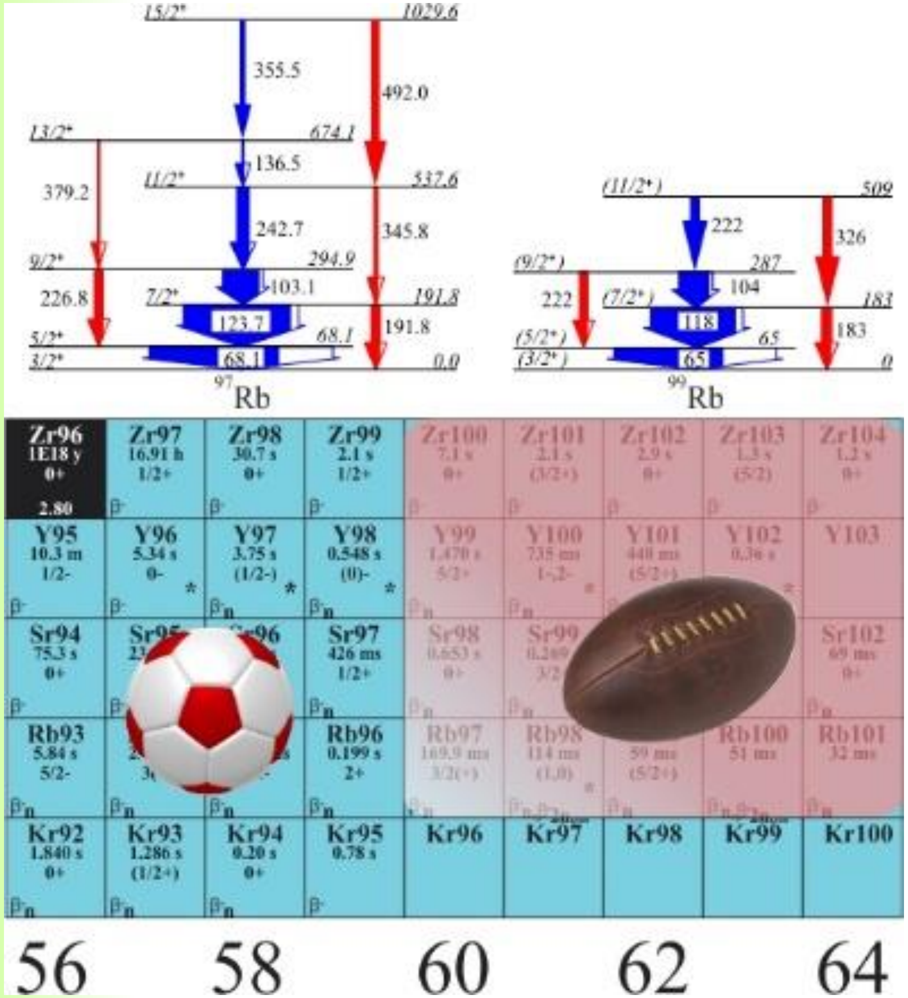
B(E2) values *(part.-rotor model)*

Fine interplay between well defined **spherical** and **well-deformed** shell gaps at Z=38 might be among the main reasons for the **sudden onset of deformation** in the neutron-rich A~100 nuclei.

C. Sotty et al., ***PRL 115 172501 (2015)***



^{97}Rb – the corner stone of the A~100 deformed region



- ^{97}Rb – the “South-West” corner stone of the region of deformation around A~100
- **Completely independent structures** (spherical and well deformed) are exchanging their relative positions right at N=60

Conclusions and perspectives

- High-accuracy experimental results on nuclear moments are needed for testing the nuclear theories
- TDRIV (on H-like ions) can provide high accuracy, model independent, measurements of short-lived excited states using RIB
- Transition probabilities and nuclear moment studies are complementary and indispensable for the correct understanding of the nuclear structure far from stability

Collaborations

TDRIV :

- **A. Kusoglu, A. Goasduff, J. Ljungvall, C. Sotty -** CSNSM, Orsay, **France**
- **A.E. Stuchbery -** ANU, Canberra, **Australia**
- **D. Balabanski -** ELI-NP, IFIN - HH, Magurele, **Romania**
- **L. Atanasova, P. Detistov -** INRNE, BAS, Sofia, **Bulgaria**
- **K. Gladnishki, M. Danchev -** University of Sofia, **Bulgaria**
- **I. Matea, I. Stefan, D. Verney, D. Yordanov -** IPN, Orsay, **France**
- **D. Radeck -** IKP, Cologne, **Germany**

Coulex:

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- **A. Stuchbery -** Department of Nuclear Physics, ANU, Canberra, **Australia**
- **M. Zielinska –** CEA, Saclay, **France**
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- **S. Das Gupsta -** Dipartimento di Fisica, Universita di Camerino, **Italy**
- **N. Bree, J. Diriken -** IKS, KU Leuven, **Belgium**
- **L. Gafney -** Oliver Lodge Laboratory, University of Liverpool, **UK**
- **K. Hadynska-Klek, P. Napiorkowski -** HIL, Warsaw University, Warsaw, **Poland**
- **F. G. Kondev -** NED, Argonne National Laboratory, **USA**
- **T. Kroell, M. Scheck -** Technische Universitat Darmstadt, Darmstadt, **Germany**
- **G. Simpson -** LPSC, Grenoble, **France**
- **J. Pakarinen, H. Törnqvist, F. Wenander -** ISOLDE, CERN, Geneva, **Switzerland**
  and **REX-ISOLDE** and **Miniball's collaborators**

Благодаря Ви за вниманието!

ISOLDE – принцип на действие

Дебела мишена
(UC_x или друг материал)

1.4 GeV протонен сноп

30-60 keV еднократно йонизирани йони
→ селекция чрез GPS или HRS сепараторите

EBIS йонен източник
зарядово състояние до A/q ~ 4

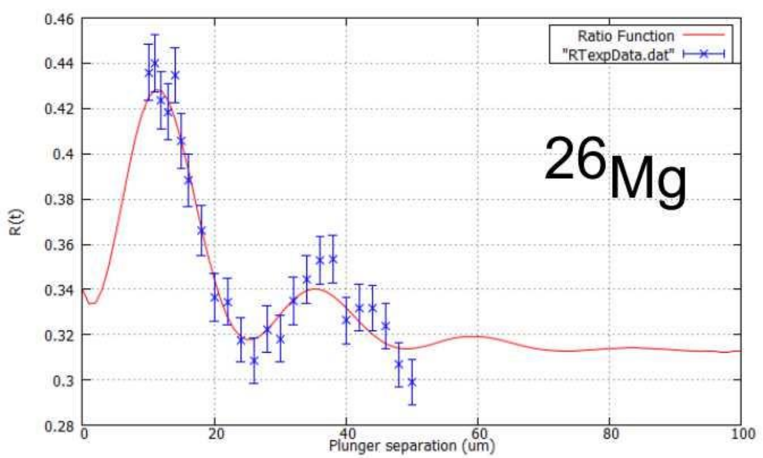
REX – ускорение на радиоактивния сноп до 3 MeV/u

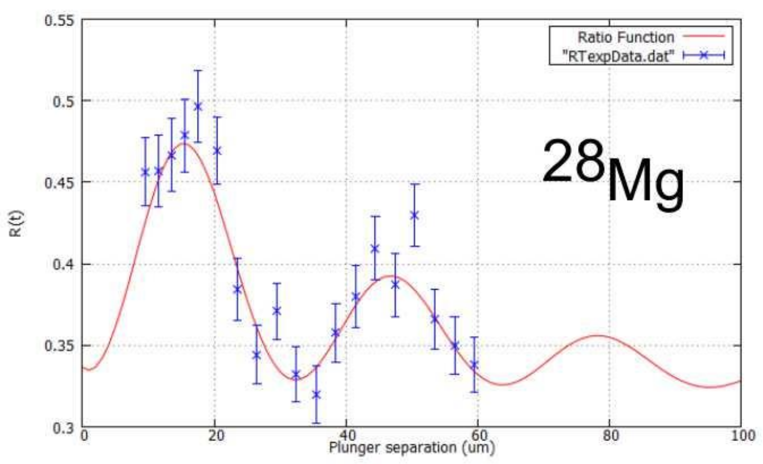
MINIBALL
спектрометър от сегментирани Ge детектори

REX trap – йонна уловка
формиране на снопа (E, t)

Ускорени радиоактивни снопове с добре дефинирани параметри (E,t, α)
Интензивности ~10^3 – 10^7 частици в секунда

Feasability





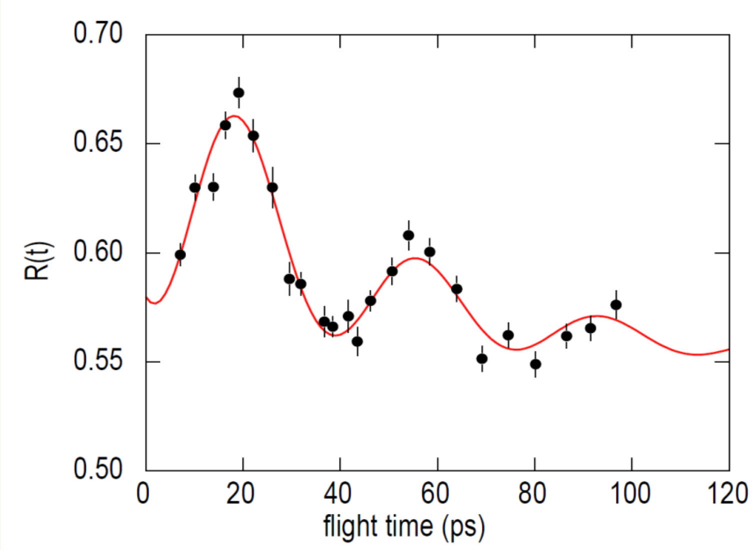
^{26}Mg – setup testing:

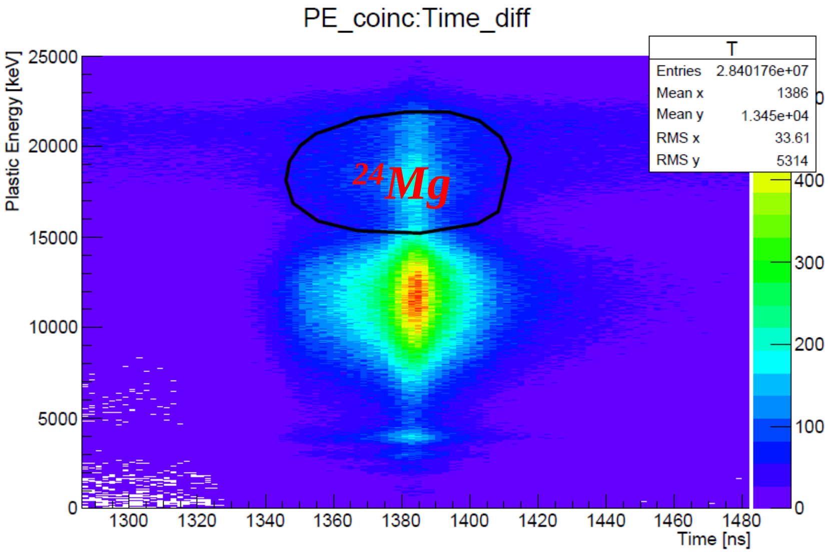
- 5×10^7 pps
- 11% TIGRESS efficiency
- 2 days measurement
- 3% g-factor accuracy

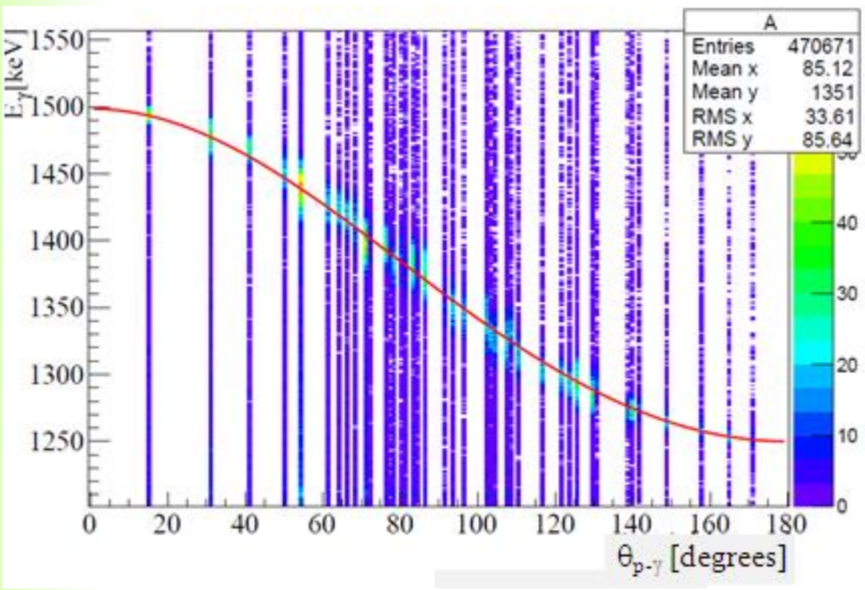
^{28}Mg – RIB measurement

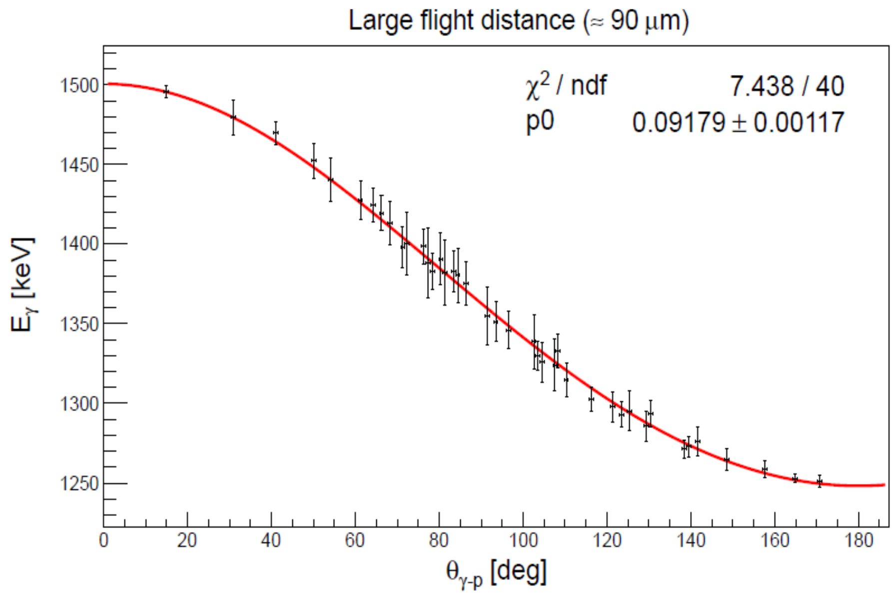
- 1×10^6 pps
- 14%TIGRESS efficiency
- 8 days measurement
- <u>< 5% accuracy</u>

Experimental spectra



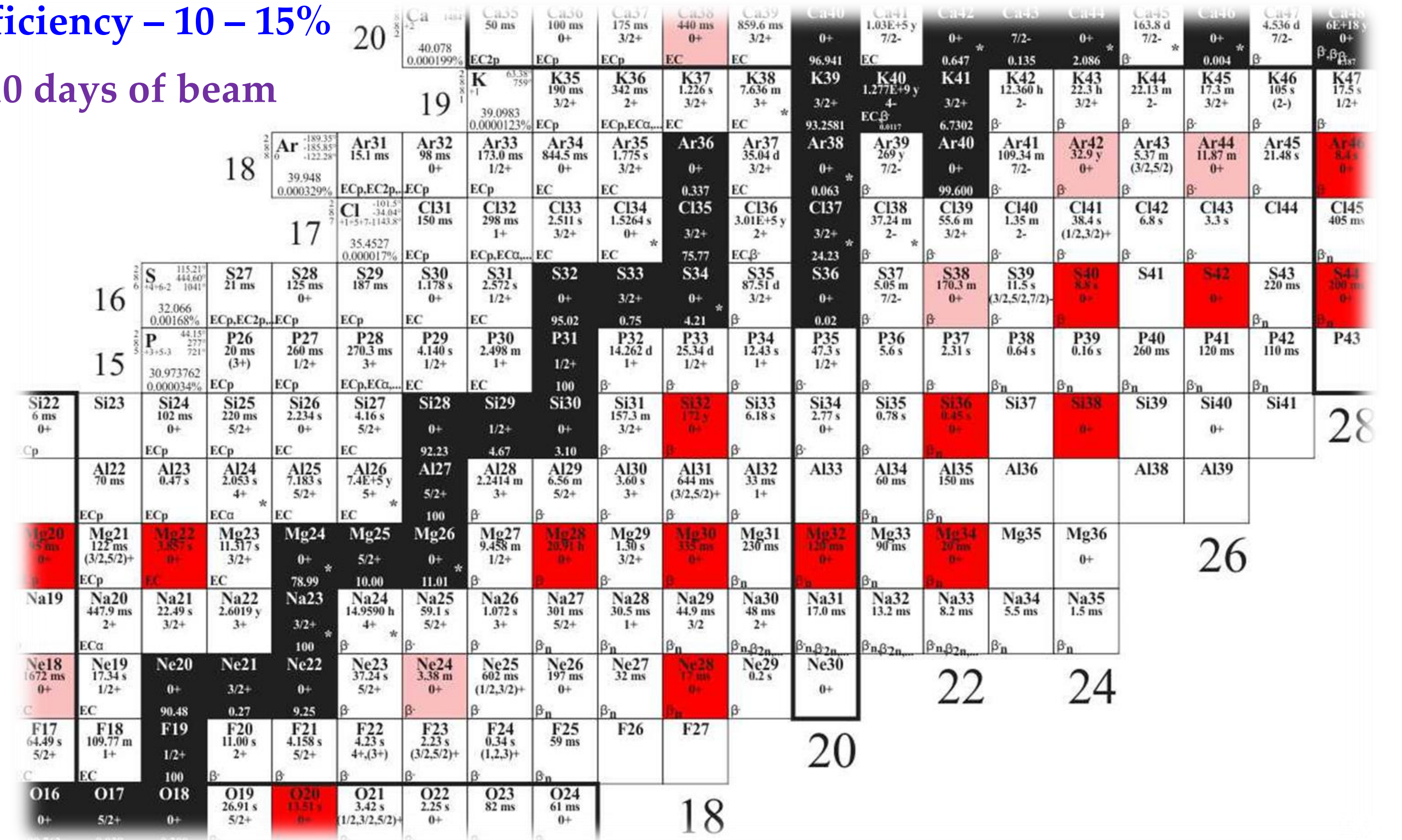






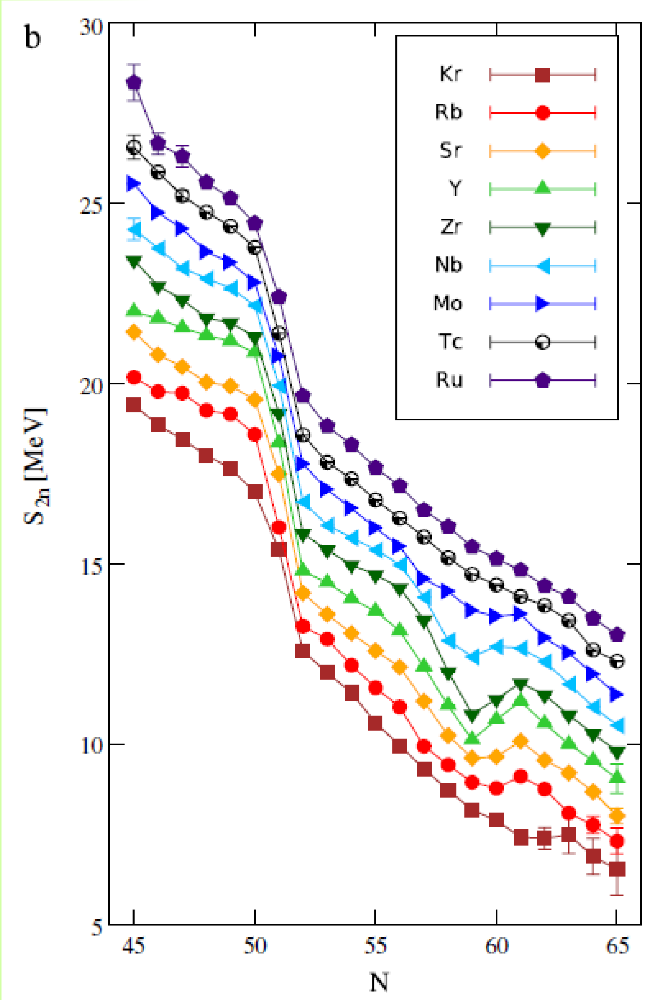
Perspectives

- **First RIB study?**
  - **e.g. ^{28}Mg case:**
    - **10^6 pps**
    - **γ-efficiency – 10 – 15%**
    - **7 – 10 days of beam**



Sudden onset of deformation at N=60

P. Campbell, I.D. Moore, M.R. Pearson
Progress in Particle and Nuclear Physics 86 (2016) 127–180



- ❑ The n-rich nuclei between Z=37 and Z=41 present at N=60 one of the most impressive deformation change in the nuclear chart
- ❑ Localized within the Z degree of freedom
  - → Point to a specific π–ν interaction