Nuclear physics:
the ISOLDE facility

Lecture 3: Physics of ISOLDE

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on behalf of the CERN ISOLDE team
www.cern.ch/isolde

Outline

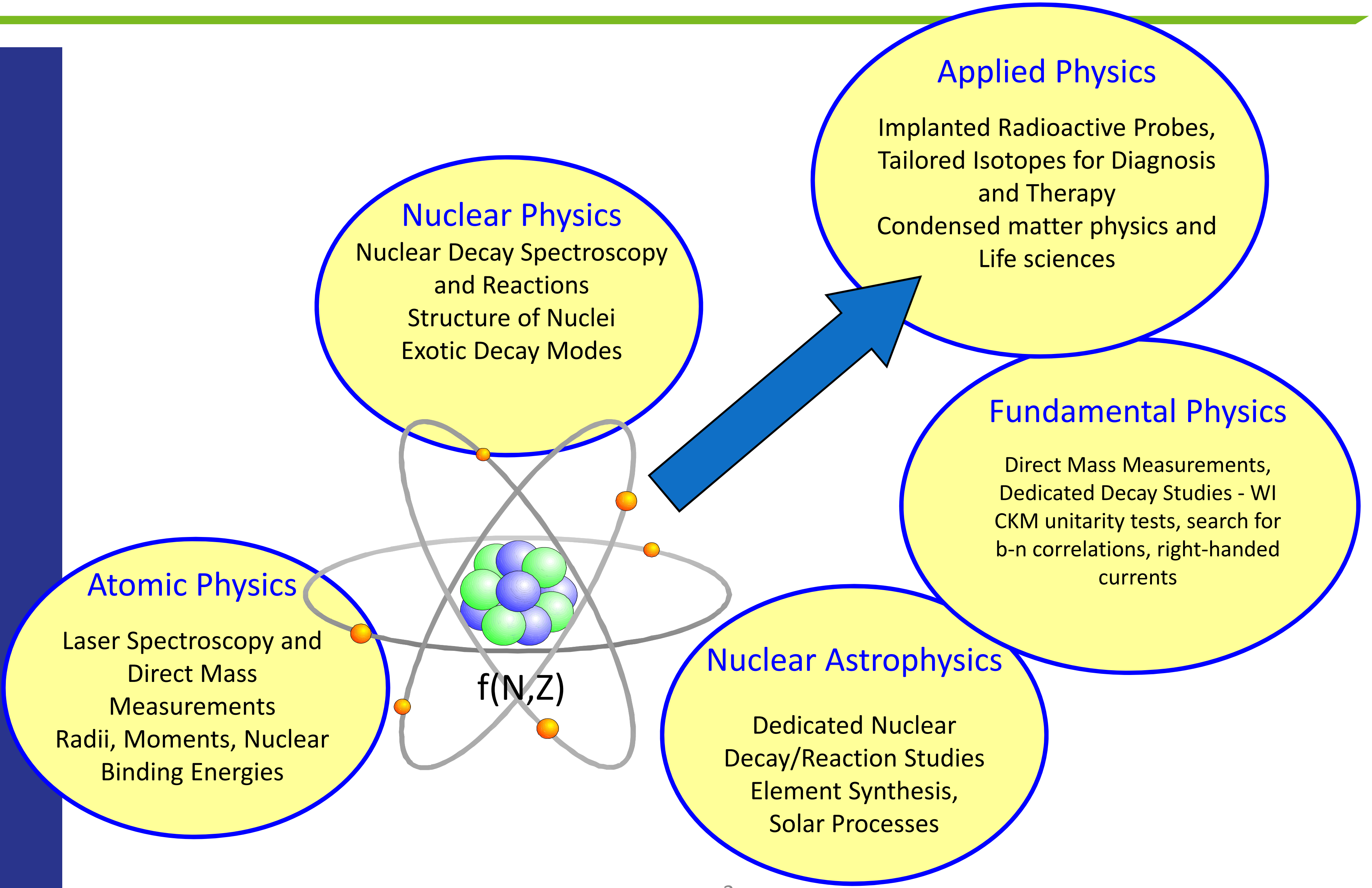
Aimed at both physics and non-physics students

- Lecture 1: Introduction to nuclear physics

- Lecture2: CERN-ISOLDE facility

- **This lecture**: Physics of ISOLDE
  - Measured properties
  - Used techniques
  - Recent results

ISOLDE physics topics



Applied Physics

Implanted Radioactive Probes,
Tailored Isotopes for Diagnosis
and Therapy
Condensed matter physics and
Life sciences

Nuclear Physics

Nuclear Decay Spectroscopy
and Reactions
Structure of Nuclei
Exotic Decay Modes

Fundamental Physics

Direct Mass Measurements,
Dedicated Decay Studies - WI
CKM unitarity tests, search for
b-n correlations, right-handed
currents

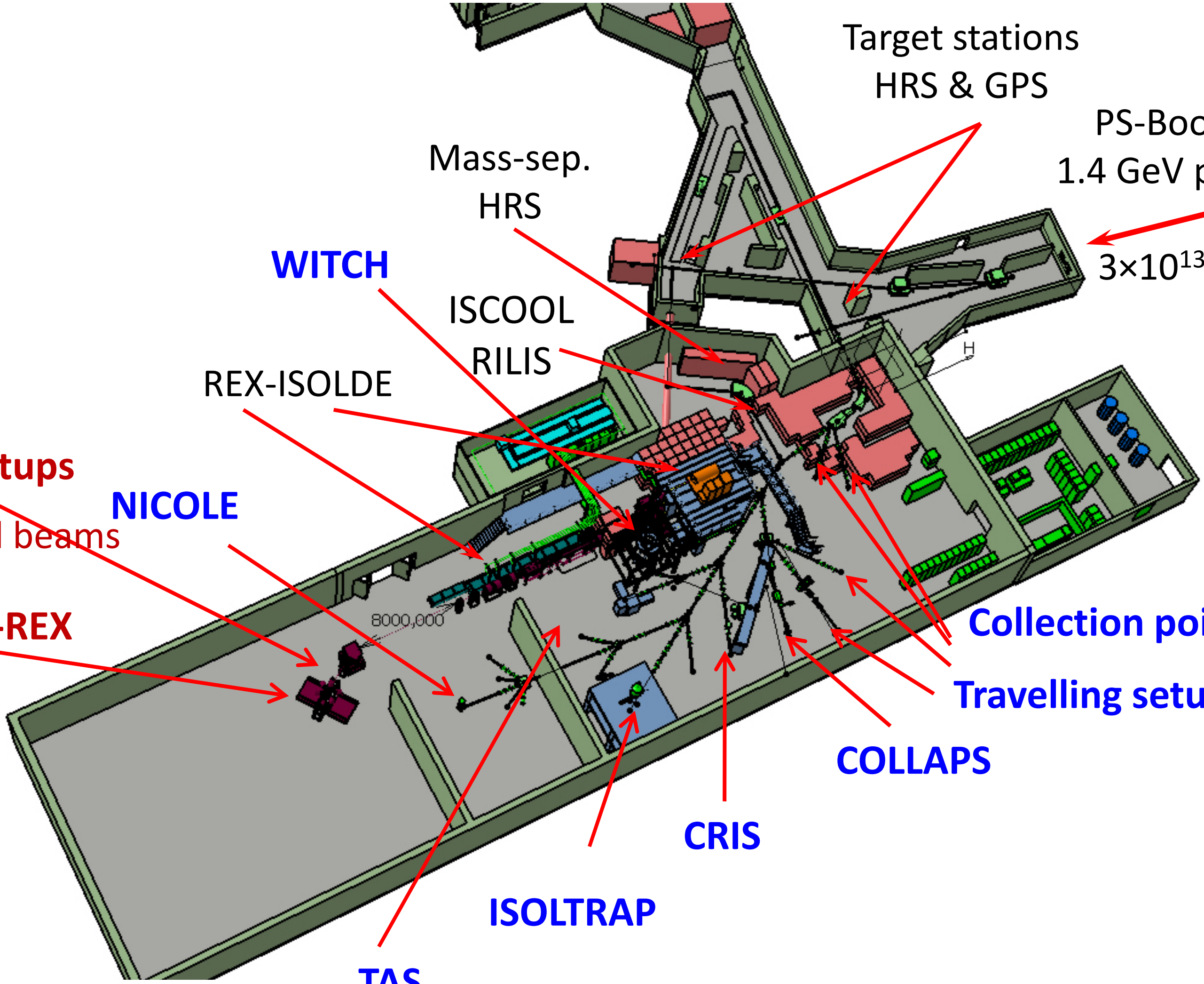
Atomic Physics

Laser Spectroscopy and
Direct Mass
Measurements
Radii, Moments, Nuclear
Binding Energies

Nuclear Astrophysics

Dedicated Nuclear
Decay/Reaction Studies
Element Synthesis,
Solar Processes

Experimental setups



Target stations
HRS & GPS

PS-Booster
1.4 GeV protons

3×10^{13} ppp

Mass-sep.
HRS

WITCH

ISCOOL

RILIS

REX-ISOLDE

Travelling setups

Post-accelerated beams

NICOLE

MINIBALL and T-REX

Collection points

Travelling setups

COLLAPS

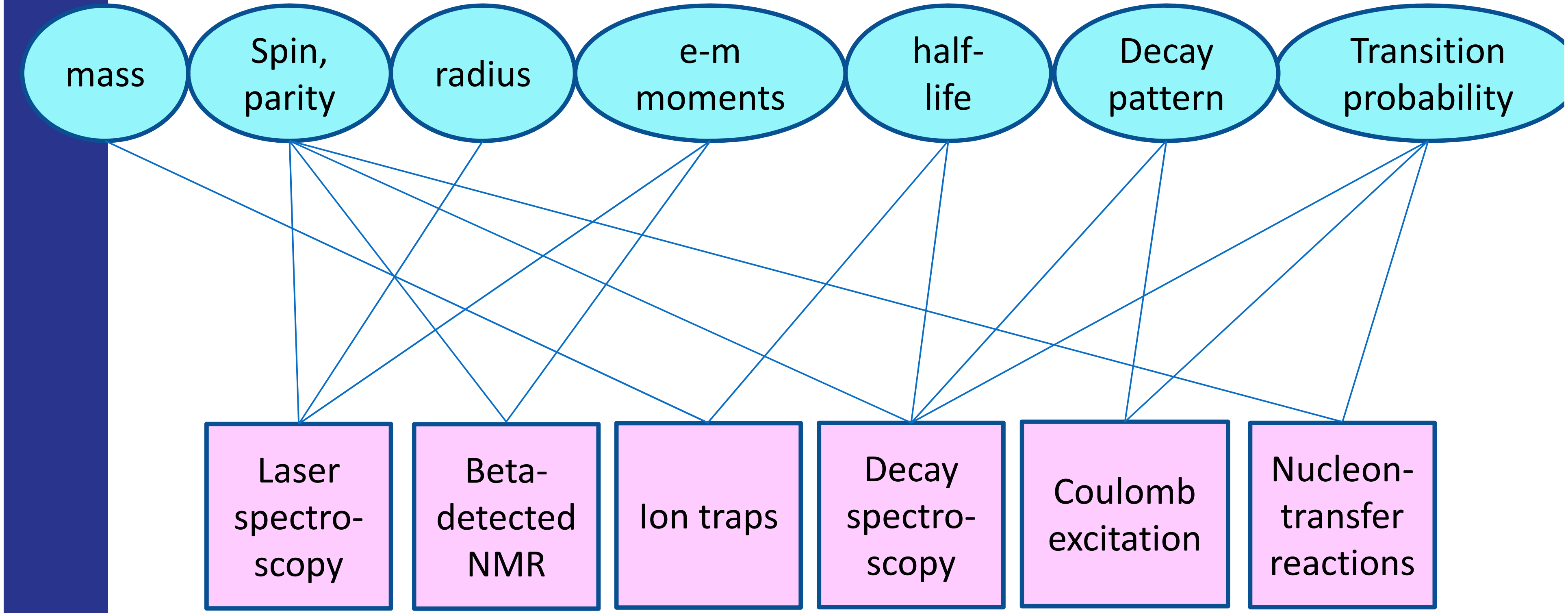
CRIS

ISOLTRAP

TAS

Studies of radioactive nuclides

Properties/observables (for ground states and isomers – long-lived excited states)



mass

Spin, parity

radius

e-m moments

half-life

Decay pattern

Transition probability

Laser spectroscopy

Beta-detected NMR

Ion traps

Decay spectroscopy

Coulomb excitation

Nucleon-transfer reactions

Techniques/ devices

To obtain the full picture: need to study several properties and use several techniques

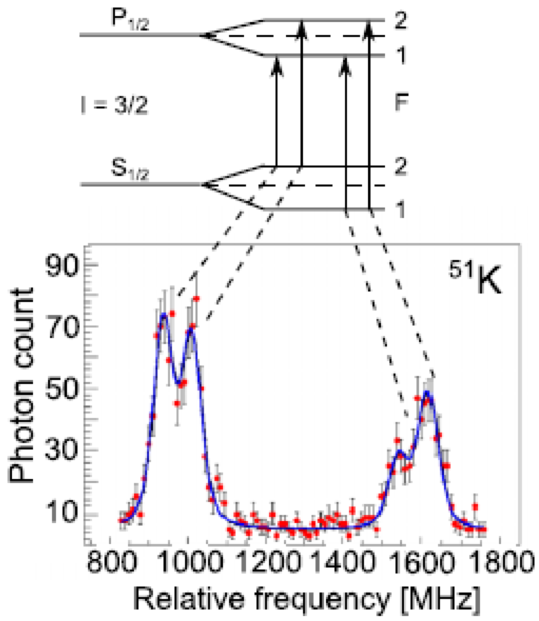
Laser spectroscopy and nuclear properties

Lasers allow studying **ground-state (and isomeric) properties of nuclei,** based on:

Atomic **hyperfine structure (HFS)**

(interaction of nuclear and atomic spins)

- HFS details depend on:
  - Spin -> orbit of last proton&neutron
  - Magnetic dipole moment -> orbits occupied by p&n
  - Electric quadrupole moment -> deformations

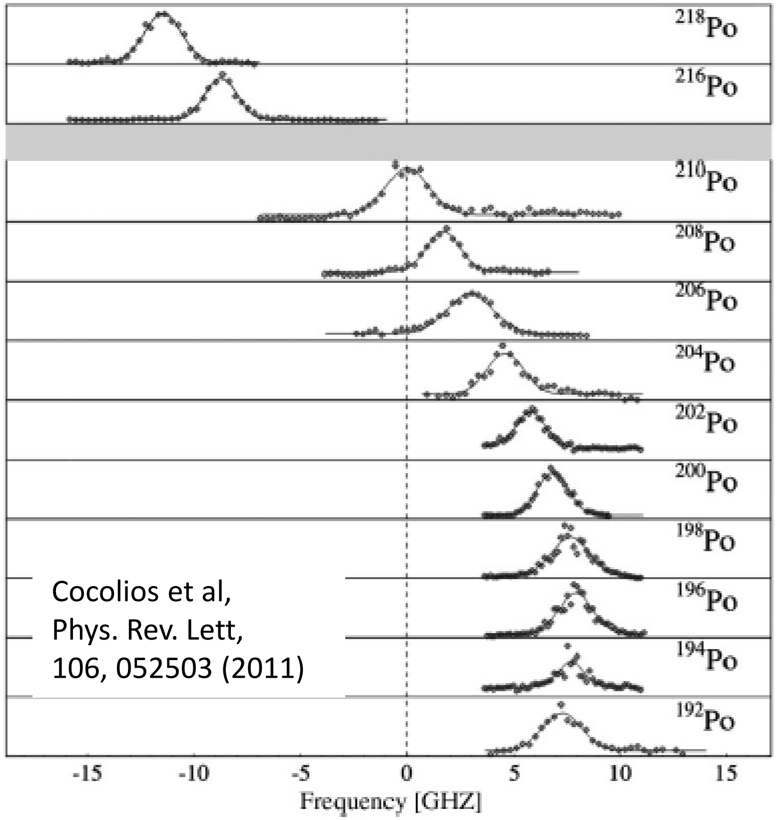


Yordanov et al,
Phys. Rev. Lett.,
110, 172503 (2013)

Isotope shifts (IS) in atomic transitions

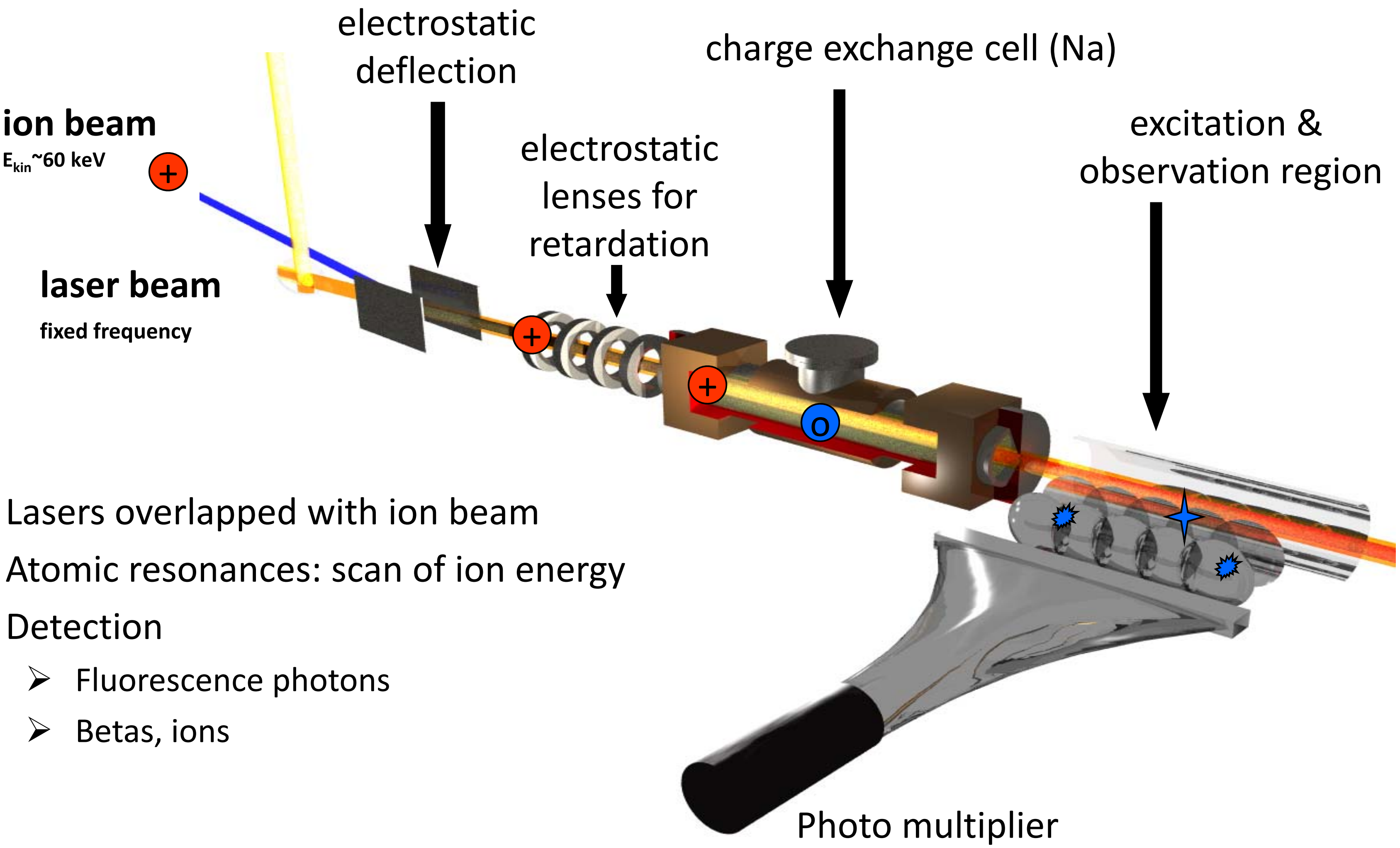
(change in mass and size of different isotopes of the same chemical element)

- IS between 2 isotopes depends on:
  - difference in their masses & charge radii



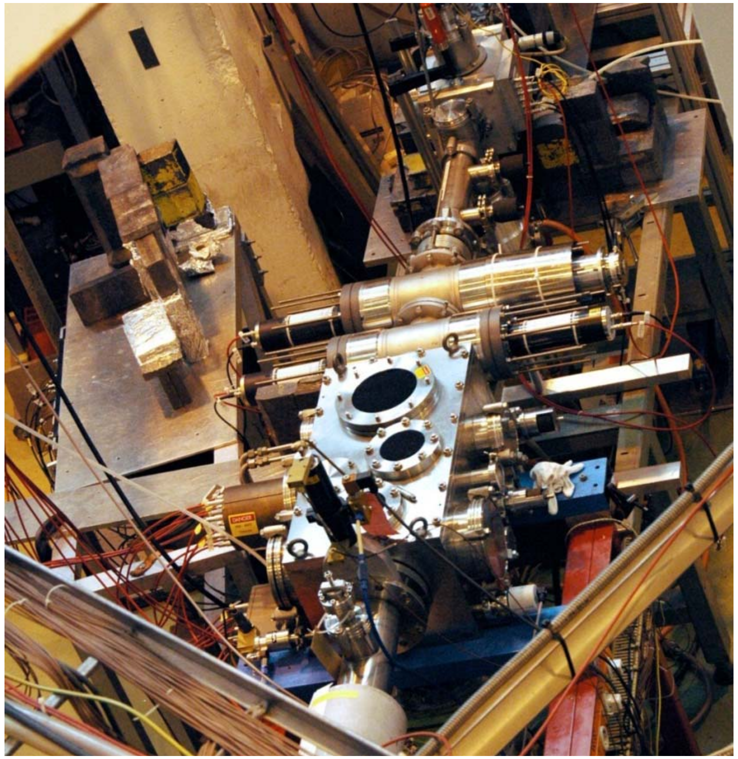
Cocolios et al,
Phys. Rev. Lett,
106, 052503 (2011)

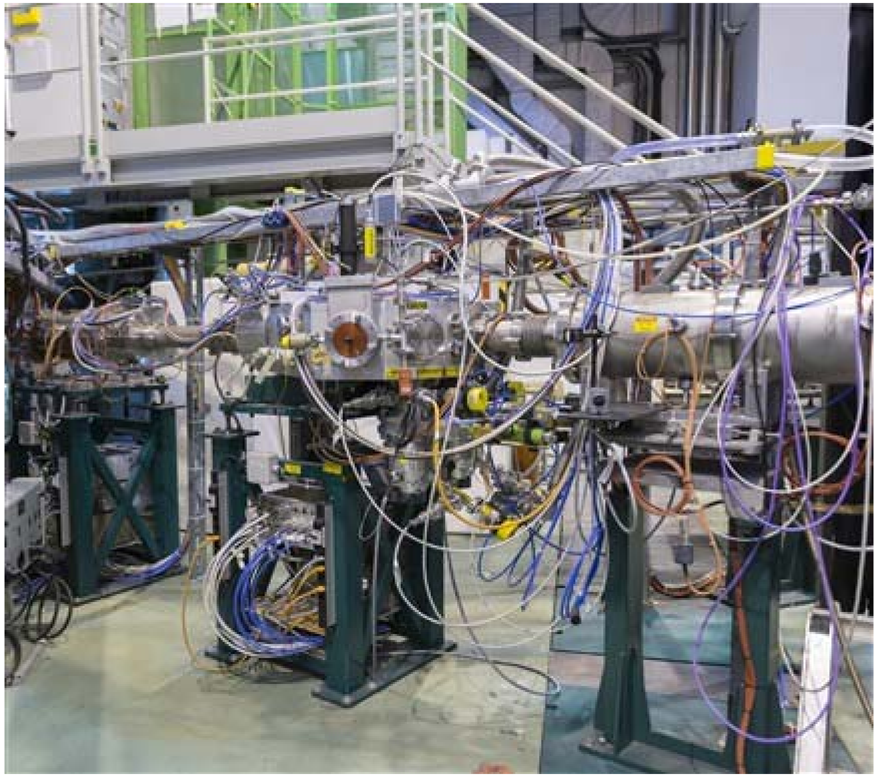
Collinear laser spectroscopy

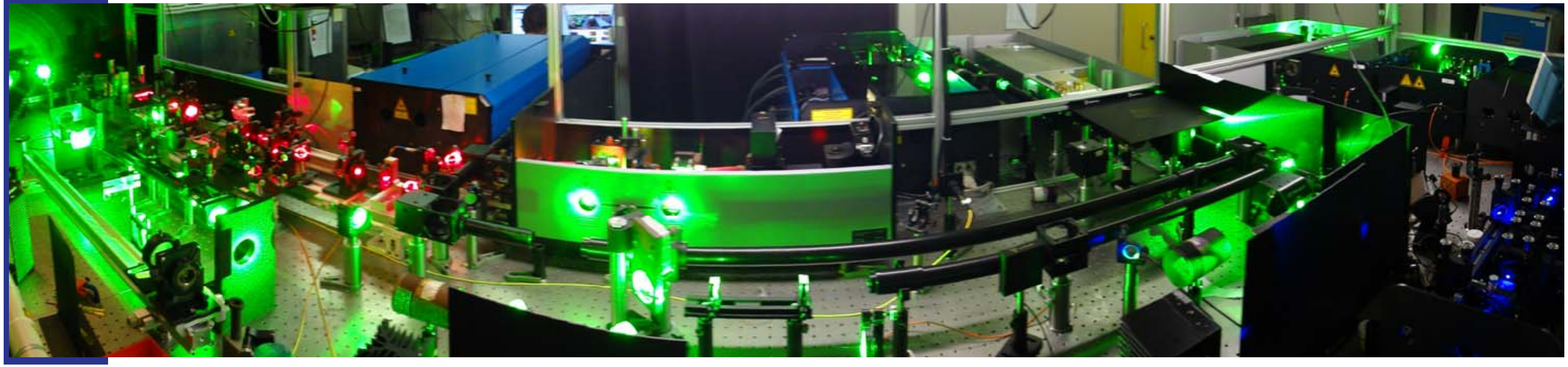


- Lasers overlapped with ion beam
- Atomic resonances: scan of ion energy
- Detection
  - Fluorescence photons
  - Betas, ions

COLLAPS, CRIS, RILIS

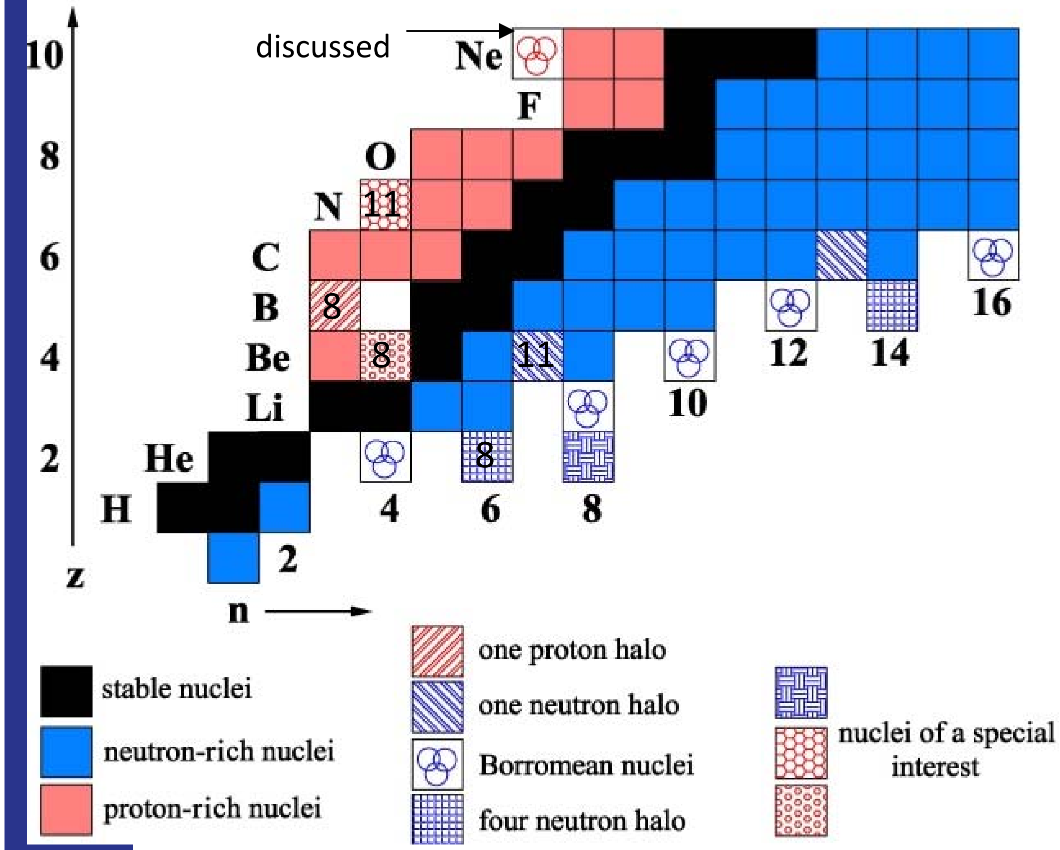


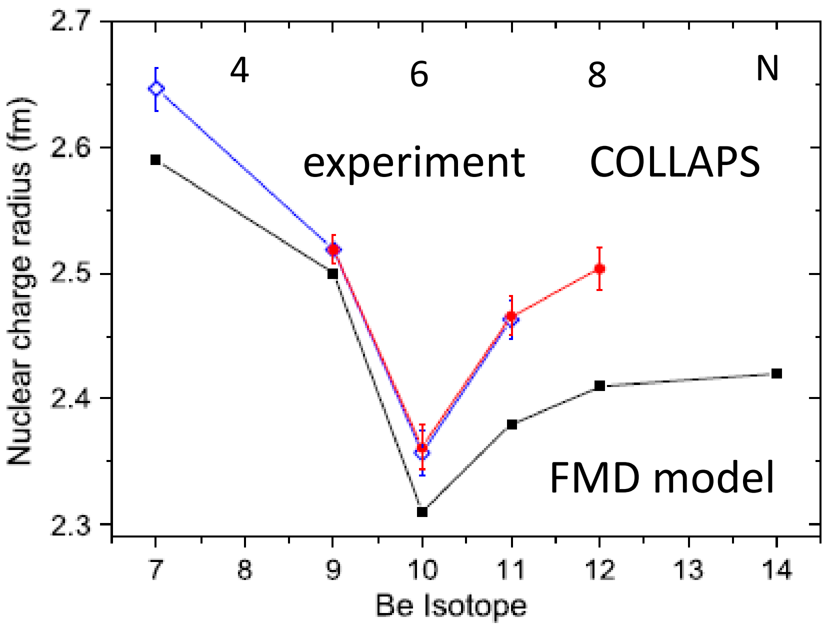


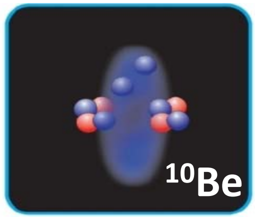


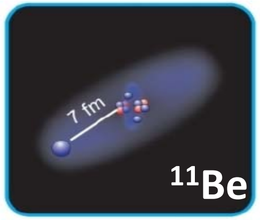
Charge radii of Be isotopes

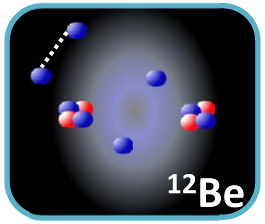
- **Halo:** nucleus built from a core and at least one neutron/proton with spatial distribution much larger than that of the core
  - ➢ Interaction of the core and halo nucleons not well understood





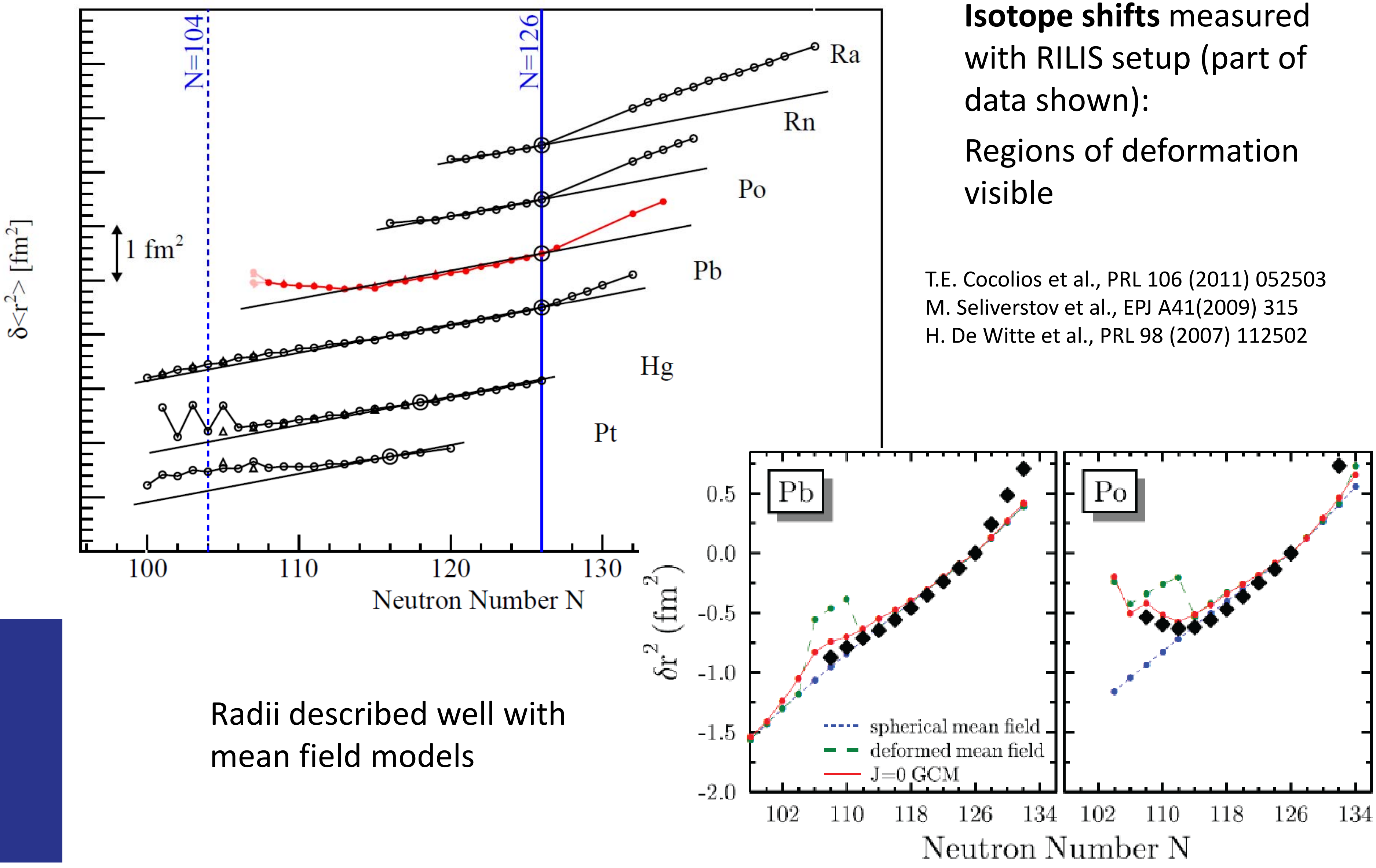






A. Krieger et al,
Phys. Ref. Lett. 108 (2012) 142501

Charge radii around lead



Isotope shifts measured with RILIS setup (part of data shown):

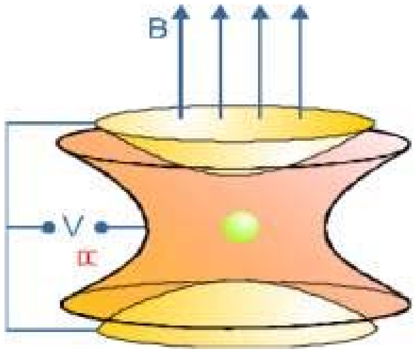
Regions of deformation visible

T.E. Cocolios et al., PRL 106 (2011) 052503
M. Seliverstov et al., EPJ A41(2009) 315
H. De Witte et al., PRL 98 (2007) 112502

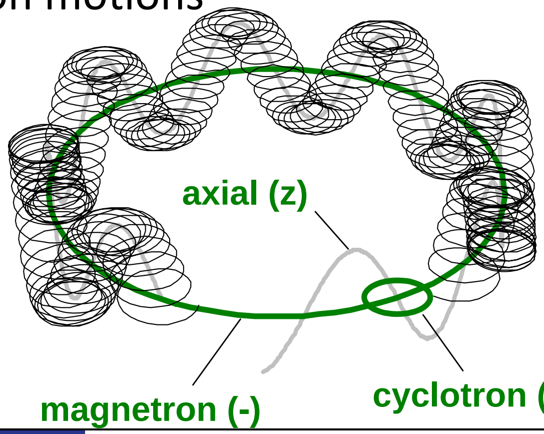
Radii described well with mean field models

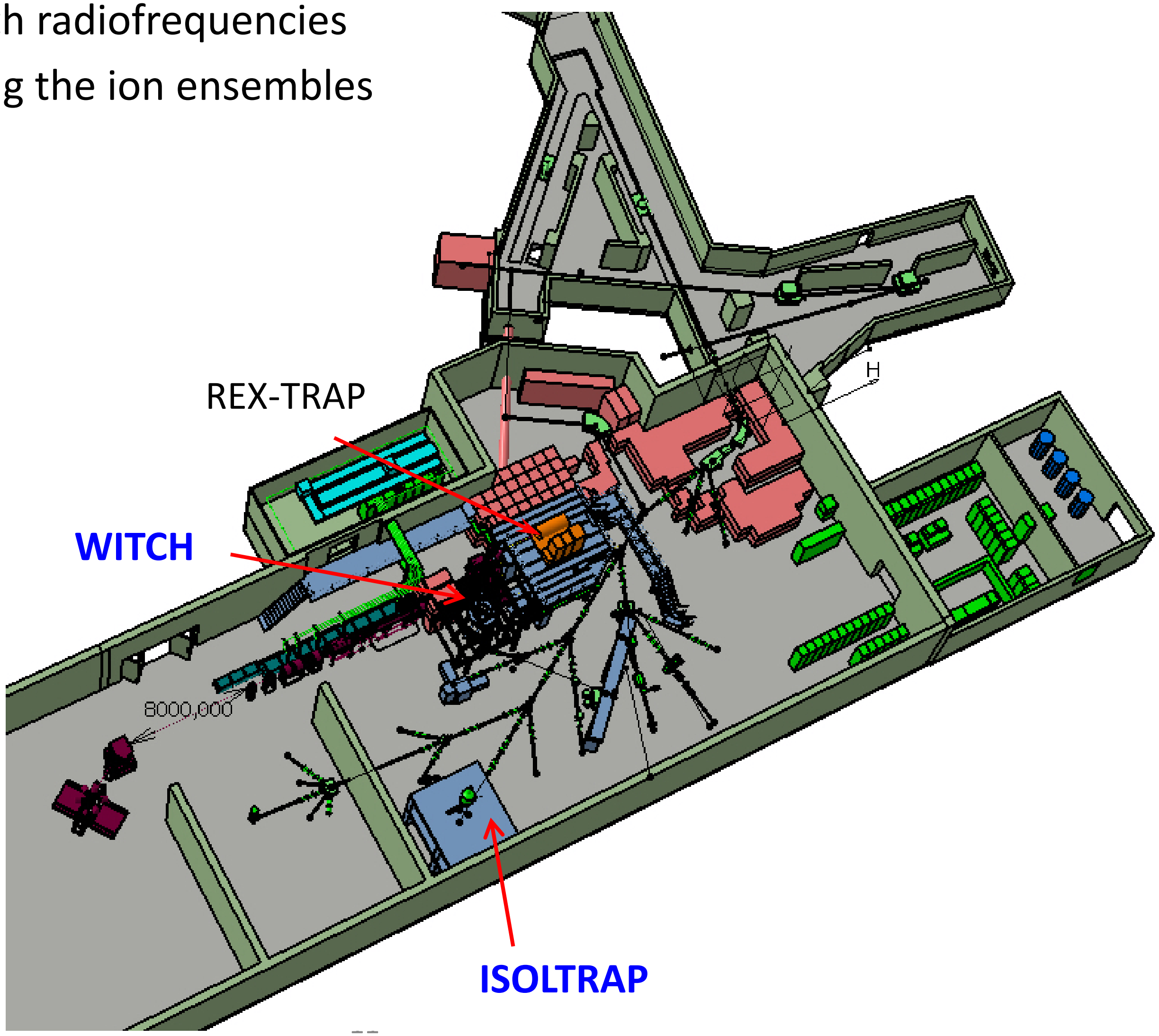
Studies with ion traps

- Penning trap = cross of magnetic and electric field
- Ion manipulation with radiofrequencies
- Possibility of purifying the ion ensembles



Ion motions





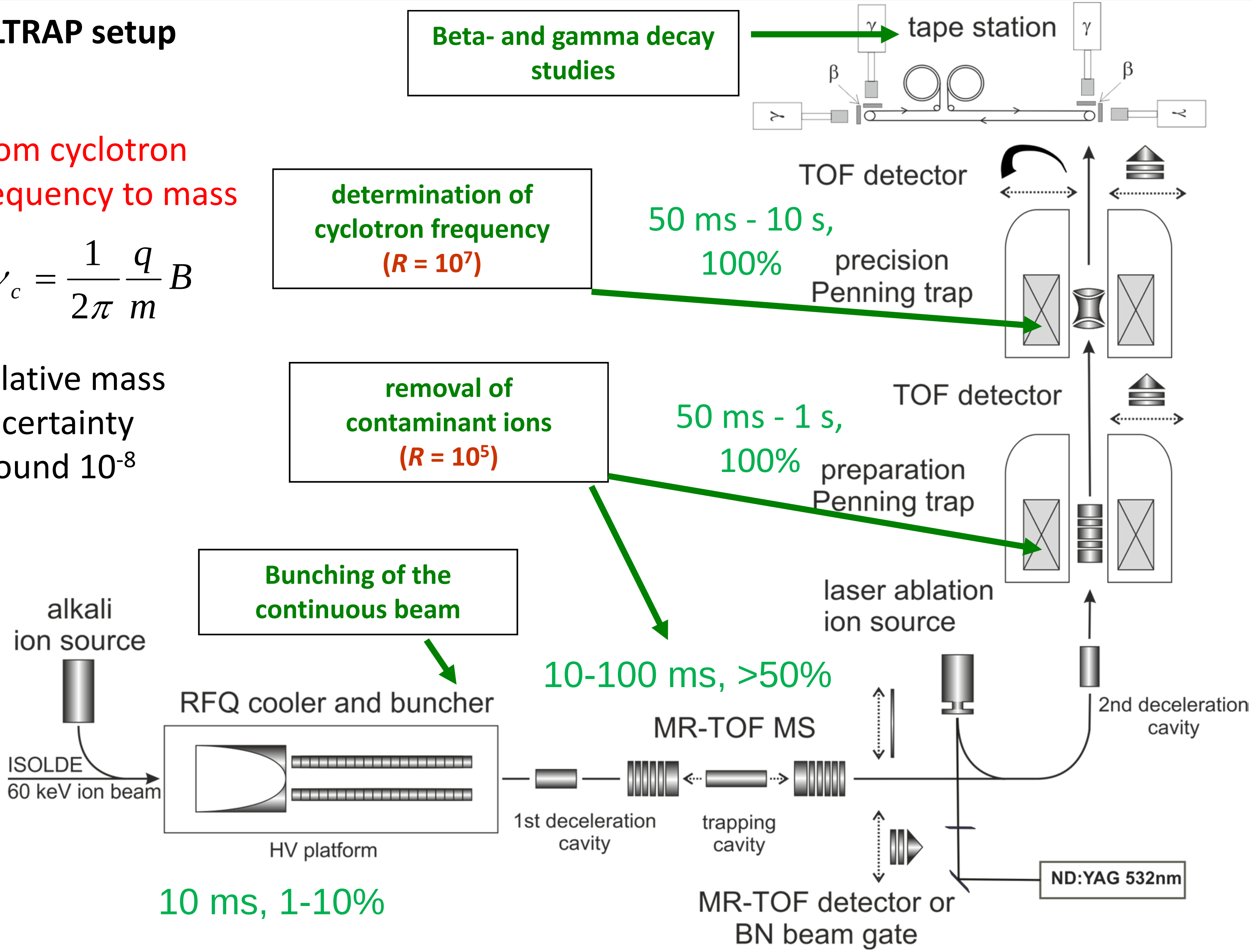
Penning-trap mass spectrometry

ISOLTRAP setup

From cyclotron frequency to mass

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Relative mass uncertainty around 10^{-8}



Beta- and gamma decay studies

determination of cyclotron frequency ($R = 10^7$)

removal of contaminant ions ($R = 10^5$)

Bunching of the continuous beam

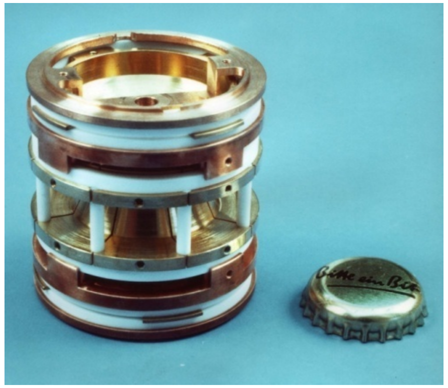
50 ms - 10 s, 100%

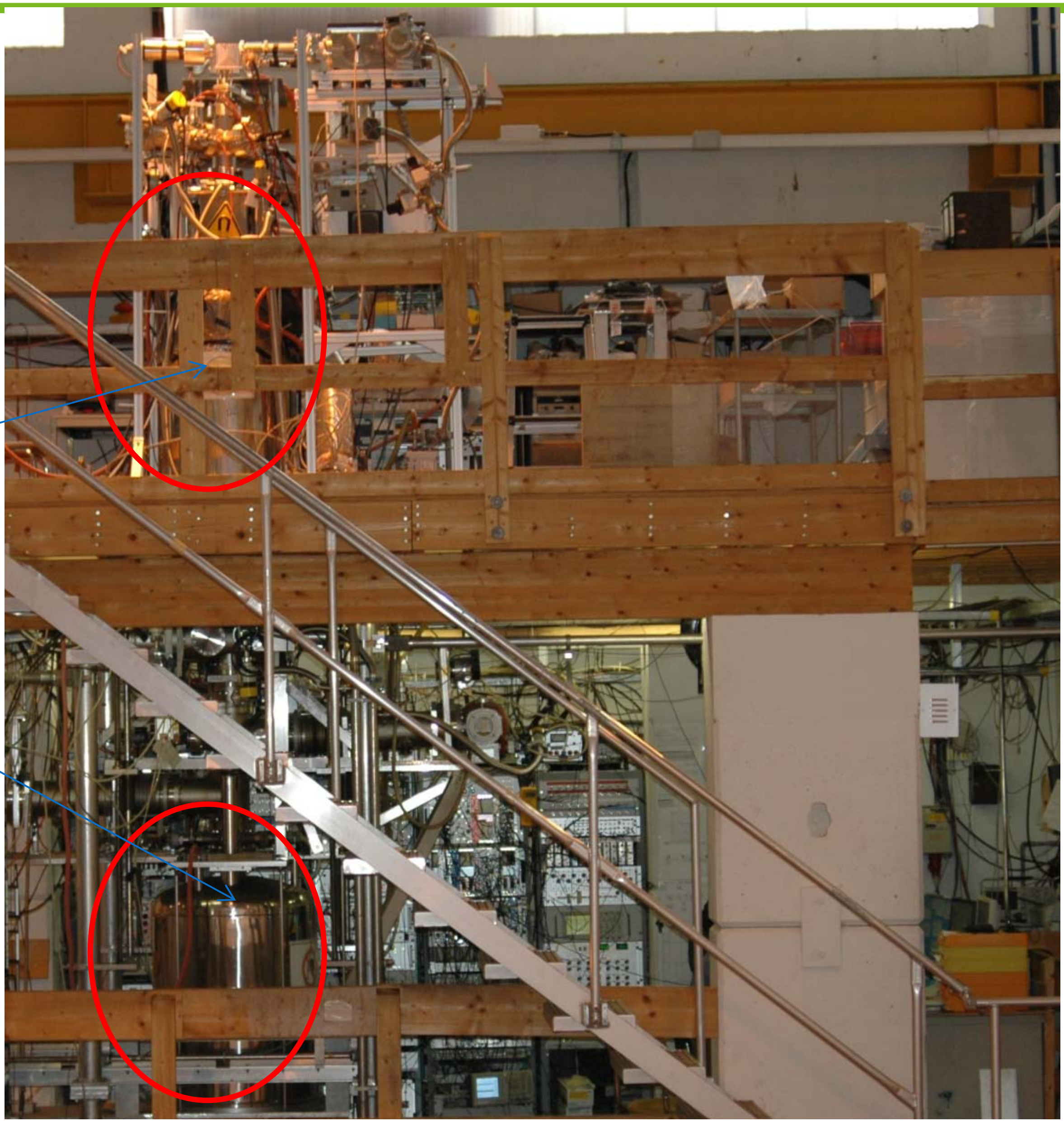
50 ms - 1 s, 100%

10-100 ms, >50%

10 ms, 1-10%

ISOLTRAP



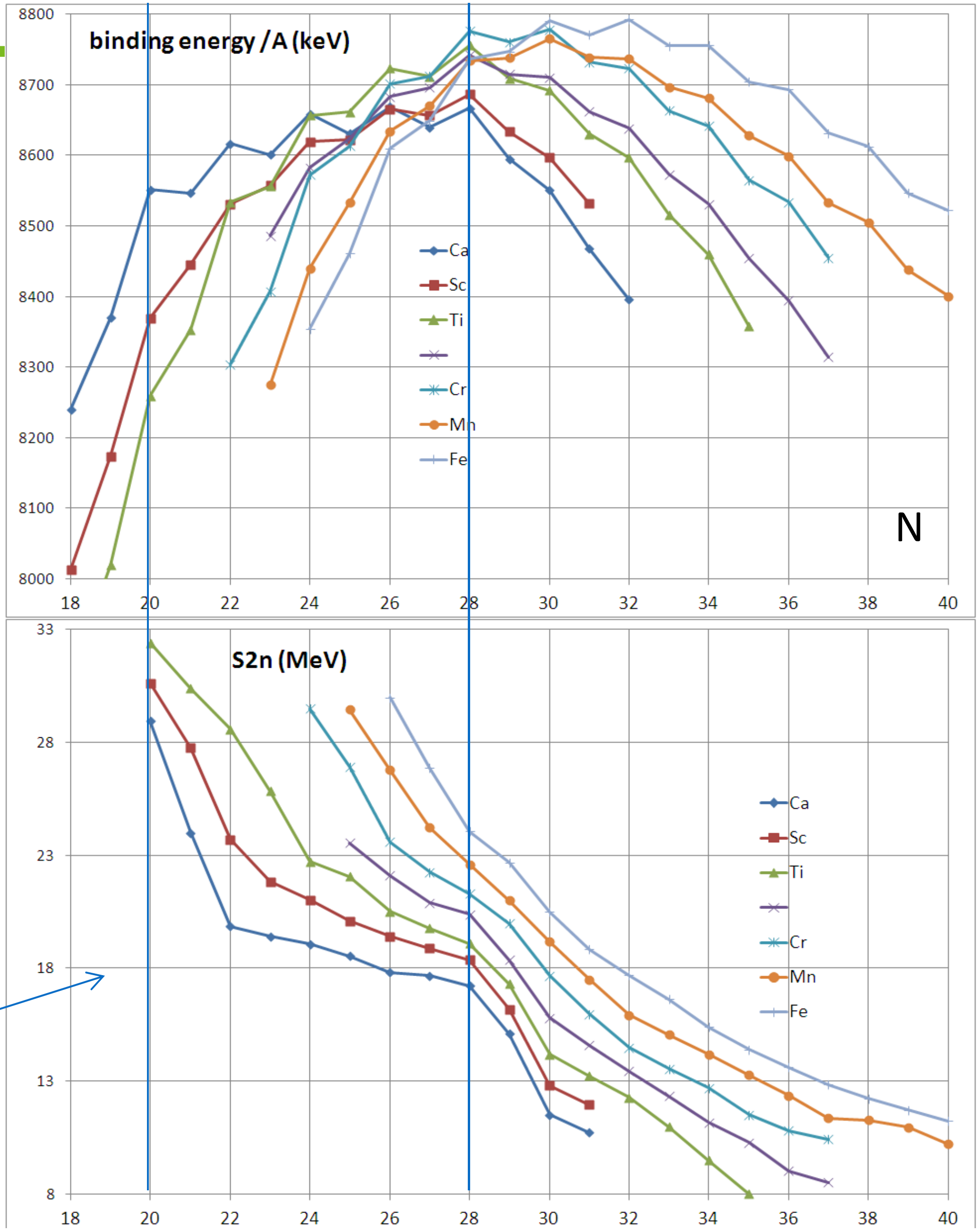


Masses and nuclear structure

- Mass filters (mass differences) to “filter out” specific effects, e.g.
  - Differences in binding energies (one- or two-neutron/proton separation energies)

Two-neutron separation energy

$$S_{2n} = B(N-2, Z) - B(N, Z),$$

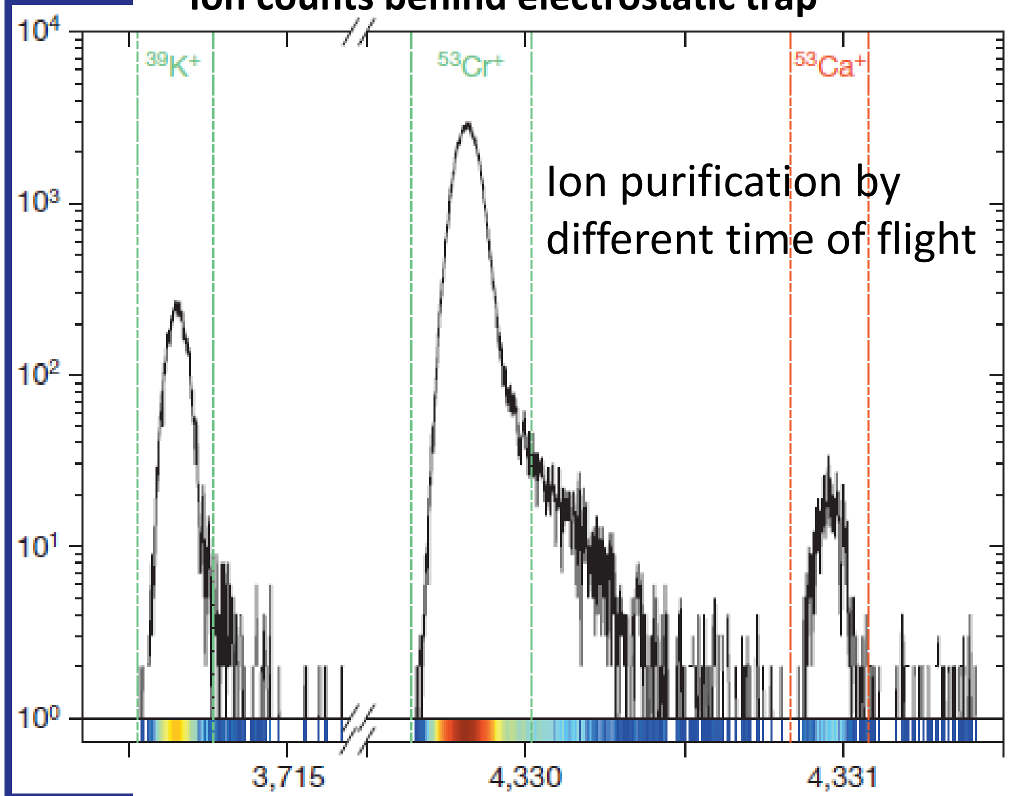


Closed shells visible as a sudden drop after the magic number (N=20 and 28)

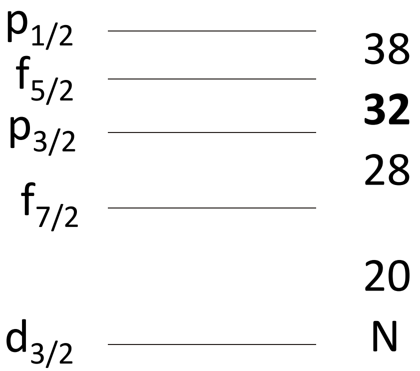
Calcium-54 and nuclear forces

F. Wienholtz et al, Nature 498 (2013), 346

Ion counts behind electrostatic trap

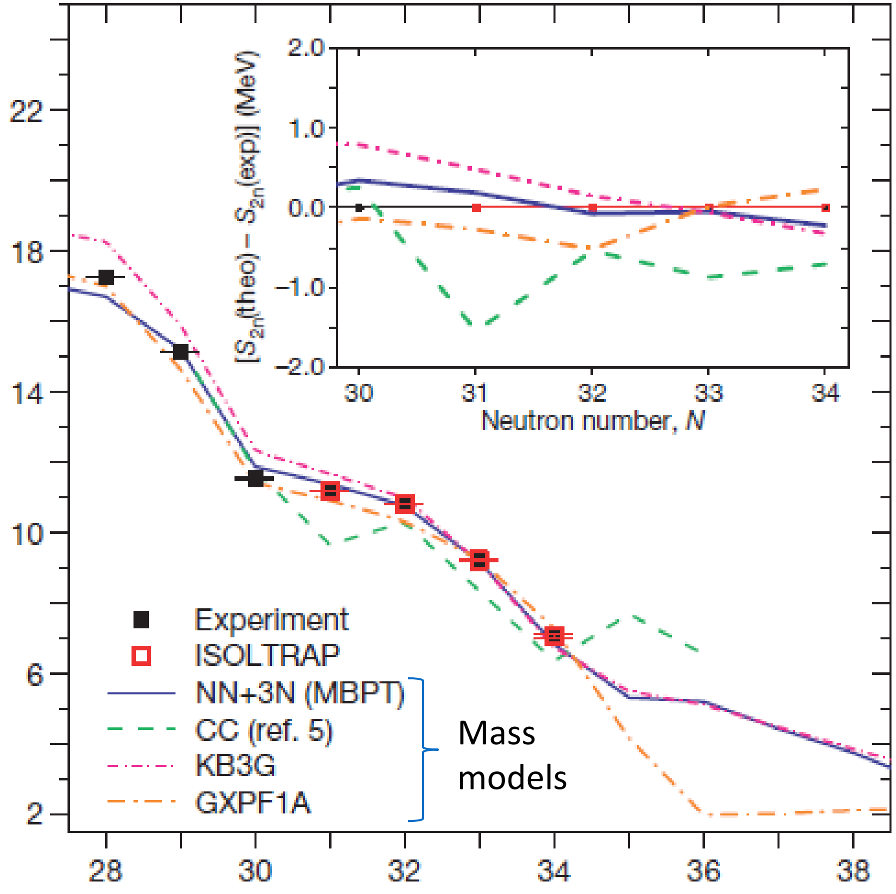


Ion purification by different time of flight



Two-neutron separation energy (MeV):

Sudden drop points to a shell closure



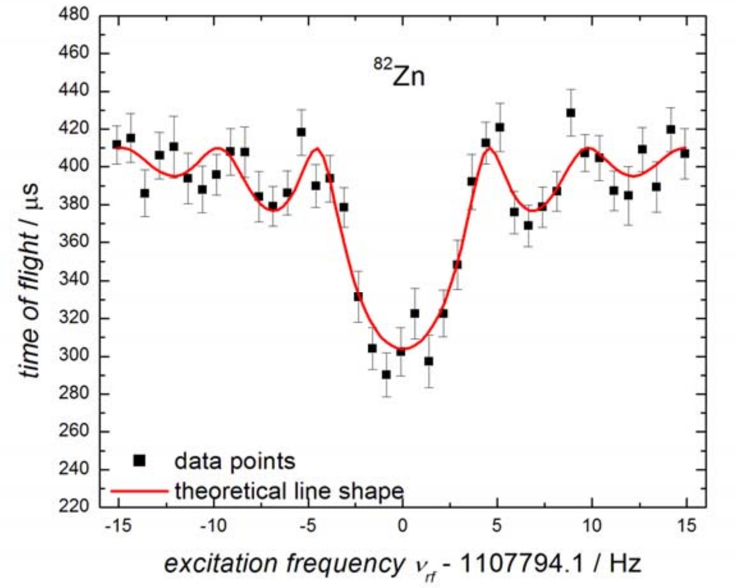
Mass models

Mass of zinc-82

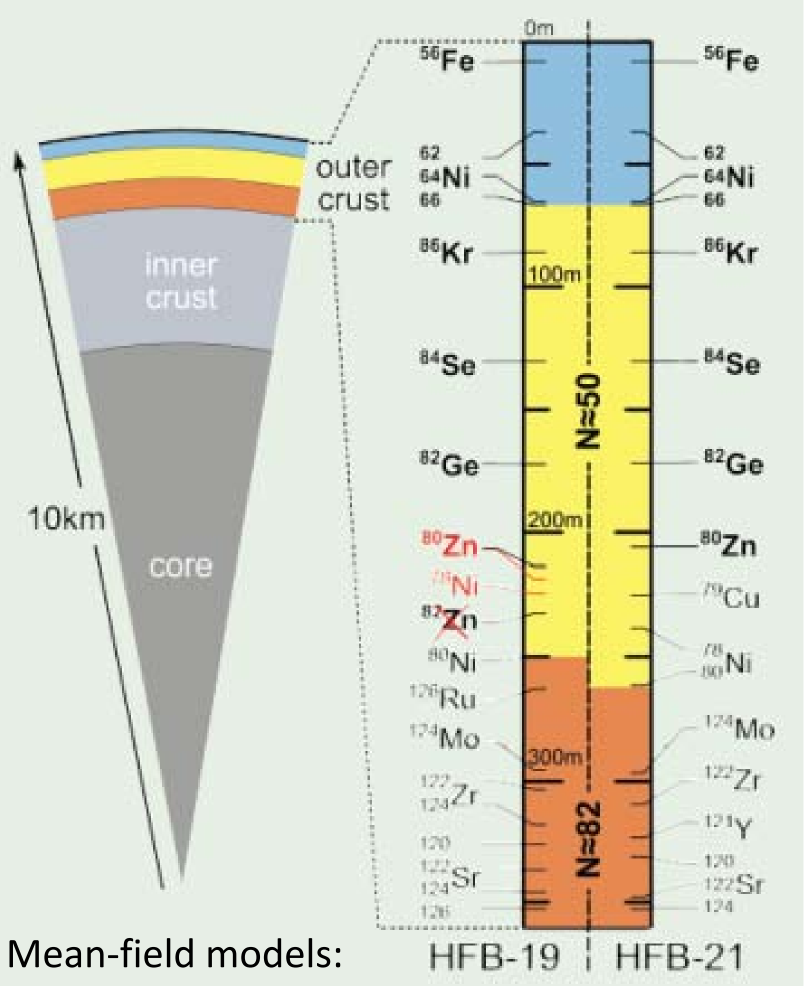
After several attempts at ISOLTRAP
and elsewhere

Neutron-star composition:
- Test of models
- 82Zn is not in the crust

- Combined ISOLDE technical know-how:
  - neutron-converter and quartz transfer line (contaminant suppression)
  - laser ionisation (beam enhancement)

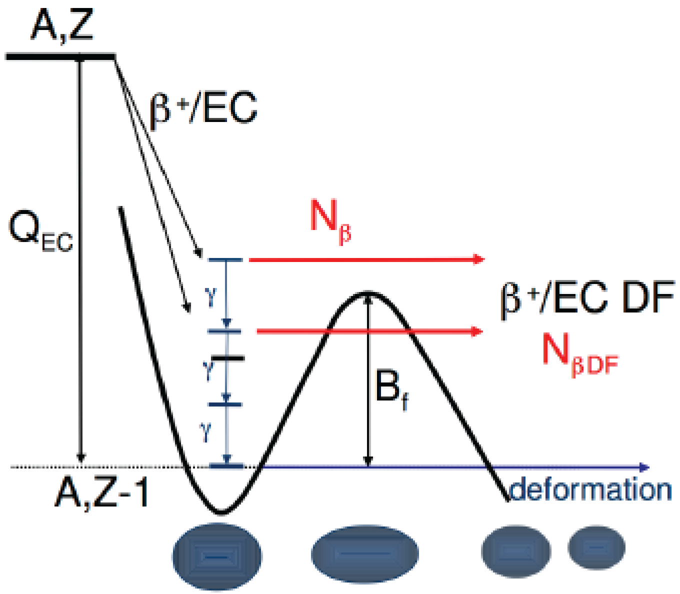


R.N. Wolf et al, Phys. Rev. Lett. 110, 041101 (2013)



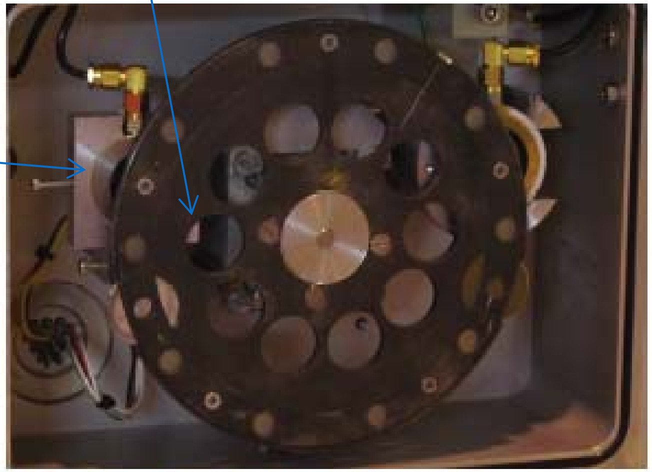
Decay spectroscopy

- Different detectors to sensitive to emitted:
  - Alpha particles
  - Beta particles
  - Gamma rays
  - Protons or neutrons
- For example WINDMILL setup:
  - Alpha and gamma detectors
  - Used for studies of beta-delayed fission (i.e. fission following a beta decay)



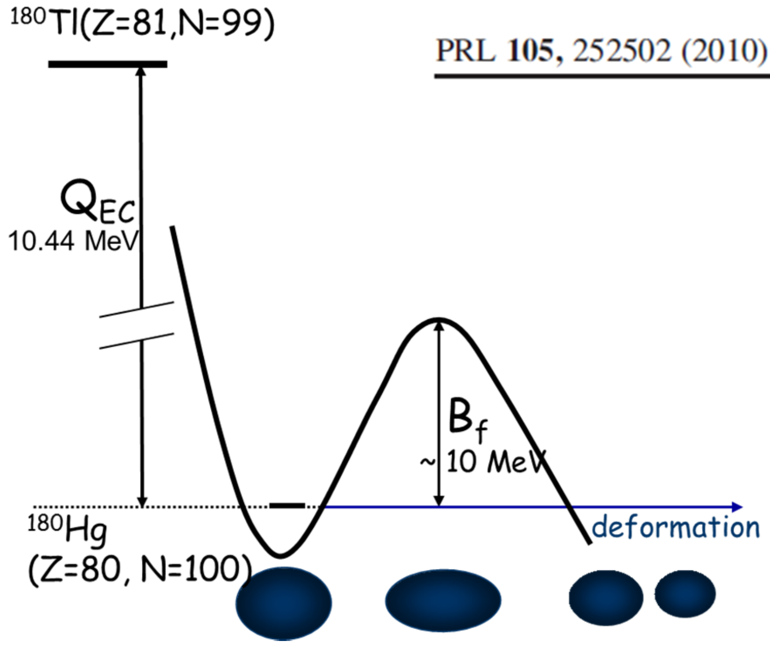
C foil for implantation

Si detector for alphas



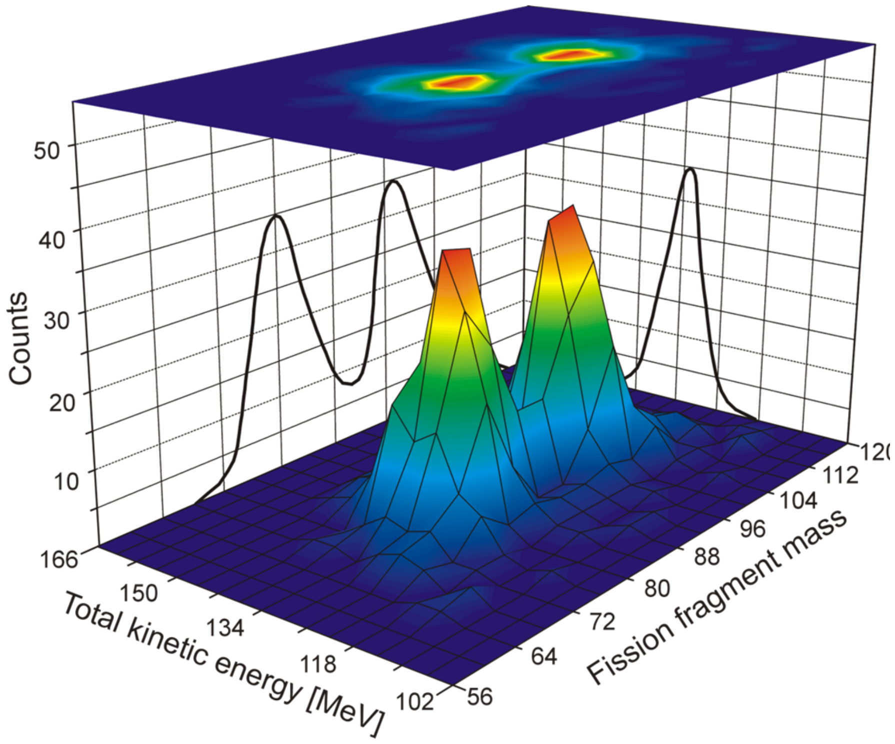
Beta-delayed fission of mercury-180

WINDMILL setup



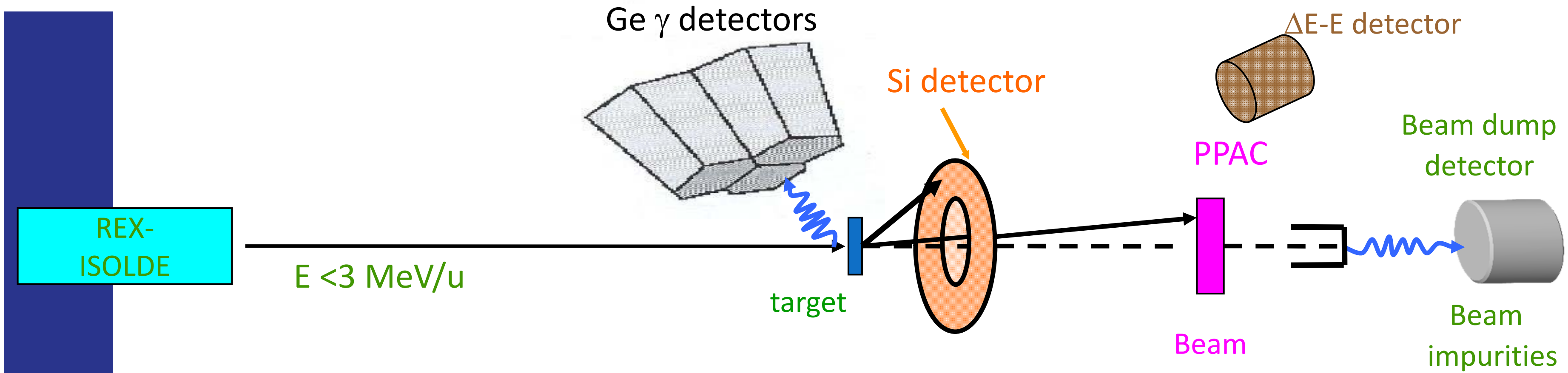
PRL **105,** 252502 (2010) PHYSICAL REVIEW LETTERS

New Type of Asymmetric Fission in Proton-Rich Nuclei

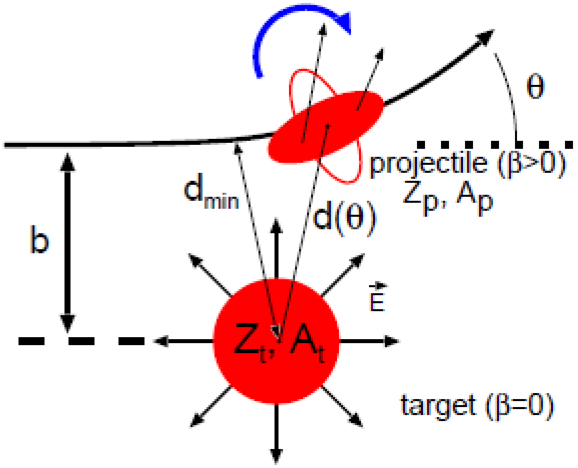


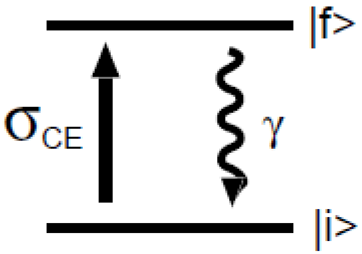
- Nuclear shell effects are important in fission, but:
  - Unexpectedly 180Hg does not fission in two semi-magic 90Zr (Z=40,N=50)
  - Fission theories do not predict the results correctly

Coulomb excitation



Excitation of a projectile nucleus (radioactive) by the electromagnetic field of the target (made of stable nuclei)

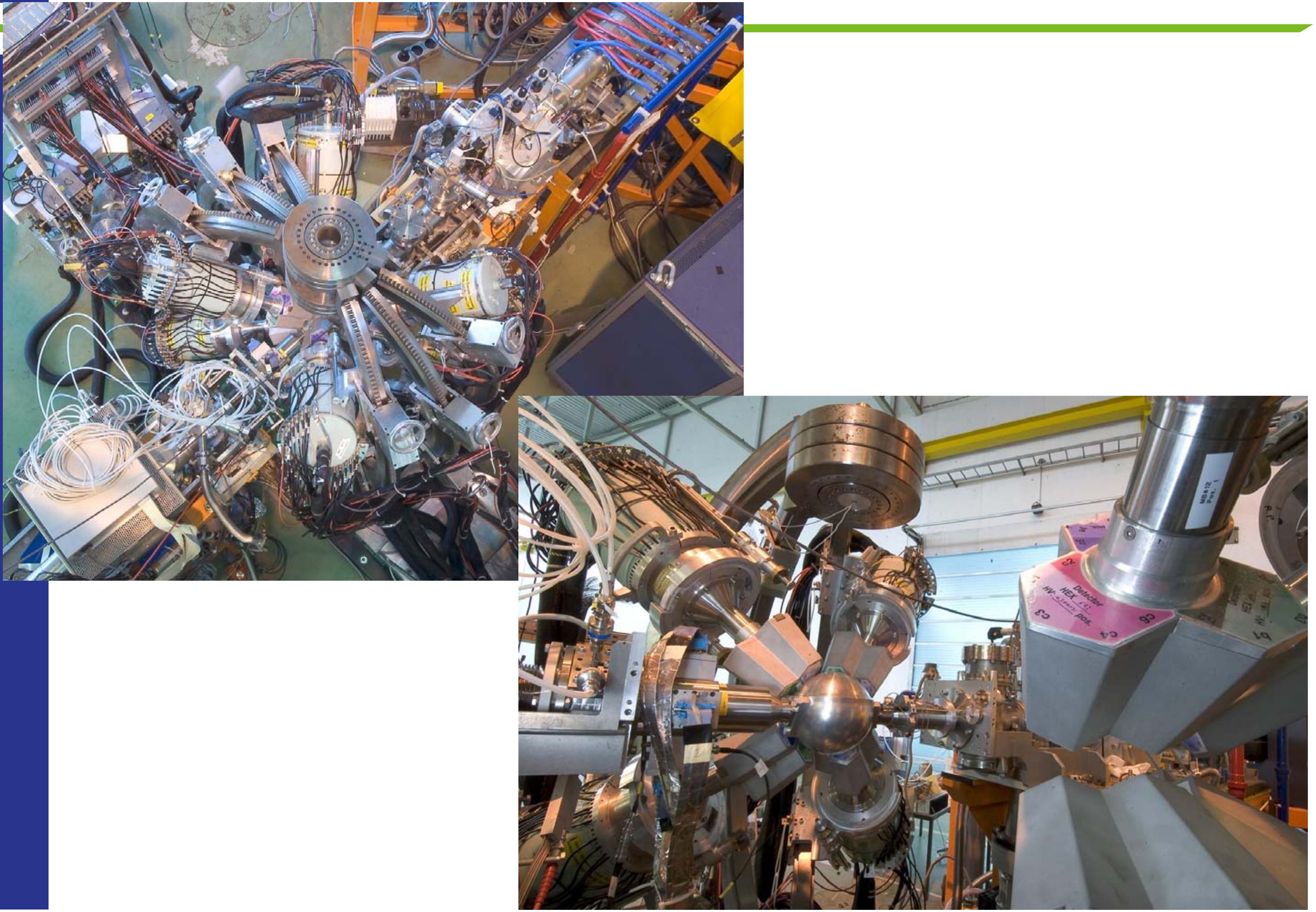




Observables: Transition energies and intensities

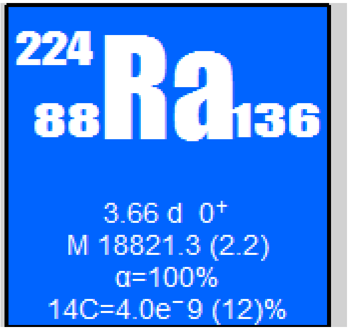
=> Determine new excited levels and study deformations

MINIBALL



Pear shape in radium-224

- Pear shape - octupole deformation
    - Very rare nuclear shape
- Coulomb excitation with MINIBALL
    - determine electric octupole transition strengths (direct measure of octupole correlations)
- Pear shape shown for the 1st time experimentally
    - Test of nuclear models
    - Important in searches for permanent atomic electric-dipole moments (EDMs)



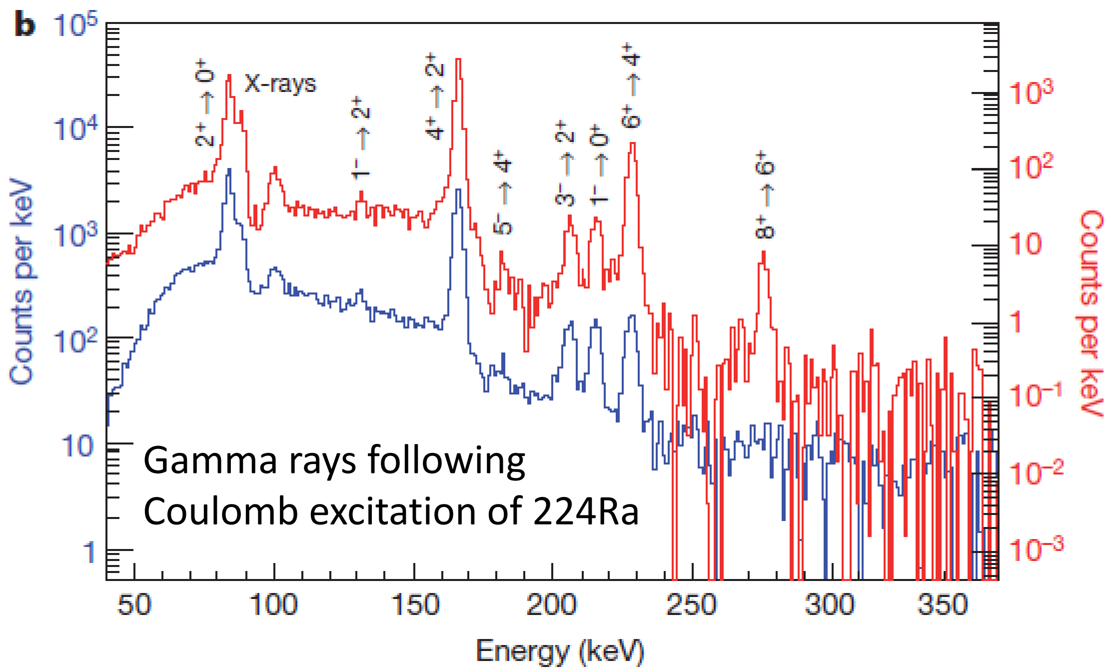
$^{224}_{88}\mathrm{Ra}_{136}$

3.66 d 0^+

M 18821.3 (2.2)

α=100%

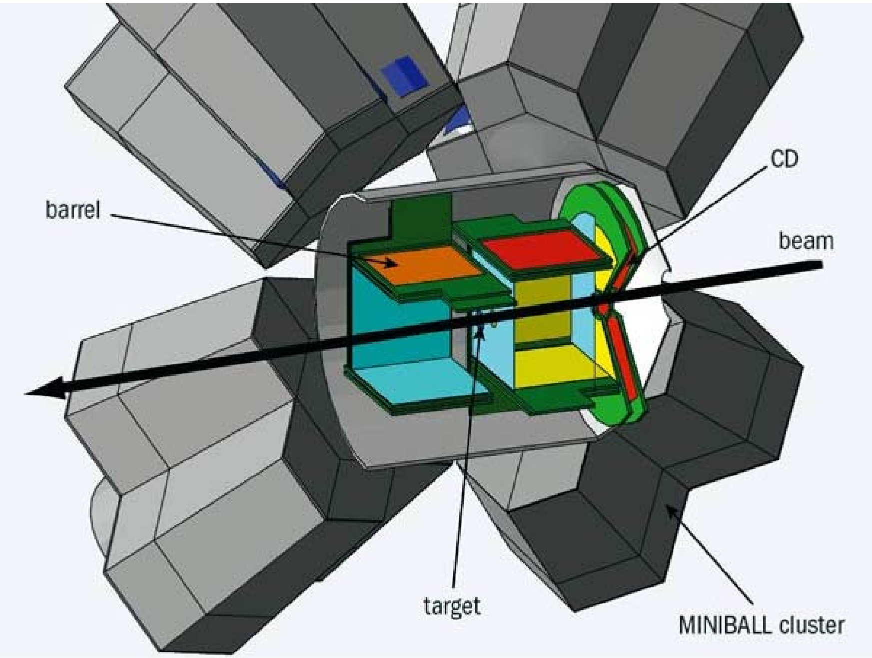
14C=4.0e⁻9 (12)%



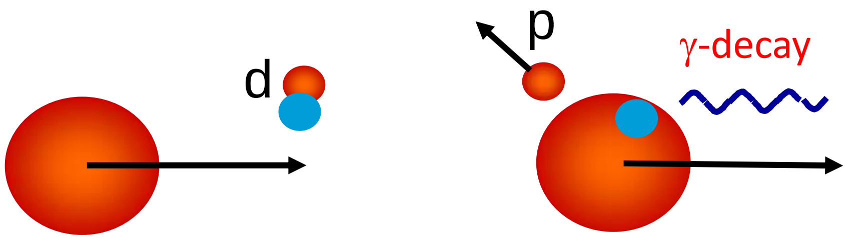
Gamma rays following Coulomb excitation of 224Ra

L.P. Gaffney et al, Nature 497 (2013) 199

Nucleon-transfer reactions



Miniball + T-REX setup (Si detector barrel): gamma detectors and particle identification



Typical reactions: one or two-nucleon transfer (d,p), (t,p)

Information:

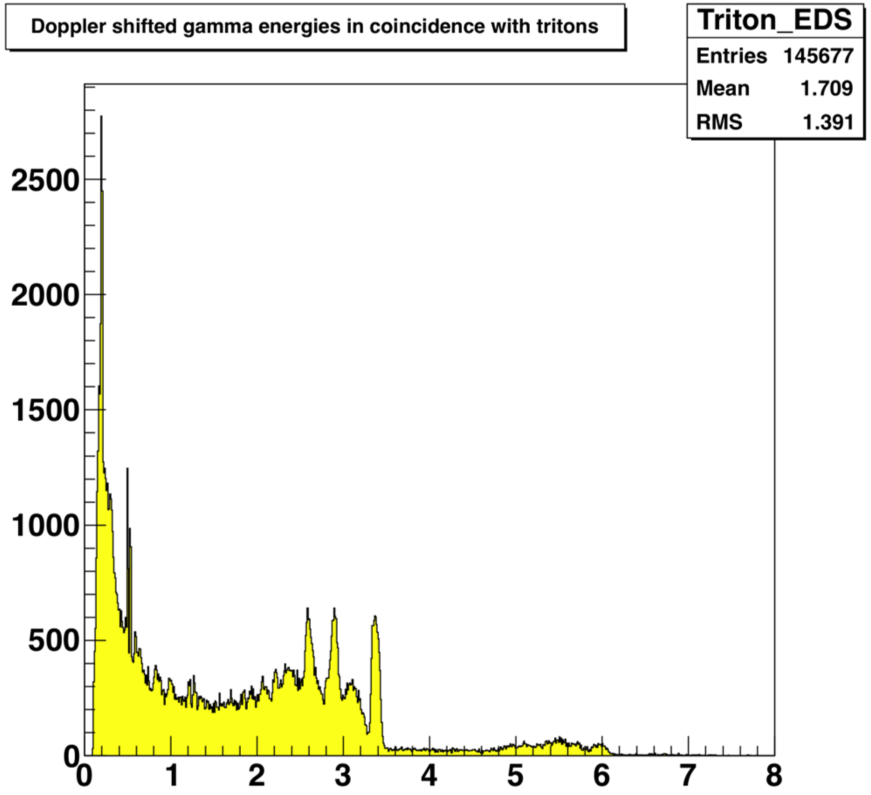
Observables

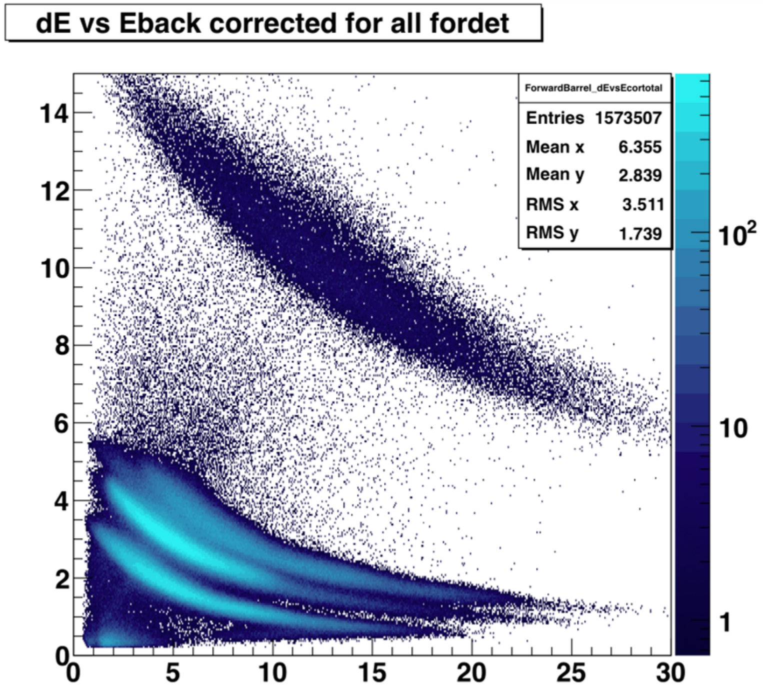
• energies of protons (+ E_g)	(single-particle) level energies
• angular distributions of protons (+ γ-rays)	spin/parity assignments
• (relative) spectroscopic factors	particle configurations

study single-particle properties of nuclei
= > Similar configurations = large overlap of wave functions =
Large probability of transfer reaction

Transfer reactions on beryllium-11

- 11Be:
  - Halo nucleus
  - Cluster structures in neighbours
  - N=8 broken in 12Be





Applications

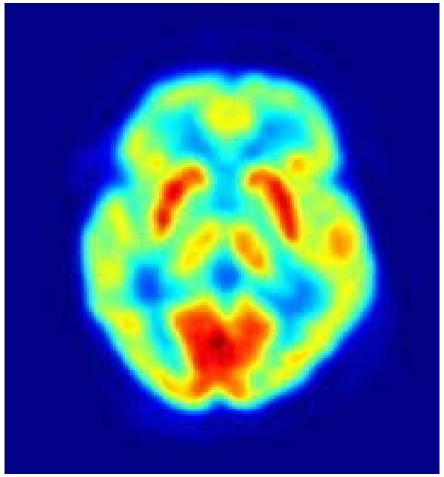
- Use known radiation from not totally exotic radioisotopes

- Profit from radionuclides:
  - Pure samples of radioisotopes (offline studies)
  - High detection efficiency for radiation (online studies)

- Techniques:
  - Emission Channeling
  - PAC (Perturbed Angular Correlations)
  - Diffusion
  - Photoluminescence

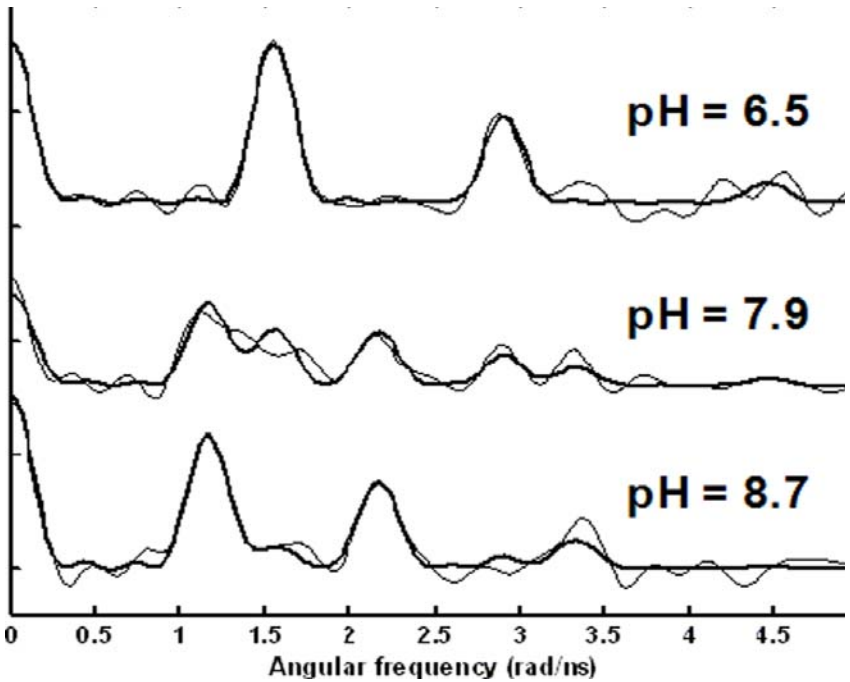
PET isotopes

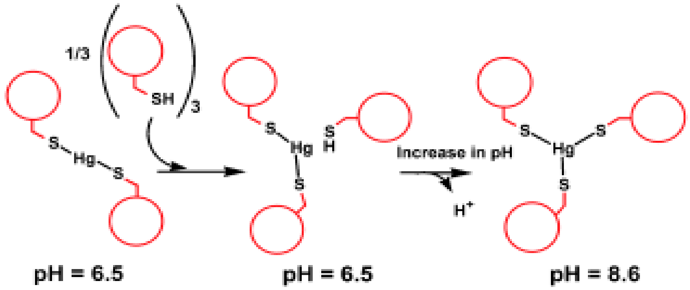
- PET (positron emission tomography) – uses $\beta+$ emitting nuclei and their annihilation inside the body in diagnosis and theraphy
- Produced at ISOLDE and later investigated together with the creators of the PET technique at the Geneva Hospital

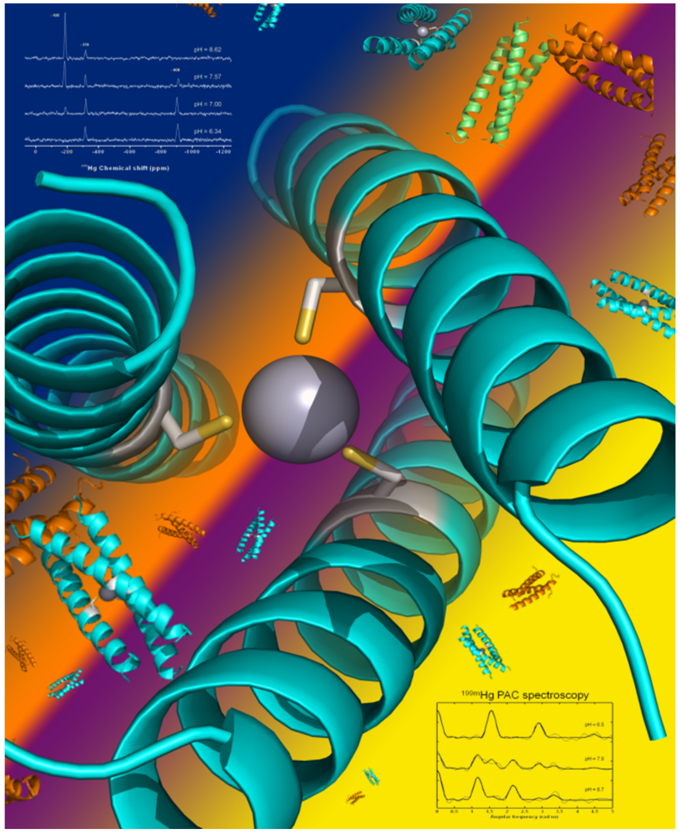


Metal binding to proteins

- Studied with Perturbed Angular Correlation method



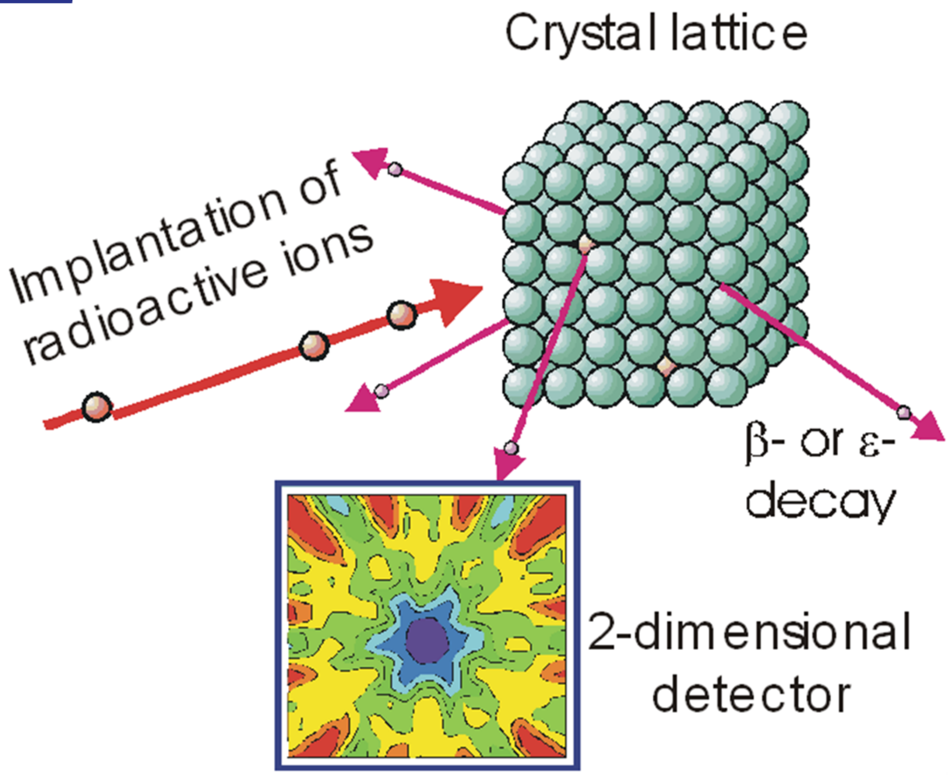


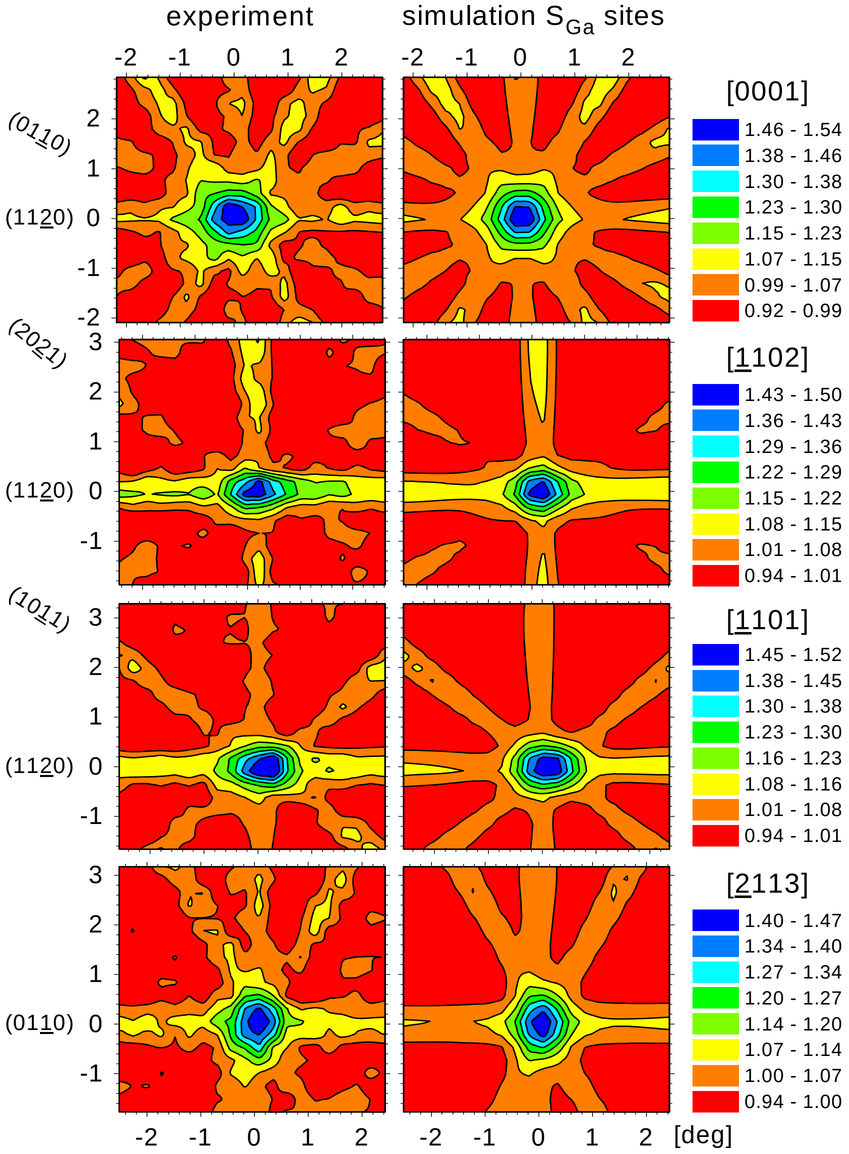


Vibenholt J et al, Inorg. Chem (2012)

Material science

- Emission channeling
  - Position of implanted ions

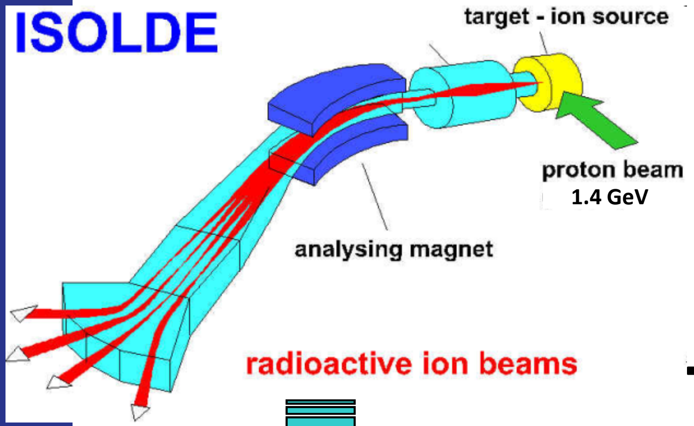




Emission channelling pattern

New medical isotopes

i. Collection at ISOLDE

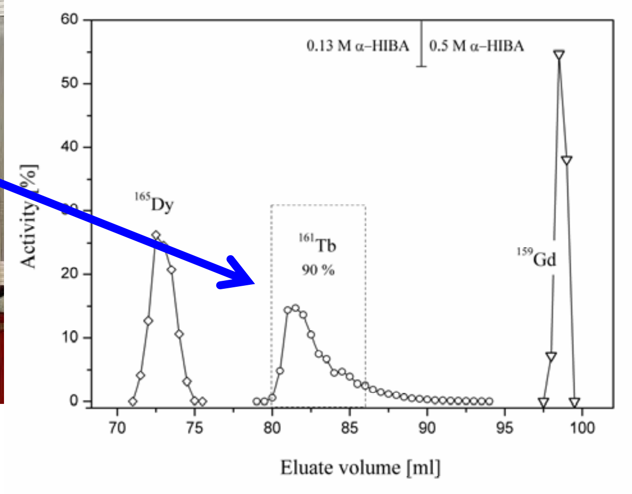


iv. Injection into mouse

v. PET/SPECT imaging and tumor treatment

ii. Shipping to PSI

iii. Radiochemical purification and labeling



After U. Koster

C Müller et al. 2012 J. Nucl. Med. 53 1951

Summary

- Research topics with radionuclides:
  - Nuclear and atomic physics
  - Astrophysics
  - Fundamental studies
  - Applications
- Studied properties:
  - mass, radius, spin, moments, half-life, decay pattern, transition probabilities
- Examples of ISOLDE experimental techniques
  - Laser spectroscopy
  - Ion traps
  - Decay spectroscopy
  - Coulomb excitation
  - Nucleon-transfer reactions
- Applications
  - Material science
  - Life sciences: bio- and medical

Fundamental studies with traps

determine beta-neutrino (βν) correlation in β decay of ^{35}Ar with $(\Delta a/a)_{stat} \leq 0.5$ %

=>test the Standard Model

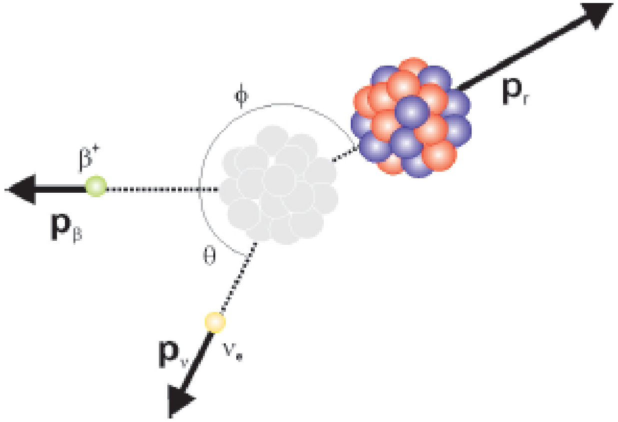
$$H_\beta = H_S + H_V + H_T + H_A + H_P$$

e.g: Fermi β decay $(0^+ \rightarrow 0^+)$

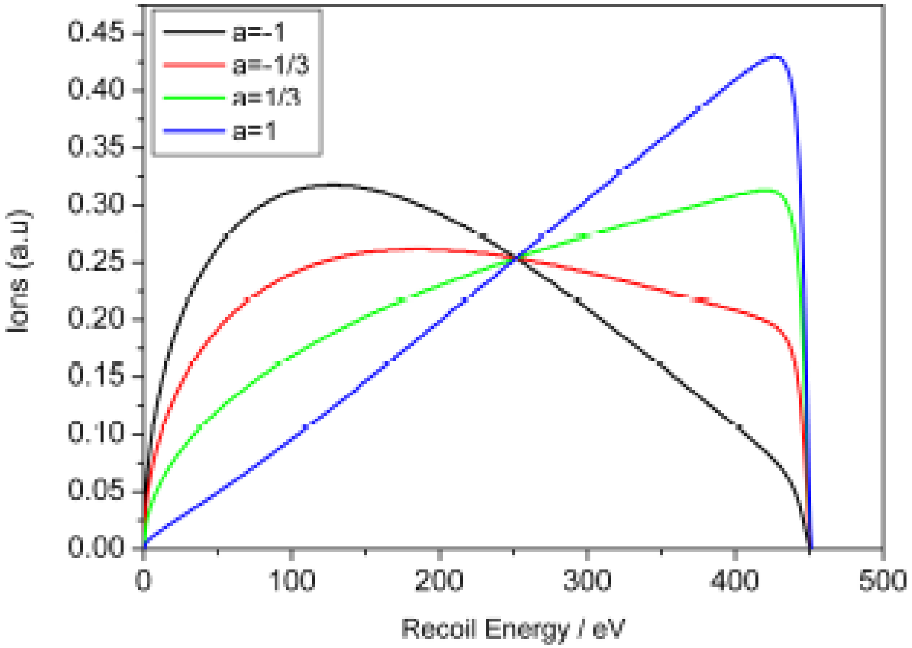
$$a \approx 1 - \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2}$$

Angular distribution of β radiation

$$W(\theta) \approx 1 + a\frac{v}{c}cos\theta$$



Simulated ion recoil for different *a*



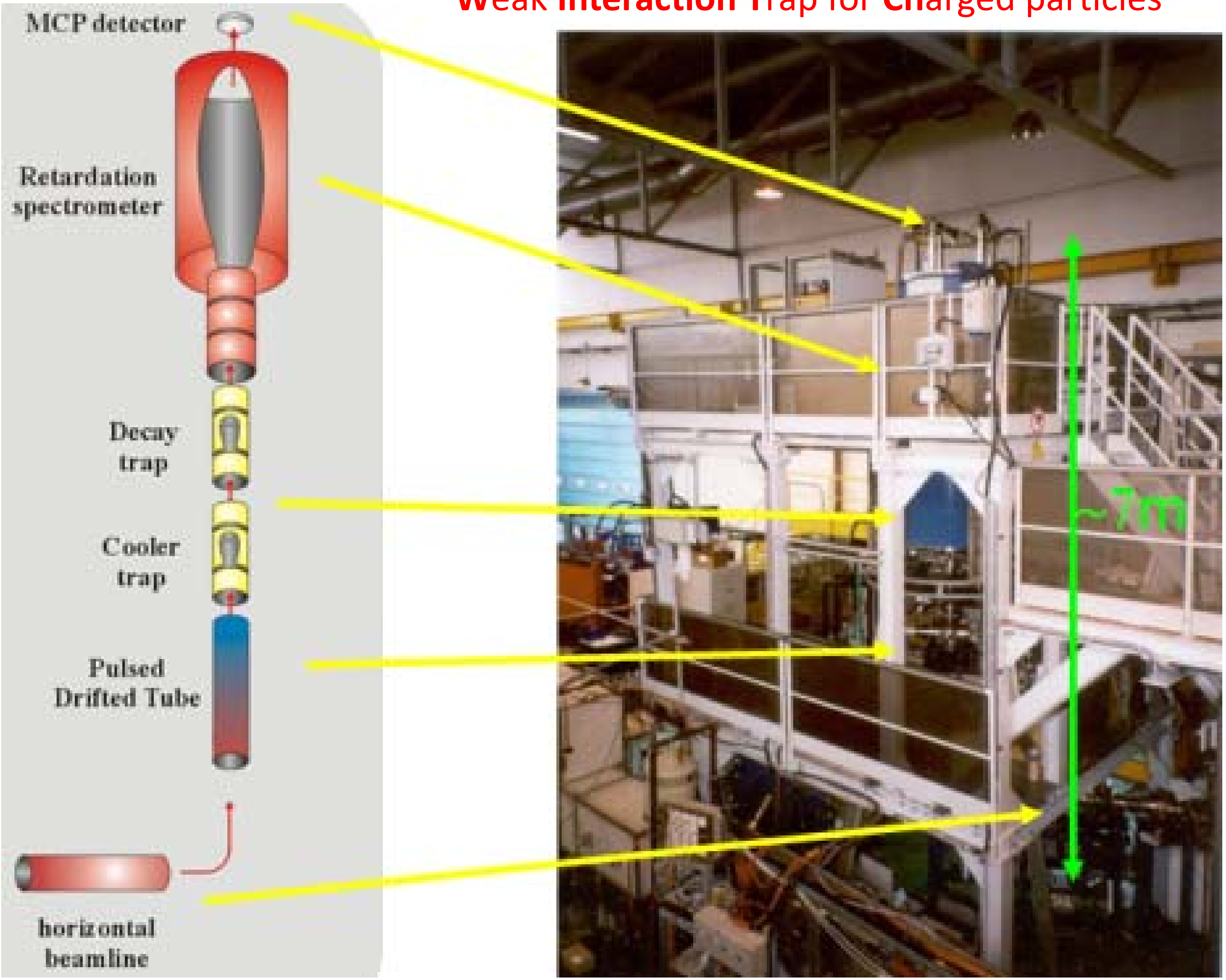
Current experimental limits:

(from nuclear & neutron β decay)

$\frac{C_S}{C_V} < 7\%$, $\frac{C_T}{C_A} < 9\%^1$

WITCH

Weak **Interaction** **T**rap for **Ch**arged particles



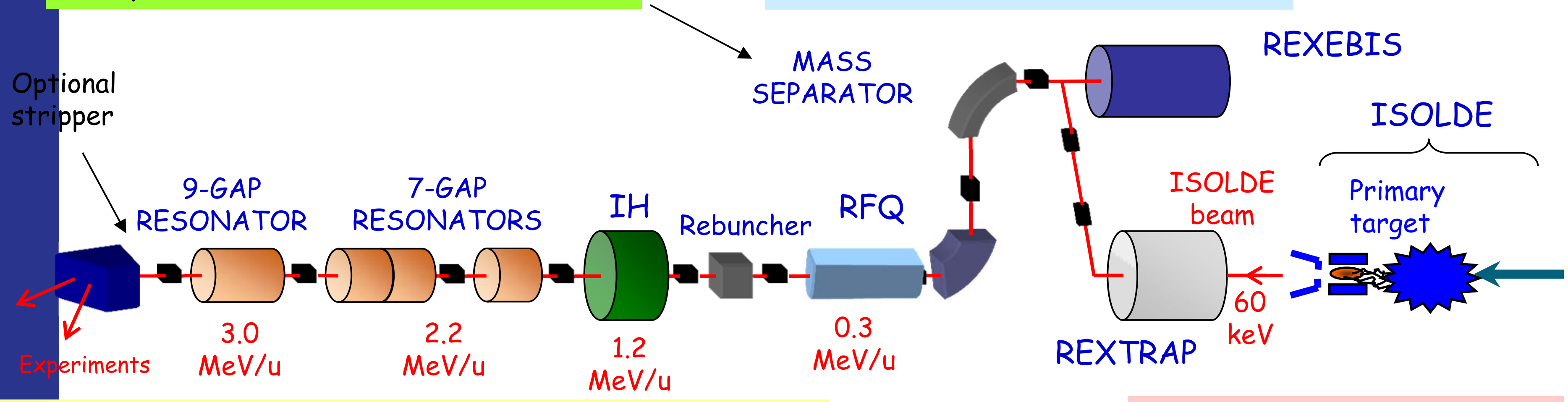
REX post-accelerator

EBIS

- Super conducting solenoid, 2 T
- Electron beam < 0.4A 3-6 keV
- Breeding time 3 to >200 ms
- Total capacity $6 \cdot 10^{10}$ charges
- A/q < 4.5

Nier-spectrometer

- Select the correct A/q and separate the radioactive ions from the residual gases.
- A/q resolution ~150



Linac

Length	11 m
Freq.	101MHz (202MHz for the 9GP)
Duty cycle	1ms 100Hz (10%)
Energy	300keV/u, 1.2-3MeV/u
A/q max.	4.5 (2.2MeV/u), 3.5 (3MeV/u)

REX-trap

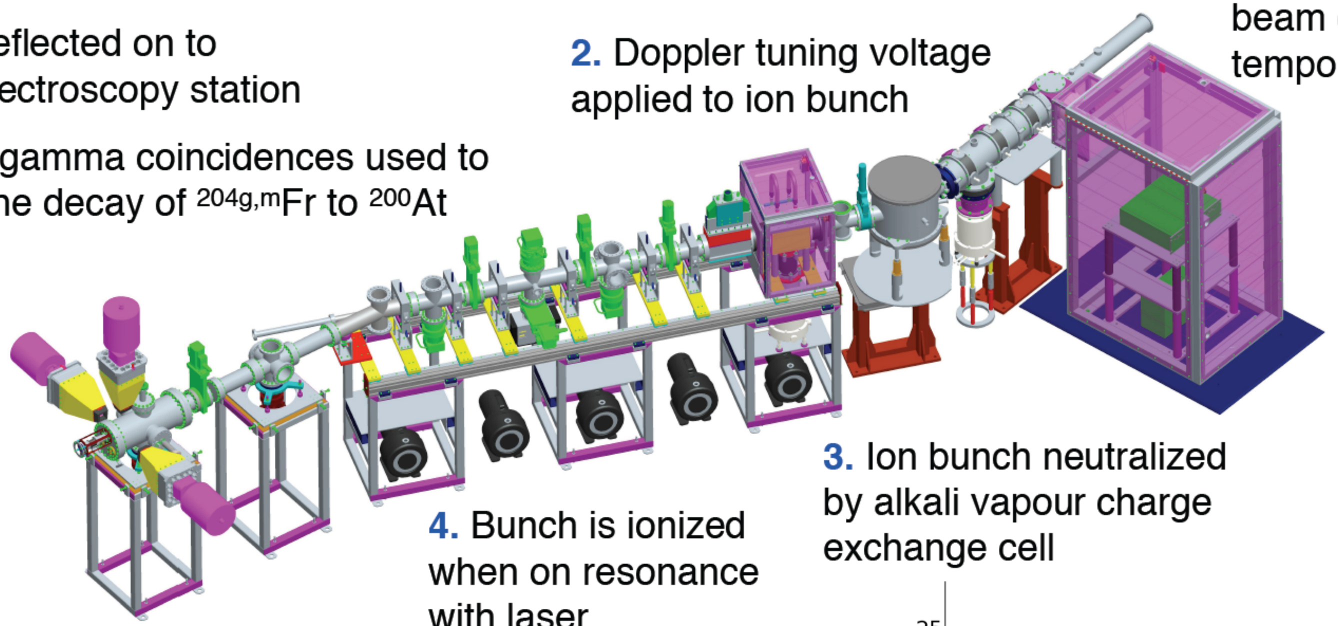
- Cooling (10-20 ms)
  Buffer gas + RF
- (He), Li,...,U
- 10^8 ions/pulse

(Space charge effects $>10^5$)

Total efficiency : 1 -10 %

CRIS

- Collinear Resonant Ionisation Spectroscopy
- High sensitivity, lower resolution -> perfect for heavy ions



1. Bunched ion beam of ~1µs temporal width

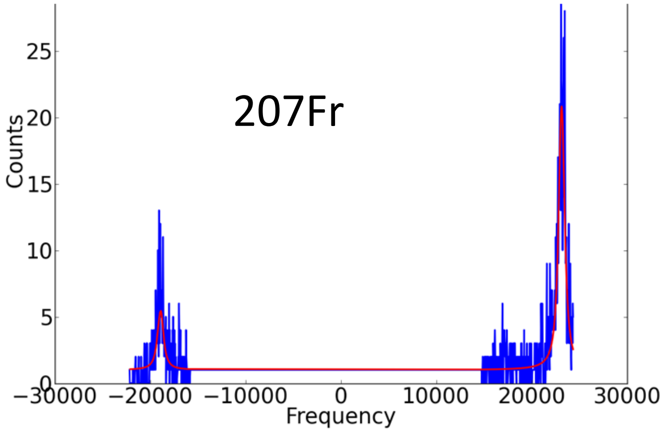
2. Doppler tuning voltage applied to ion bunch

3. Ion bunch neutralized by alkali vapour charge exchange cell

4. Bunch is ionized when on resonance with laser

5. Ions deflected on to decay spectroscopy station

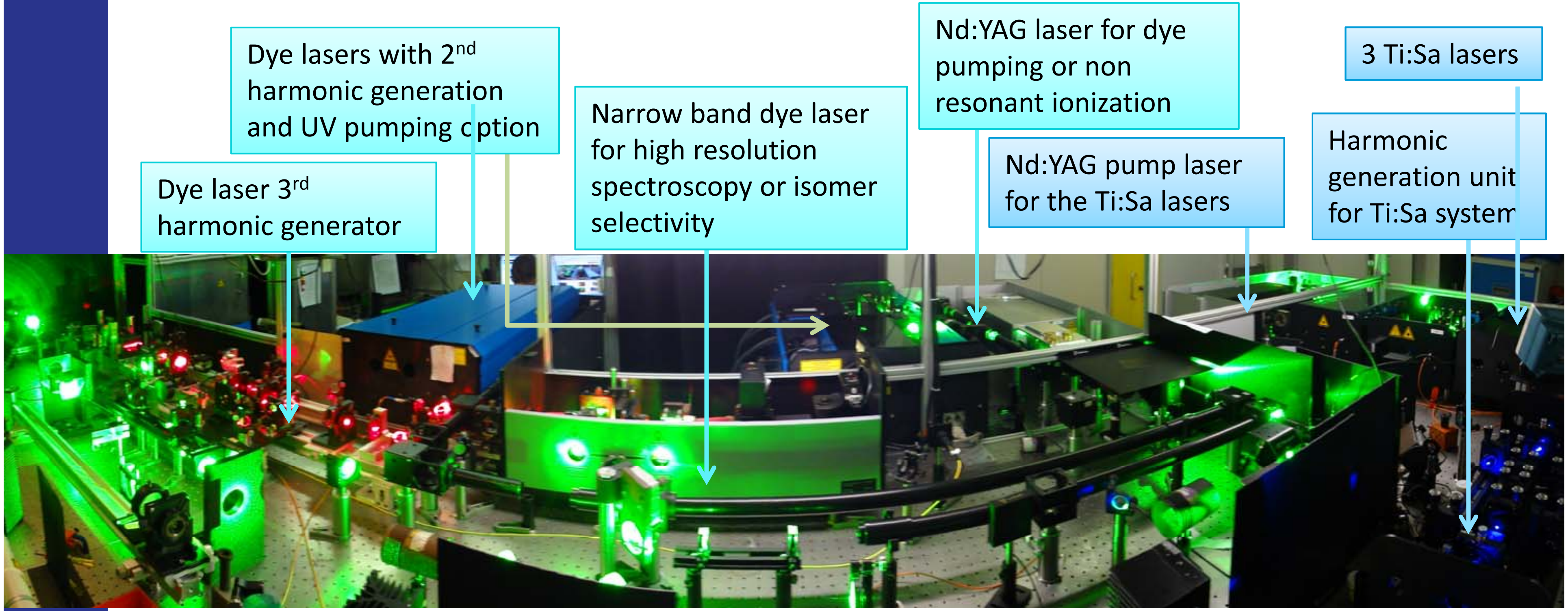
6. Alpha-gamma coincidences used to identify the decay of ^{204g,m}Fr to ^{200}At



Open projects:
IS471: Collinear resonant ionization laser spectroscopy of rare francium isotopes
IS531: Collinear resonant ionization spectroscopy for neutron rich copper isotopes

RILIS

- Resonant Ionization Laser Ion Source



Dye laser 3rd harmonic generator

Dye lasers with 2nd harmonic generation and UV pumping option

Narrow band dye laser for high resolution spectroscopy or isomer selectivity

Nd:YAG laser for dye pumping or non resonant ionization

Nd:YAG pump laser for the Ti:Sa lasers

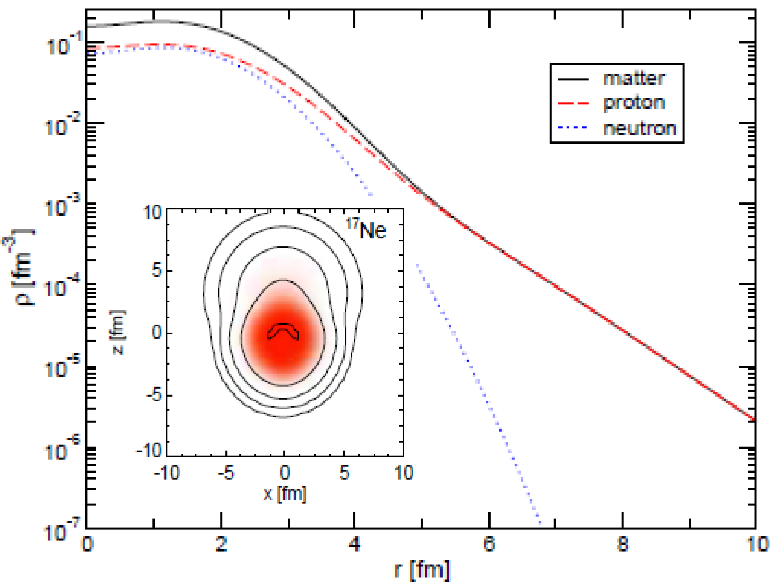
3 Ti:Sa lasers

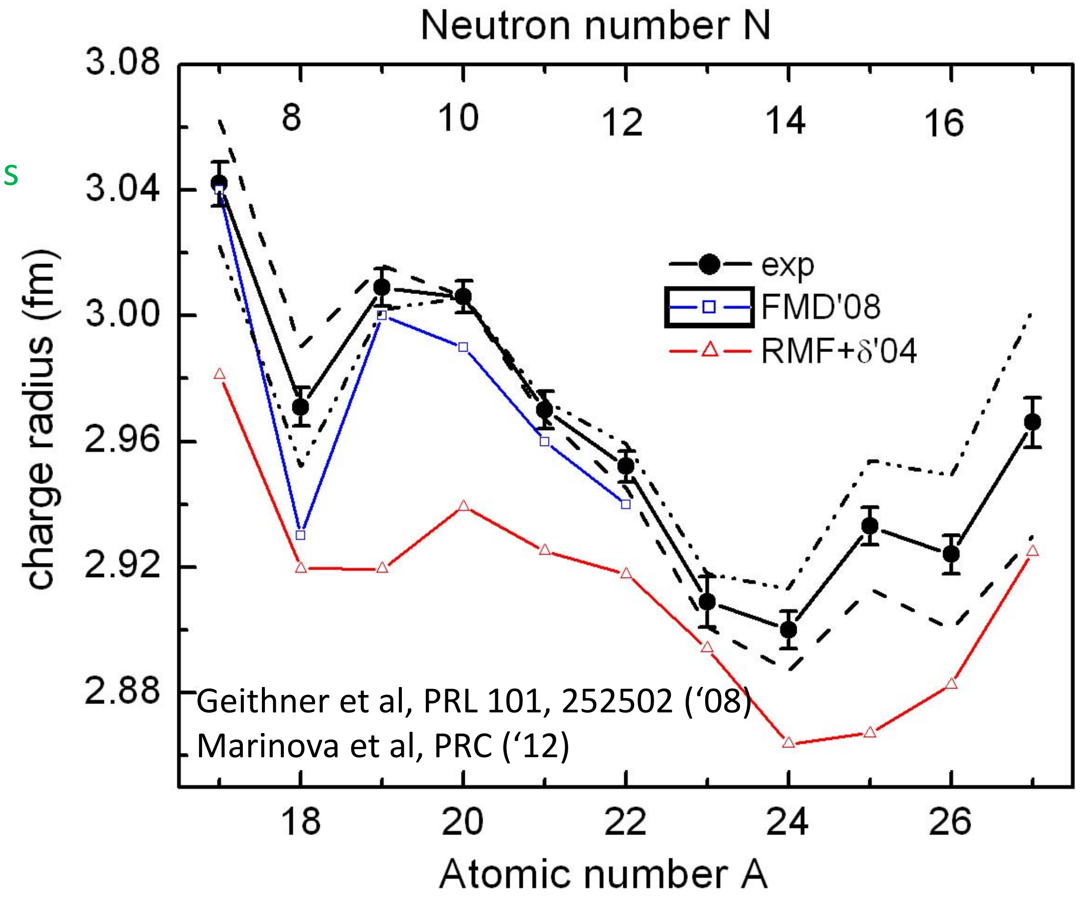
Harmonic generation unit for Ti:Sa system

COLLAPS – Ne charge radii

Laser spectroscopy

Intrinsic density distributions of dominant proton FMD configurations





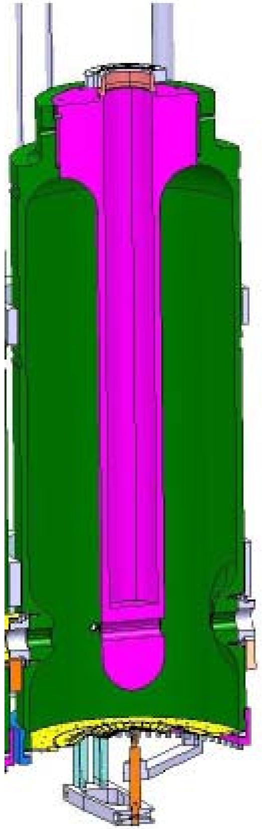
Geithner et al, PRL 101, 252502 (‘08)

Marinova et al, PRC (‘12)

HIE-ISOLDE

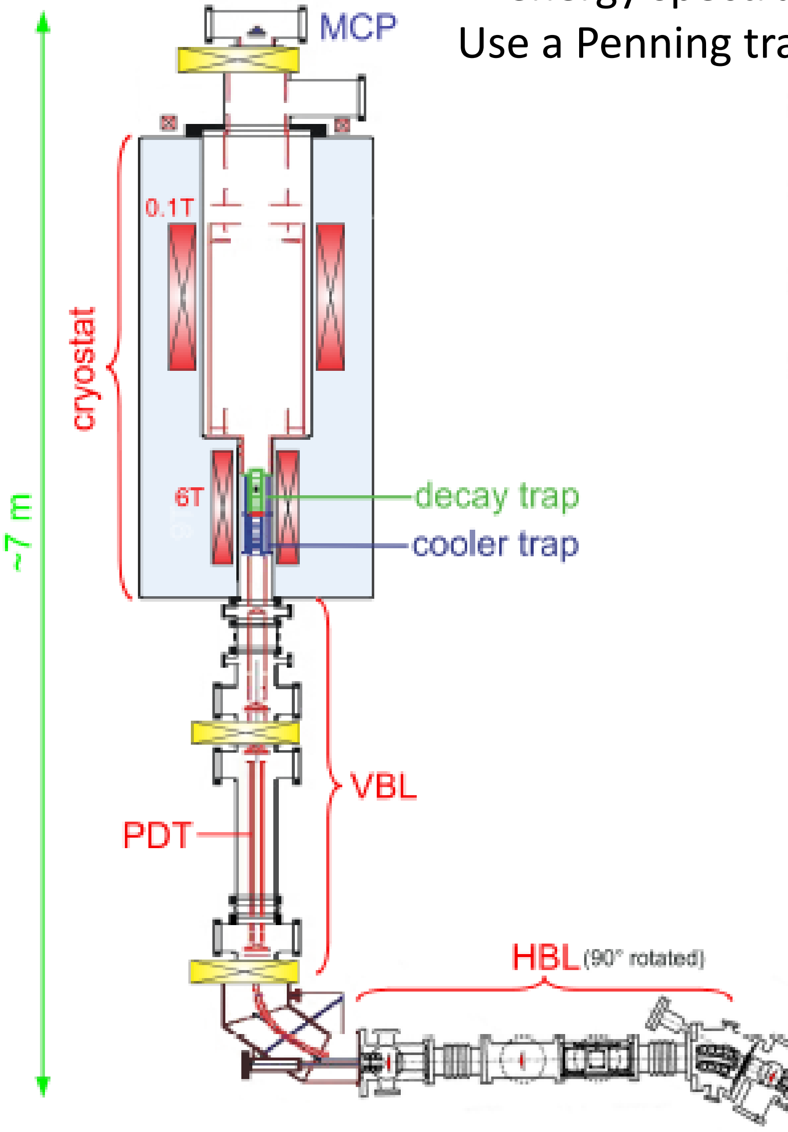
- SC-linac between 1.2 and 10 MeV/u
- 32 SC QWR (20 @ β_0=10.3% and 12@ β_0=6.3%)
- Energy fully variable; energy spread and bunch length are tunable. Average synchronous phase fs= -20 deg
- 2.5<A/q<4.5 limited by the room temperature cavity
- 16.02 m length (without matching section)
- No ad-hoc longitudinal matching section (incorporated in the lattice)
- New beam transfer line to the experimental stations

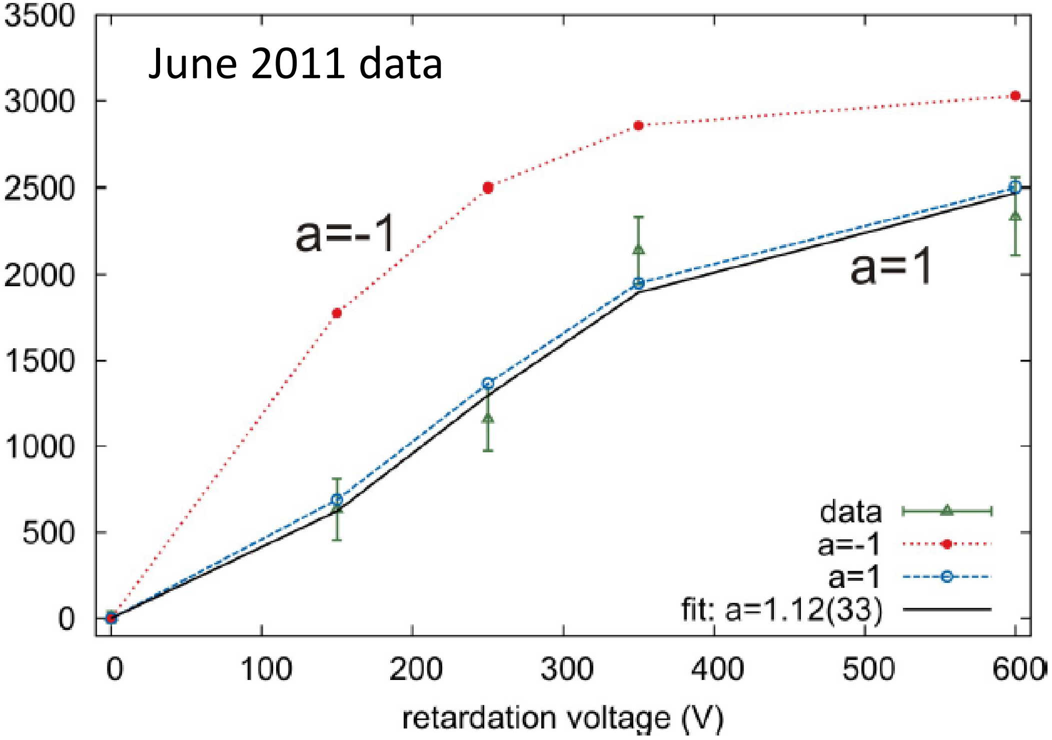
Quarter-wave resonators
(Nb sputtered)



WITCH

-> energy spectrum of recoiling ions with a retardation spectrometer
Use a Penning trap to create a small, cold ion bunch





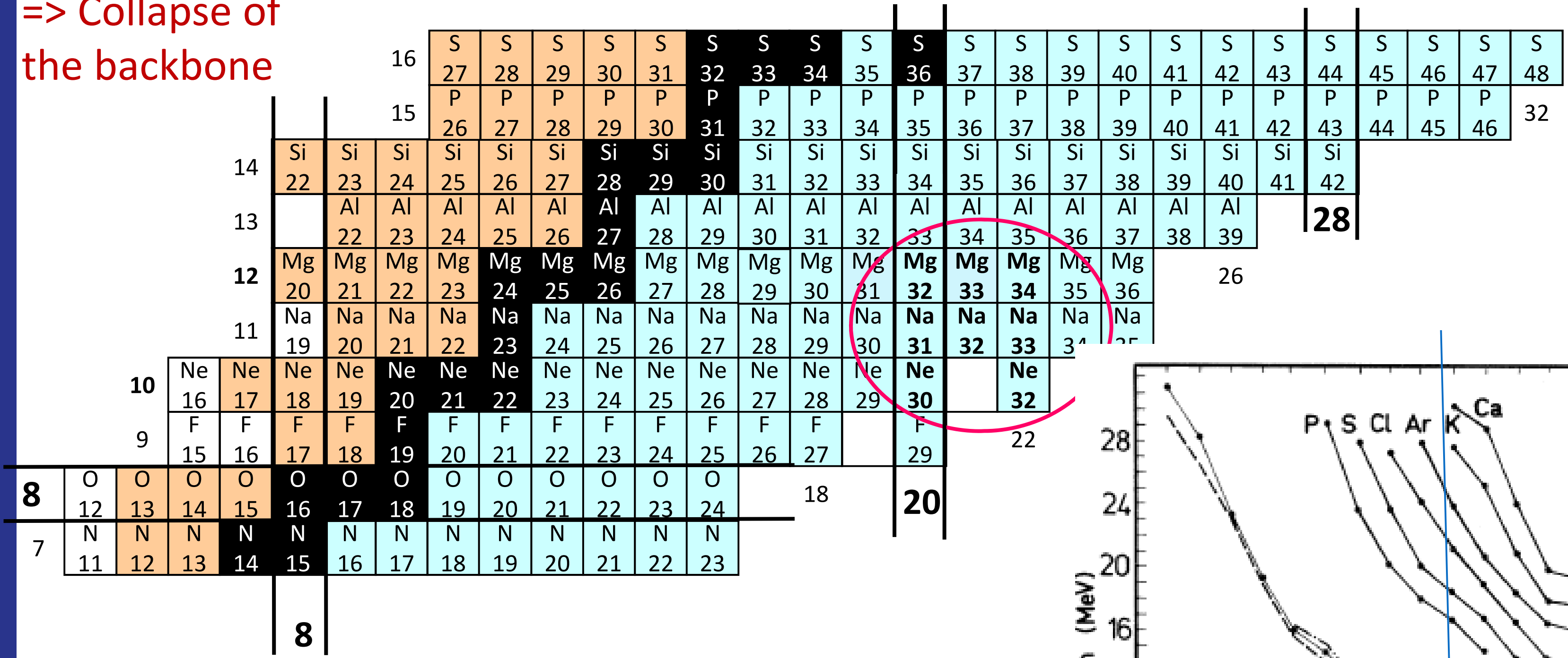
First high-statistics run in Nov 2011: under analysis

M. Beck et al., Eur. Phys. J. A47 (2011) 45
M. Tandecki et al., NIM A629 (2011) 396
S. Van Gorp et al., NIM A638 (2011) 192

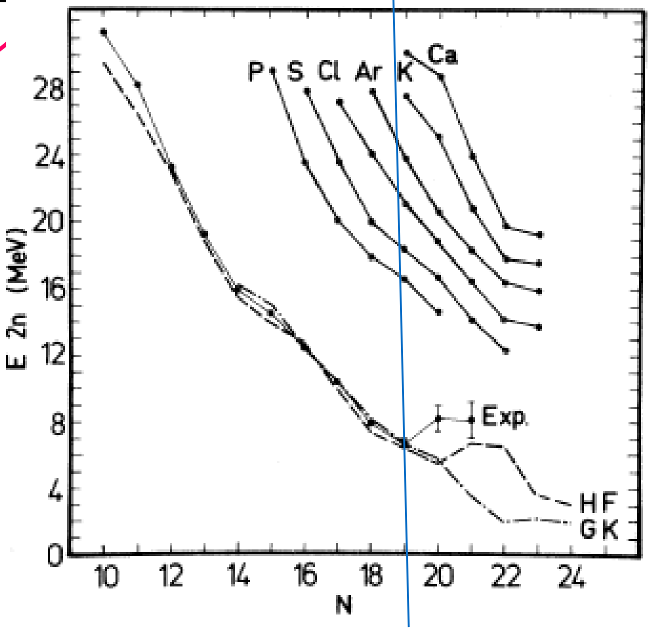
“Island of inversion”: discovery

Nuclear shell model developed on stable nuclei works very well until 1975: mass measurements of neutron-rich Ne, Na, Mg isotopes => trend in binding energies can be only explained by large deformation and thus **no shell closure at N=20**

=> Collapse of the backbone



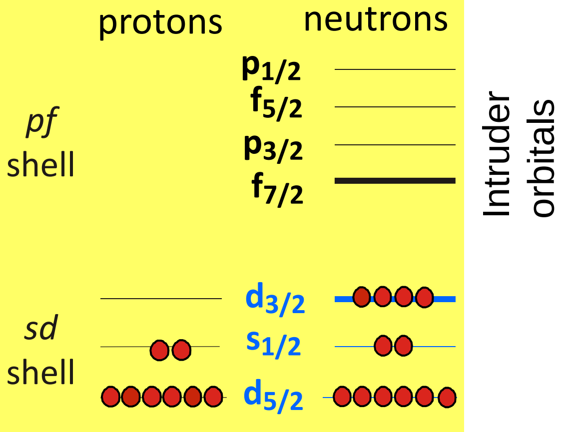
16								S 27	S 28	S 29	S 30	S 31	S 32	S 33	S 34	S 35	S 36	S 37	S 38	S 39	S 40	S 41	S 42	S 43	S 44	S 45	S 46	S 47	S 48
15								P 26	P 27	P 28	P 29	P 30	P 31	P 32	P 33	P 34	P 35	P 36	P 37	P 38	P 39	P 40	P 41	P 42	P 43	P 44	P 45	P 46	32
14					Si 22	Si 23	Si 24	Si 25	Si 26	Si 27	Si 28	Si 29	Si 30	Si 31	Si 32	Si 33	Si 34	Si 35	Si 36	Si 37	Si 38	Si 39	Si 40	Si 41	Si 42				
13						Al 22	Al 23	Al 24	Al 25	Al 26	Al 27	Al 28	Al 29	Al 30	Al 31	Al 32	Al 33	Al 34	Al 35	Al 36	Al 37	Al 38	Al 39		**28**				
12					Mg 20	Mg 21	Mg 22	Mg 23	Mg 24	Mg 25	Mg 26	Mg 27	Mg 28	Mg 29	Mg 30	Mg 31	**Mg 32**	**Mg 33**	**Mg 34**	Mg 35	Mg 36		26						
11					Na 19	Na 20	Na 21	Na 22	Na 23	Na 24	Na 25	Na 26	Na 27	Na 28	Na 29	Na 30	**Na 31**	**Na 32**	**Na 33**	Na 34	Na 35								
10			Ne 16	Ne 17	Ne 18	Ne 19	Ne 20	Ne 21	Ne 22	Ne 23	Ne 24	Ne 25	Ne 26	Ne 27	Ne 28	Ne 29	**Ne 30**		**Ne 32**										
9			F 15	F 16	F 17	F 18	F 19	F 20	F 21	F 22	F 23	F 24	F 25	F 26	F 27		F 29		22										
8	O 12	O 13	O 14	O 15	O 16	O 17	O 18	O 19	O 20	O 21	O 22	O 23	O 24		18														
7	N 11	N 12	N 13	N 14	N 15	N 16	N 17	N 18	N 19	N 20	N 21	N 22	N 23																
					8												**20**												



Mass measurements at PS-CERN
C. Thibault et al., Phys. Rev. C 12, 644 (1975)

Island of inversion: explanation

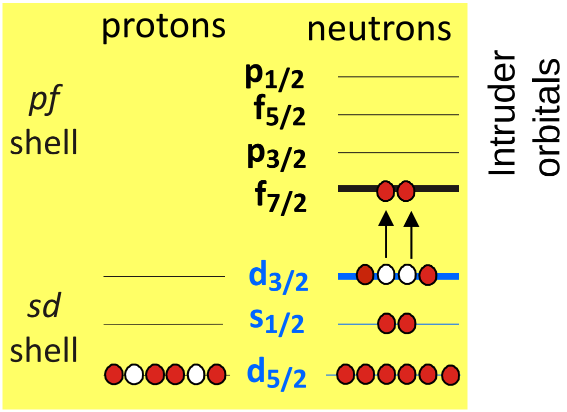
^{36}**S**: 16p and 20n



“normal”

Decreased N=20 shell gap
(or even dissapeared)
Increased correlations

^{32}**Mg**: 12p and 20n



inversion of the
level filling

In low-lying excited states and even in the ground state
neutrons occupy higher (intruder) orbitals before the usual shell is closed

Inversion of the usual level filling
But for nuclei with more protons N = 20 is again a magic number

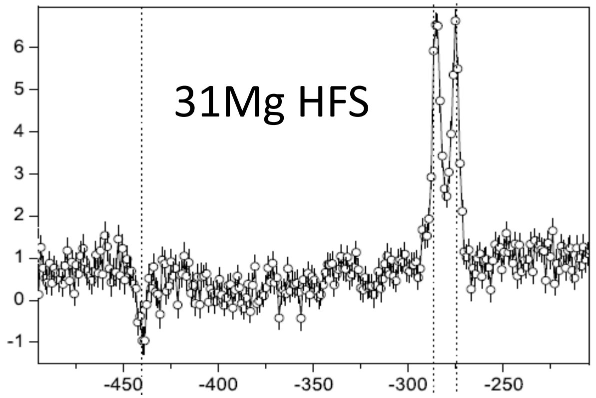
Name: island of inversion

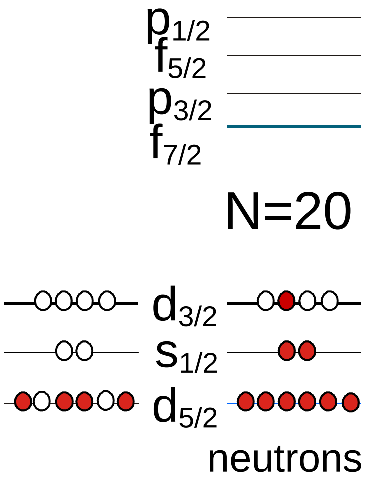
This hypothesis has to be tested/confirmed experimentally

Mg spins and moments

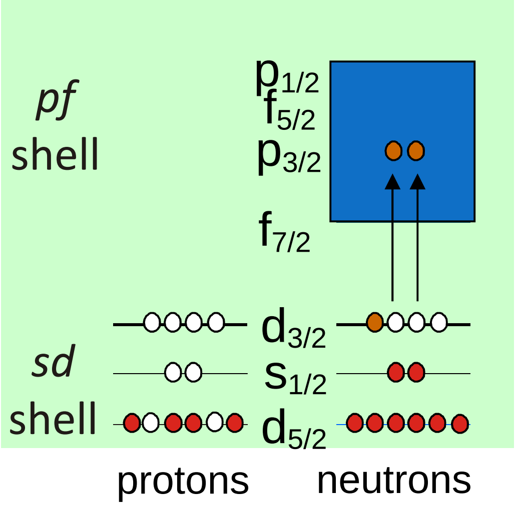
Spins, parities and magnetic moments =>
single-particle nature

Laser and beta-NMR
spectroscopy on 29-33Mg
With COLLAPS setup

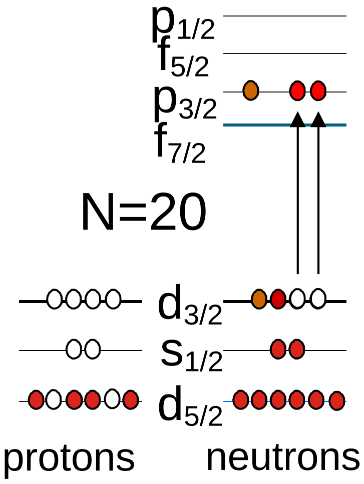




29Mg



31Mg



33Mg

29Mg outside the "island"

31,33Mg inside; with 2 nucleons across N=20

G. Neyens , M. Kowalska et al, Phys. Rev. Lett. 94, 022501 (2005)

D. Yordanov, M. Kowalska et al, Phys. Rev. Lett. 99 (2007) 212501

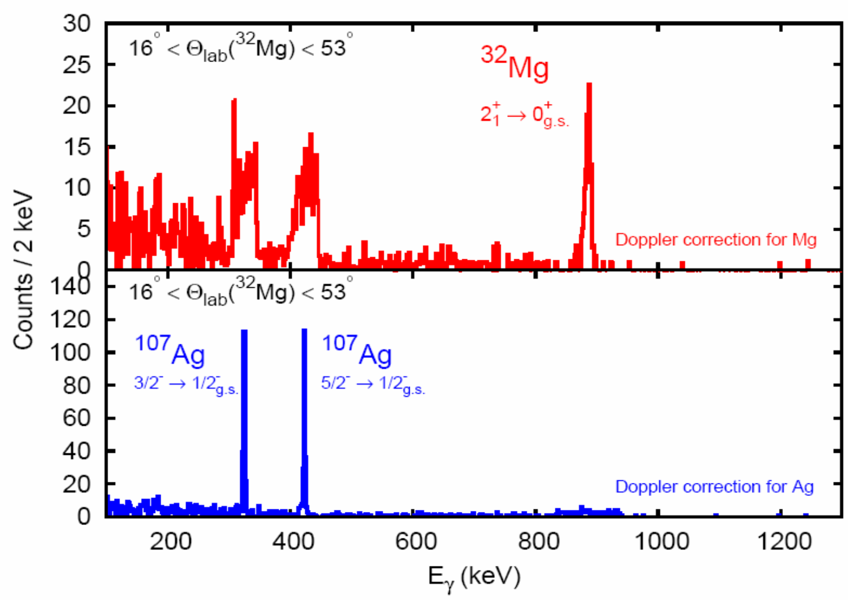
M. Kowalska , D. Yordanov et al Phys. Rev. C77 (2008) 034307

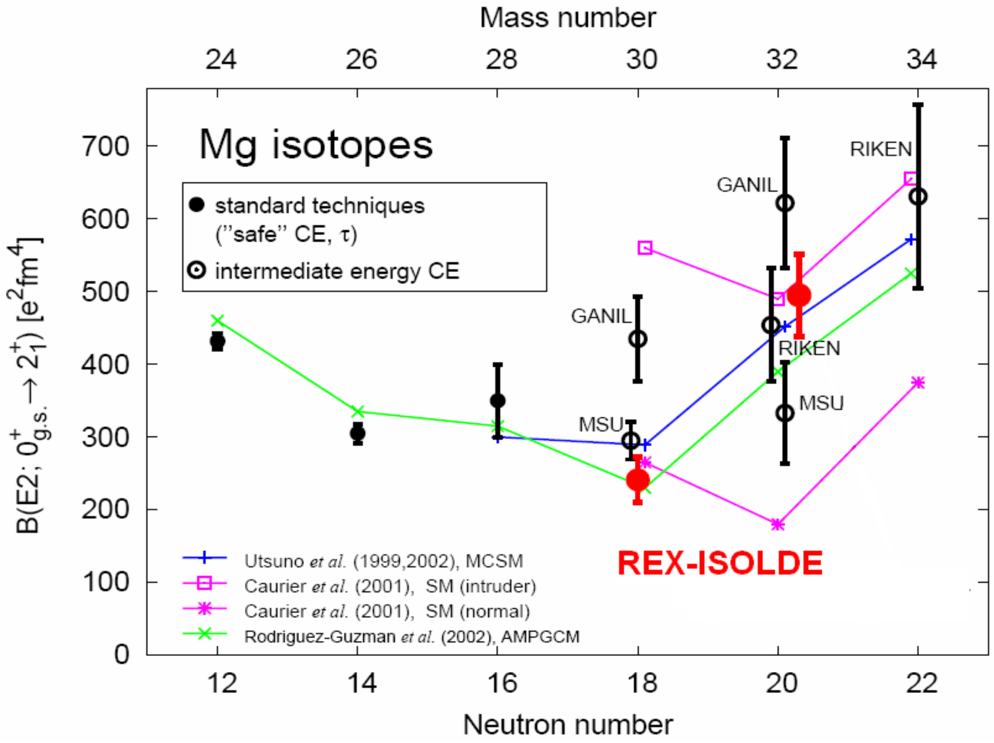
Mg Coulomb excitation

Coulomb excitation on 30,32Mg
with MINIBALL setup

Excitations across N=20 will increase collectivity,
due to more active nucleons and thus more correlations

World results for Mg Coulomb excitation:
only ISOLDE can provide pure e.m. excitation ("safe Coulex")





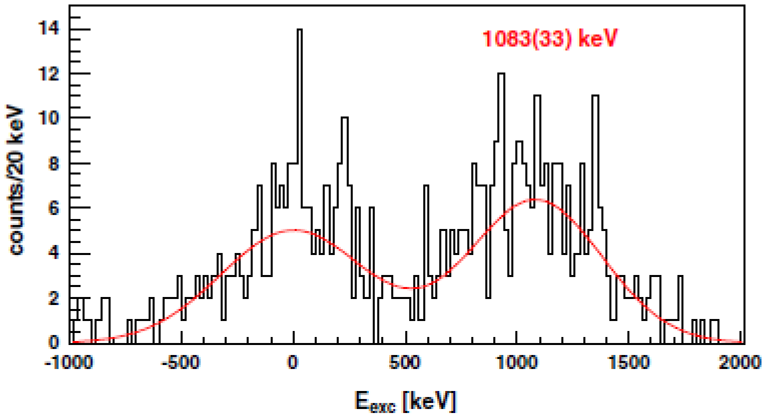
Increase in collectivity from 30Mg to 32Mg (N=20)

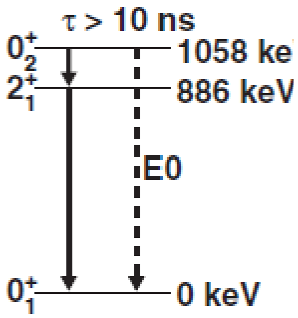
O. Niedermaier et al, Phys. Rev. Lett. 94 (2005) 172501
M. Seidlitz et al , Phys.Lett. B 700 (2011) 181

32Mg, transfer reaction

Two-neutron (t,p) transfer reactions on 30,32Mg

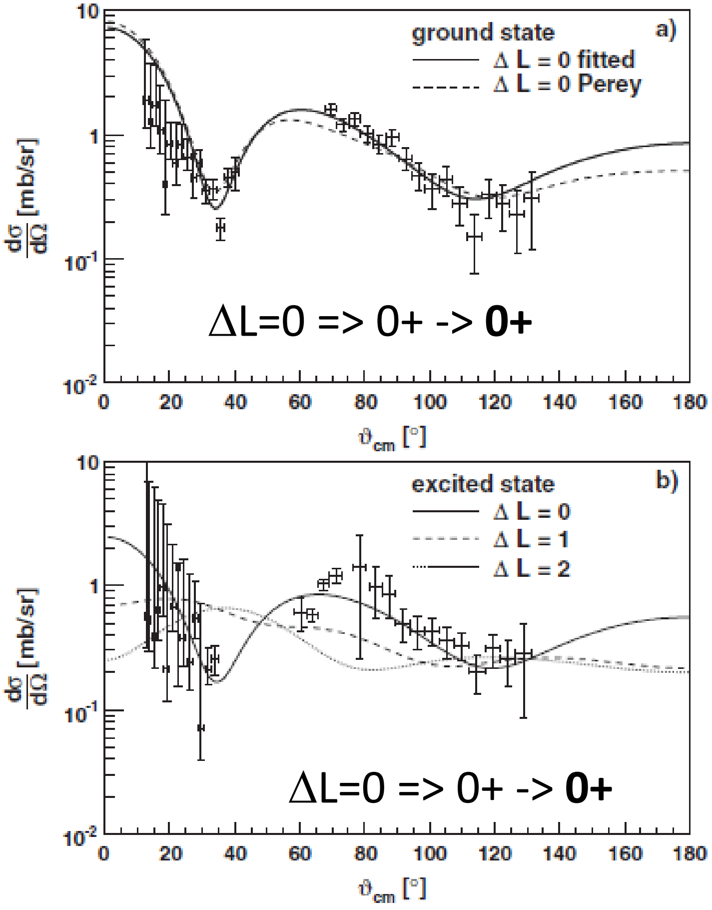
Allow finding 1st excited 0+ state and probing its nature: “normal” spherical structure or deformed structure based on 2 neutrons excited across N=20





existence of excited 0+ state in 32Mg at 1058 keV

proton angular distributions



ΔL=0 => 0+ -> **0+**

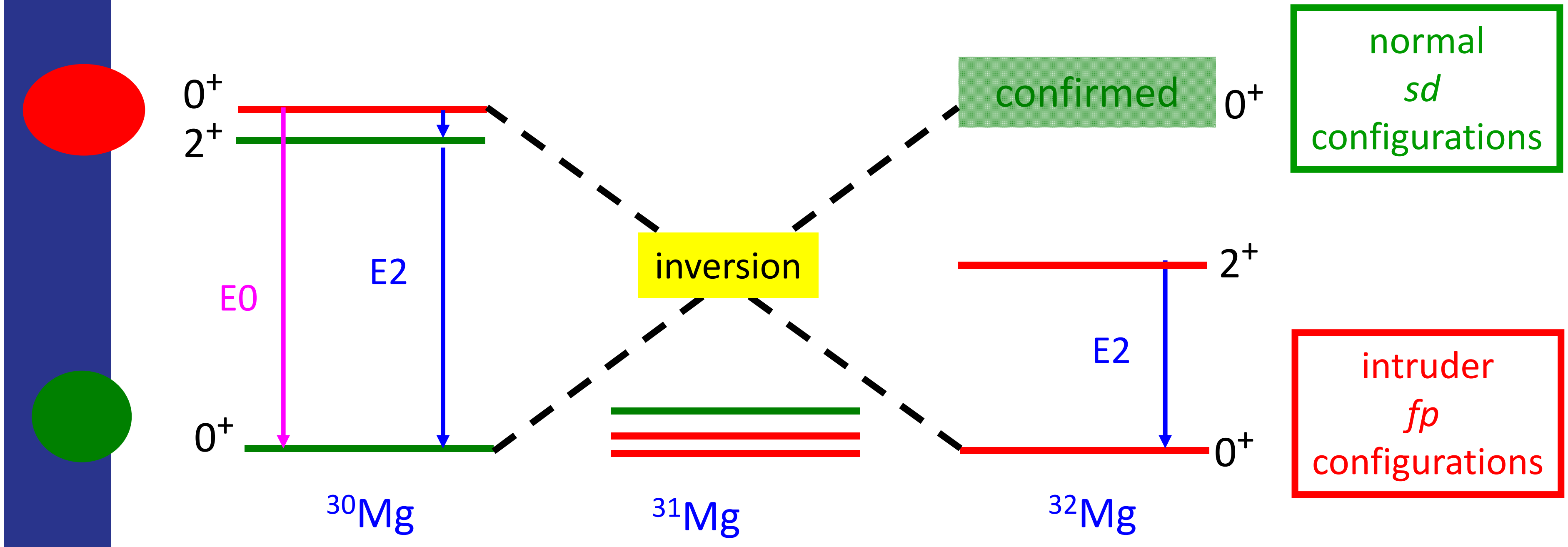
ΔL=0 => 0+ -> **0+**

cross section to populate 32Mg excited 0+ state points to its similarity to 30Mg ground-state, i.e. **spherical structure made of orbitals below N=20**

K. Wimmer et al, Phys. Rev. Lett. 105 (2010) 252501

32Mg, transfer reaction

Coexistence of spherical
and deformed states

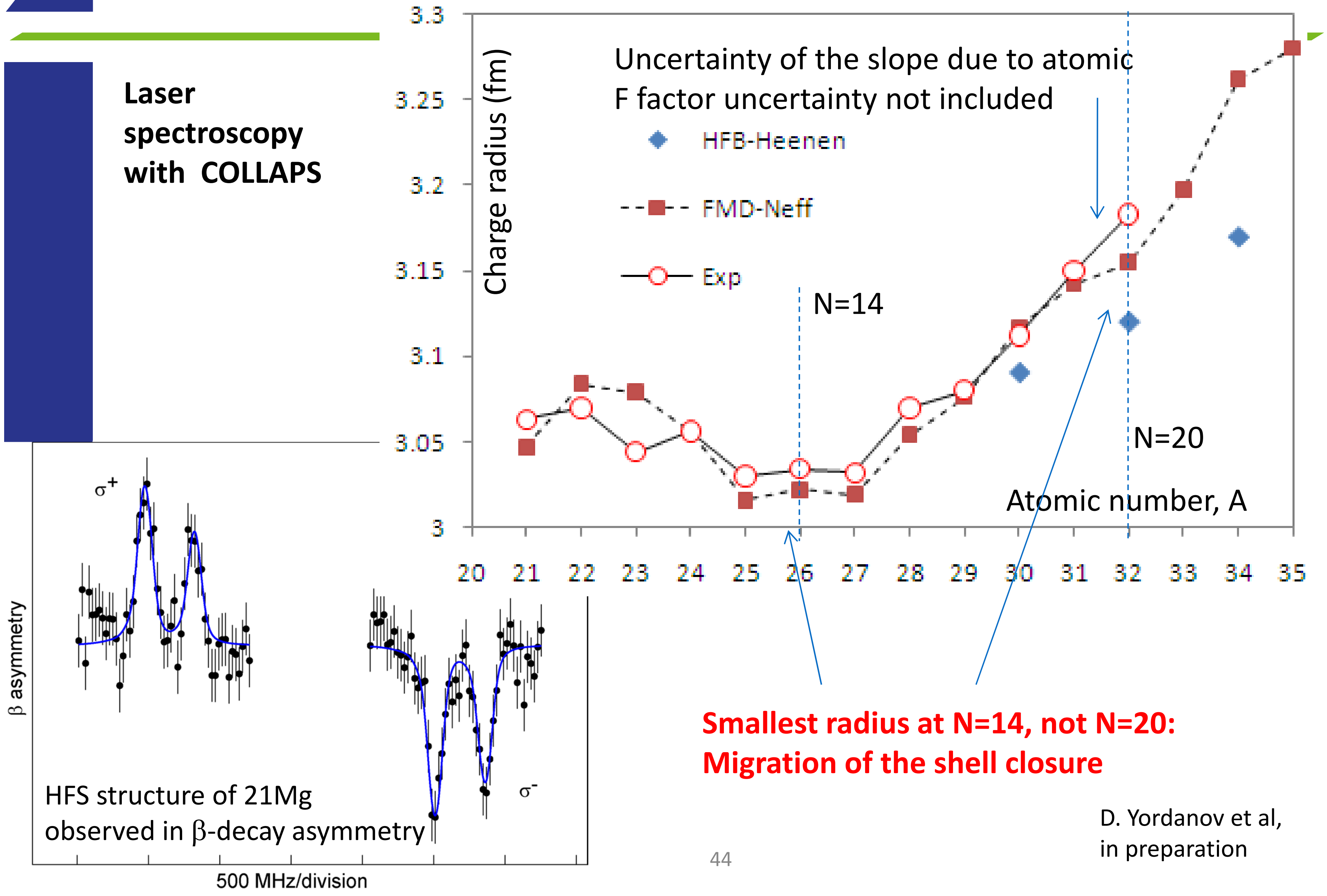


normal
sd
configurations

intruder
fp
configurations

Mg: laser spectroscopy

Laser spectroscopy with COLLAPS

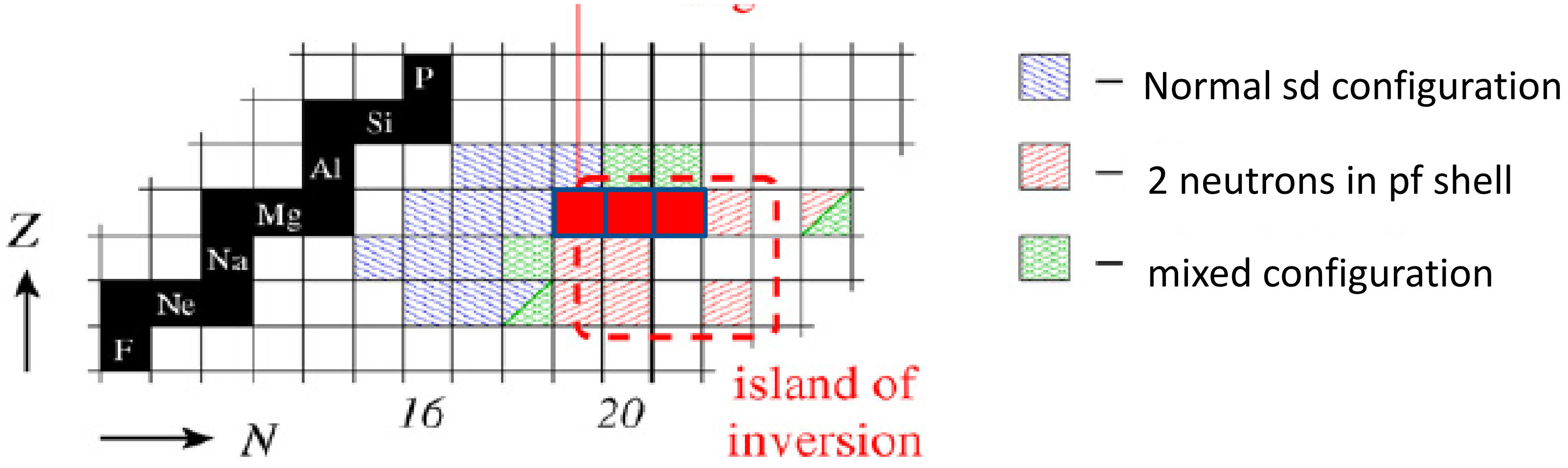

Uncertainty of the slope due to atomic F factor uncertainty not included

HFS structure of 21Mg observed in β-decay asymmetry

Smallest radius at N=14, not N=20: Migration of the shell closure

D. Yordanov et al, in preparation

What did we learn?

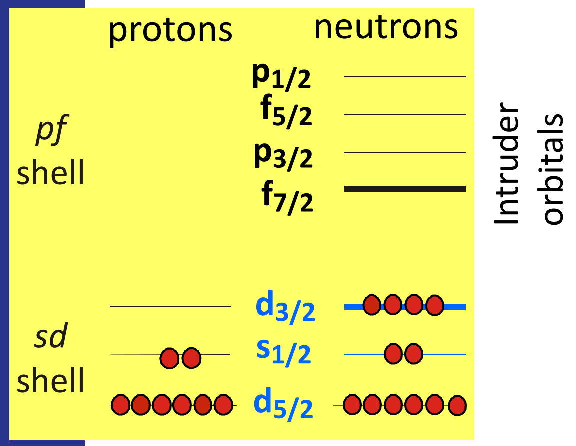


- Already at N=19 neutrons occupy higher orbits
- Transition to island of inversion is sudden
- Spherical and deformed shapes coexist at low energies
- Deformed ground states show mainly 2 neutrons across N=20 (in pf shell)
- New magic number (N=14 or N=16) appears
- Theories start agreeing with experiment

=> Mechanism driving the island connected to tensor part of nuclear interaction
=> There can be other islands like this one
(but interaction details need to be worked out based on more experiments)

Example – island of inversion

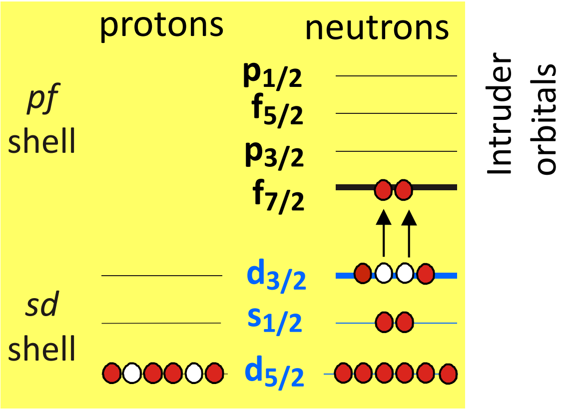
^{36}S: 16p and 20n



"normal"

Decreased N=20 shell gap (or even dissapeared)
Increased correlations

^{32}Mg: 12p and 20n



inversion of the level filling

In low-lying excited states and even in the ground state
neutrons occupy higher (intruder) orbitals before the usual shell is closed

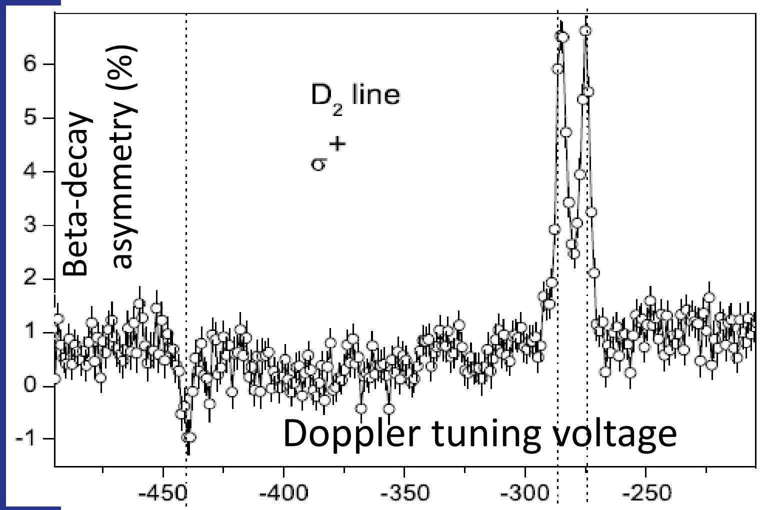
Inversion of the usual level filling
But for nuclei with more protons N = 20 is again a closed shell

Name: island of inversion

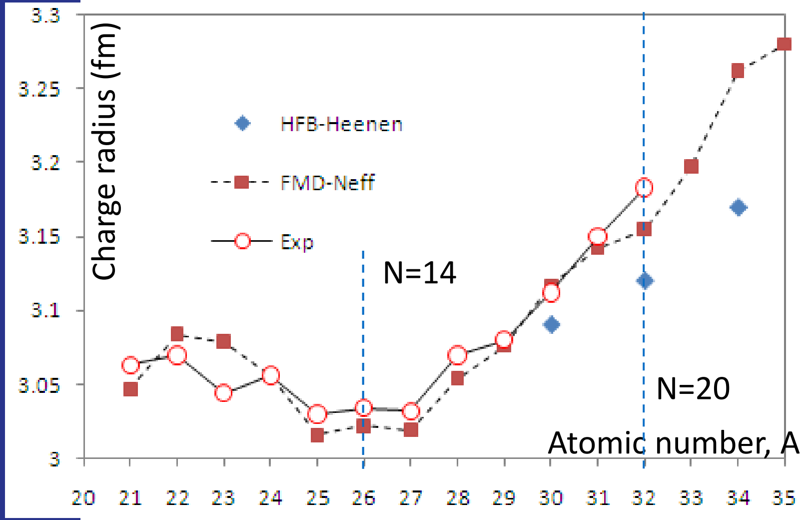
This hypothesis has to be investigated experimentally

Results – island of inversion

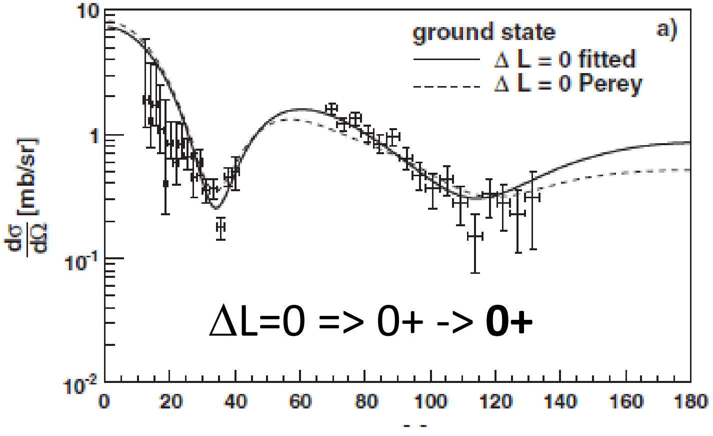
- Laser and NMR spectroscopy



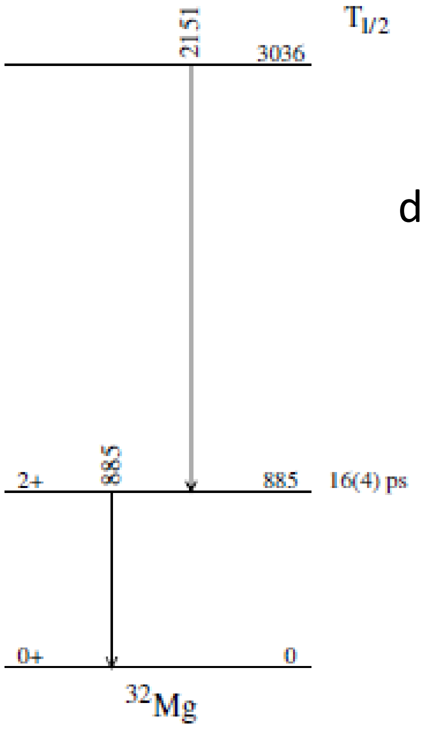
- Laser spectroscopy



- Transfer reactions

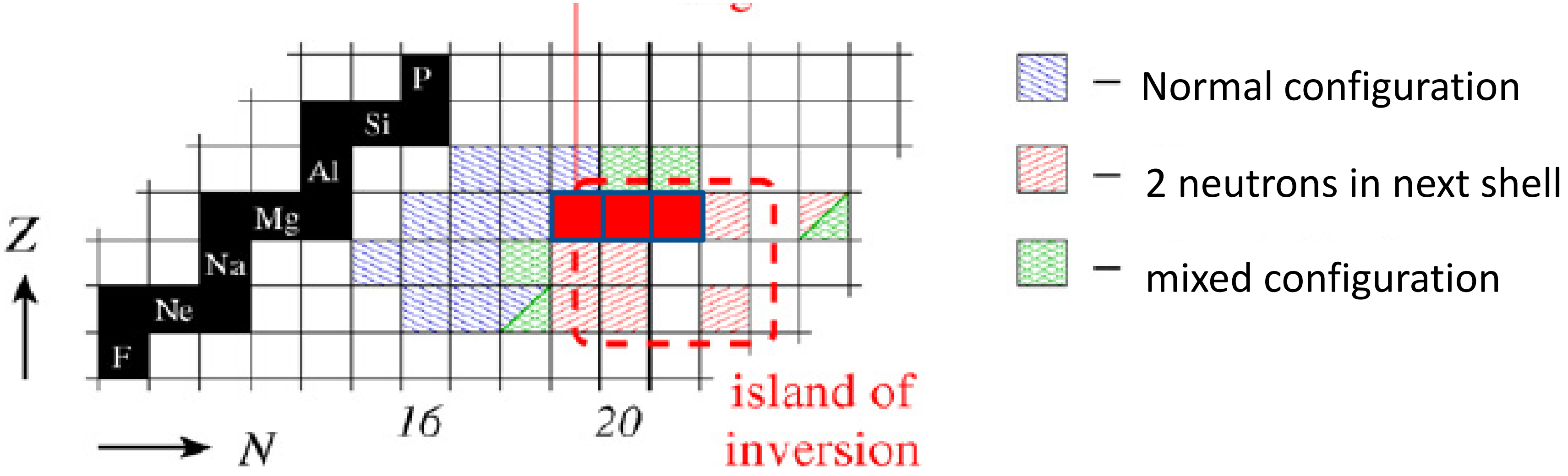


ΔL=0 => 0+ -> **0+**



decay

Results - island of inversion

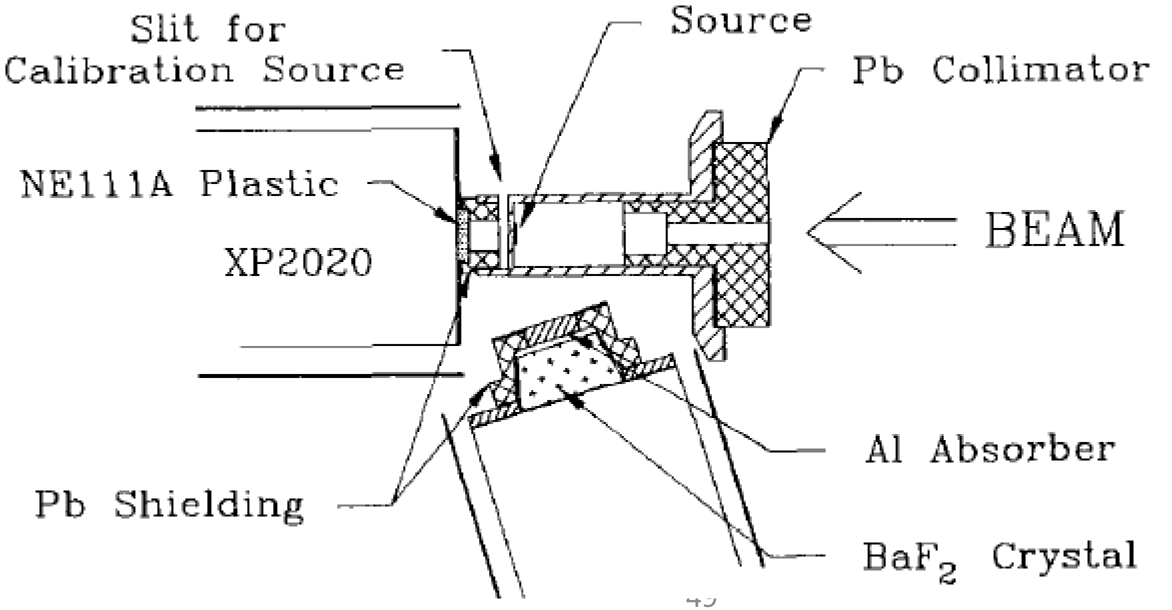


=> Theories can now reproduce most results
=> Mechanism driving the island connected to tensor part of nuclear interaction
=> There can be other islands like this one
(but interaction details need to be worked out based on more experiments)

Fast-timing gamma spectroscopy

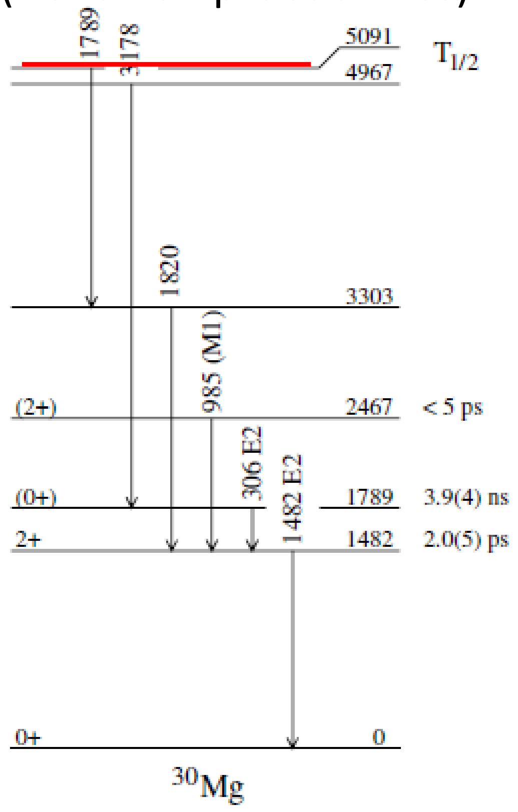
Gamma spectroscopy with BaF2 crystals
(very fast response, <ps lifetime studies)

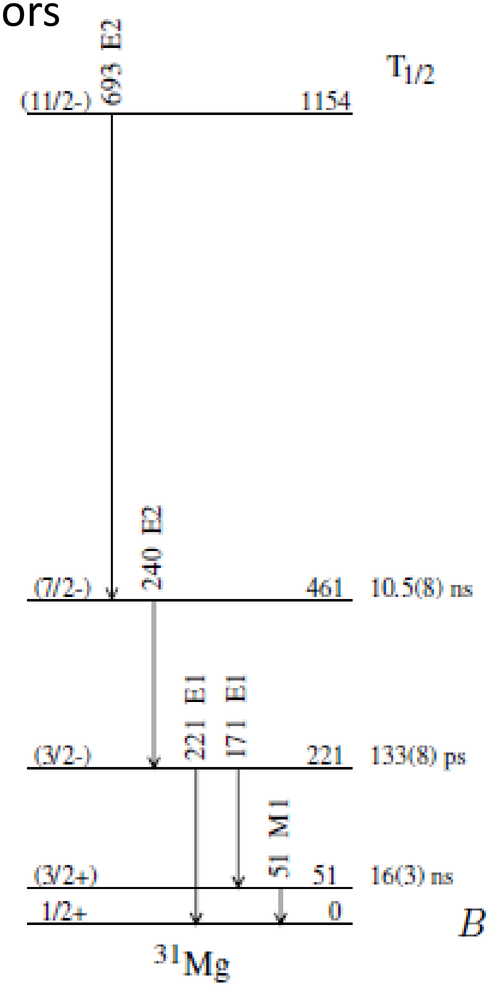
=> Transition energies and probabilities, deformations

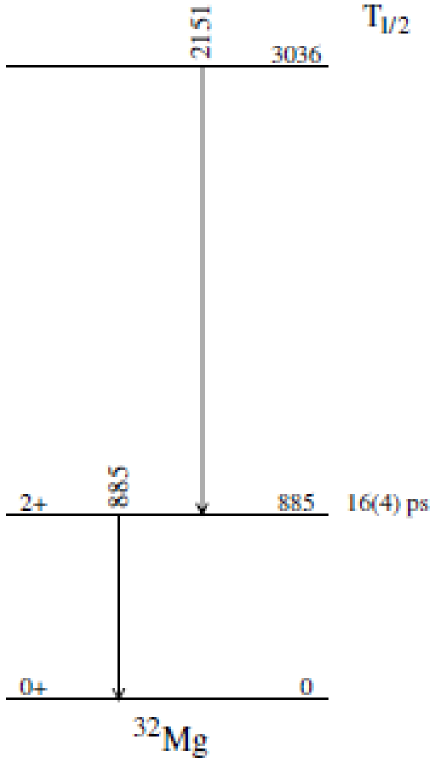


Mg: fast-timing

fast timing $\beta\gamma\gamma(t)$ using BaF_2 detectors
=>level lifetimes in 30,31,32Mg
(transition probabilities)







2+ state lifetime:

$$B(E2;0^+ \rightarrow 2^+) = 327(87)\ e^2\mathrm{fm}^4,$$

Spherical ground state

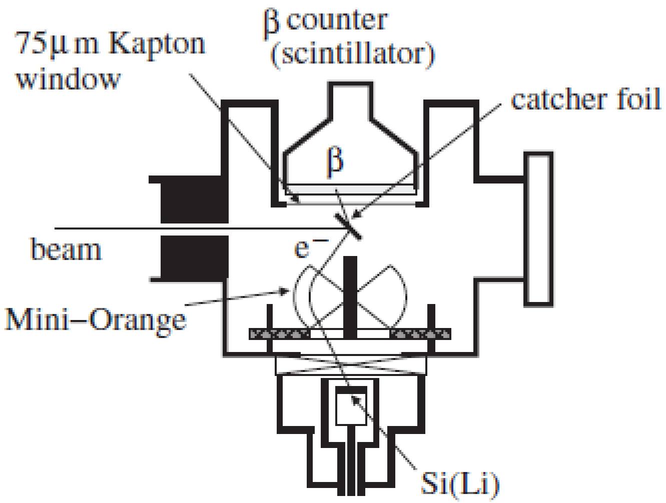
Deformed ground state

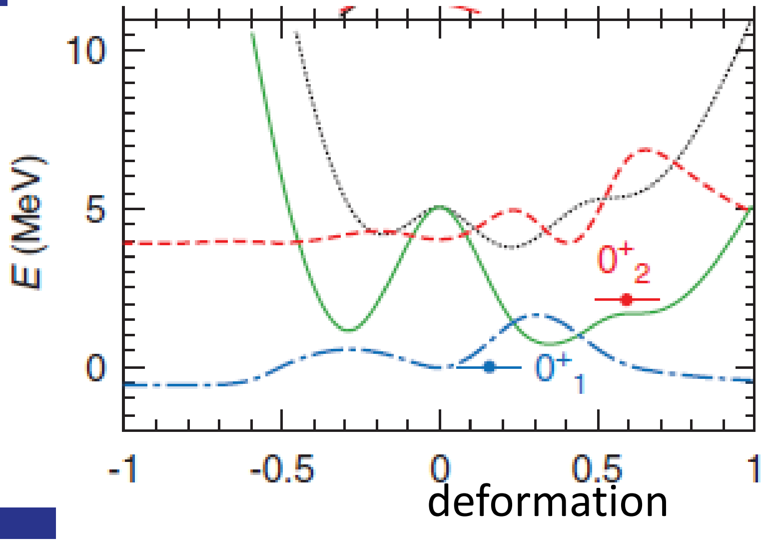
1789 keV level established : candidate for deformed 0+ configuration in 30Mg

H. Mach et al., Eur. Phys. J. A 25, s01, 105 (2005)

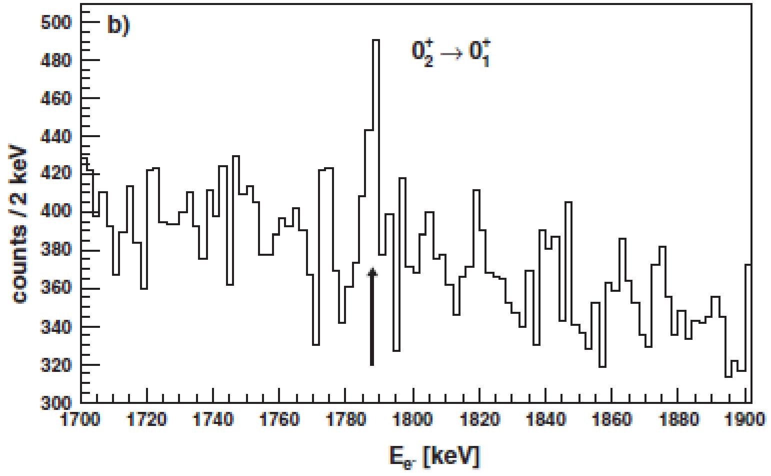
30Mg: E0 transition

E0 decay of 30Mg
electron spectrometer





Identification of 0+ state at 1789 keV ; small mixing amplitude with spherical ground state => deformed state

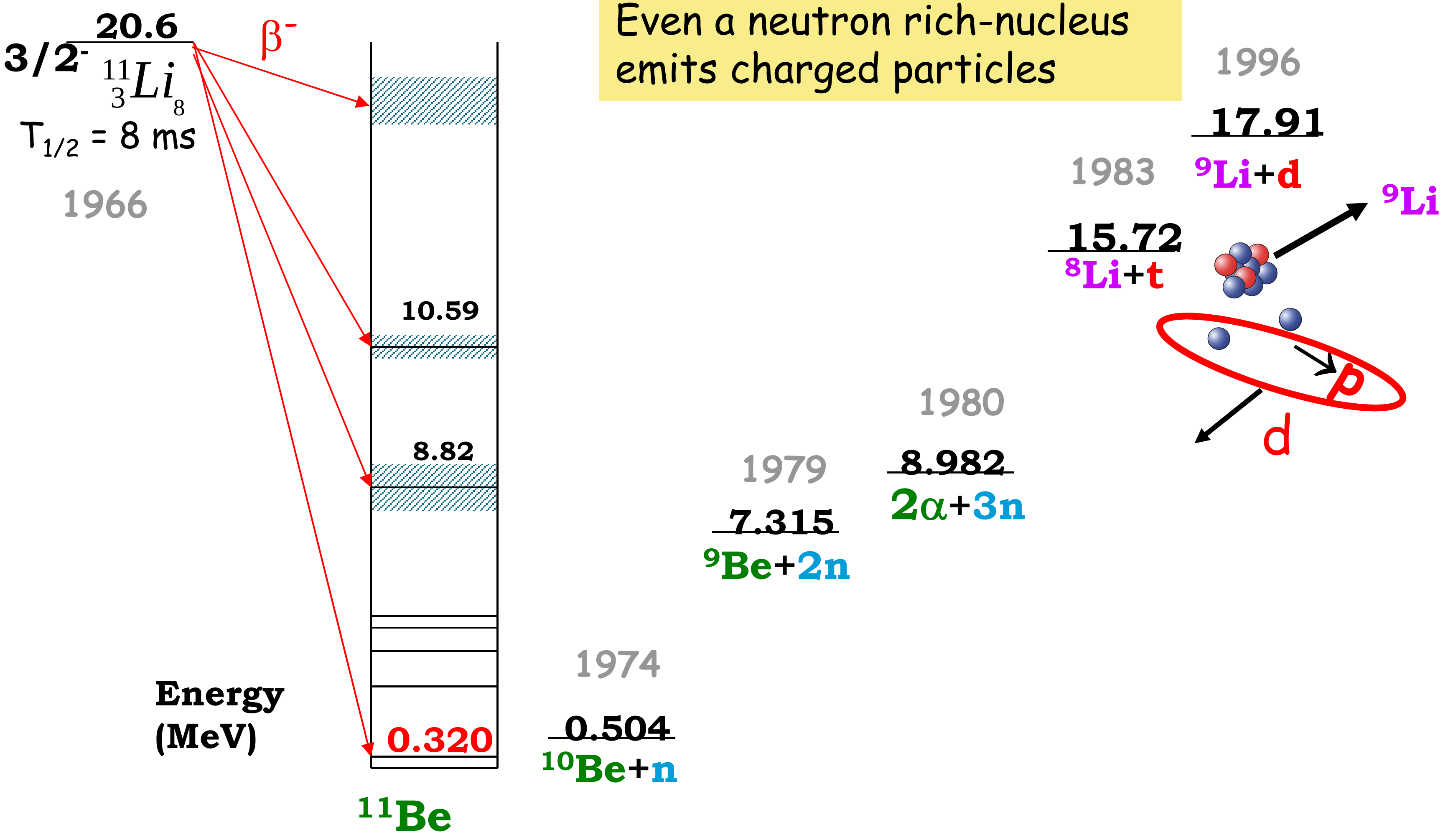


30Mg: spherical 0+ground-state, deformed 1st 0+ state (2 neutrons across N=20) => **shape coexistence**

W. Schwerdtfeger et al., Phys. Rev. Lett. 103, 012501 (2009)

Results – decay of light nuclei

Even a neutron rich-nucleus emits charged particles



20.6

$3/2^-$ $^{11}_{3}Li_8$

$T_{1/2}$ = 8 ms

1966

β^-

10.59

8.82

0.320

Energy (MeV)

^{11}Be

1974

0.504

$^{10}Be+n$

1979

7.315

$^{9}Be+2n$

1980

8.982

$2\alpha+3n$

1983

15.72

$^{8}Li+t$

1996

17.91

$^{9}Li+d$

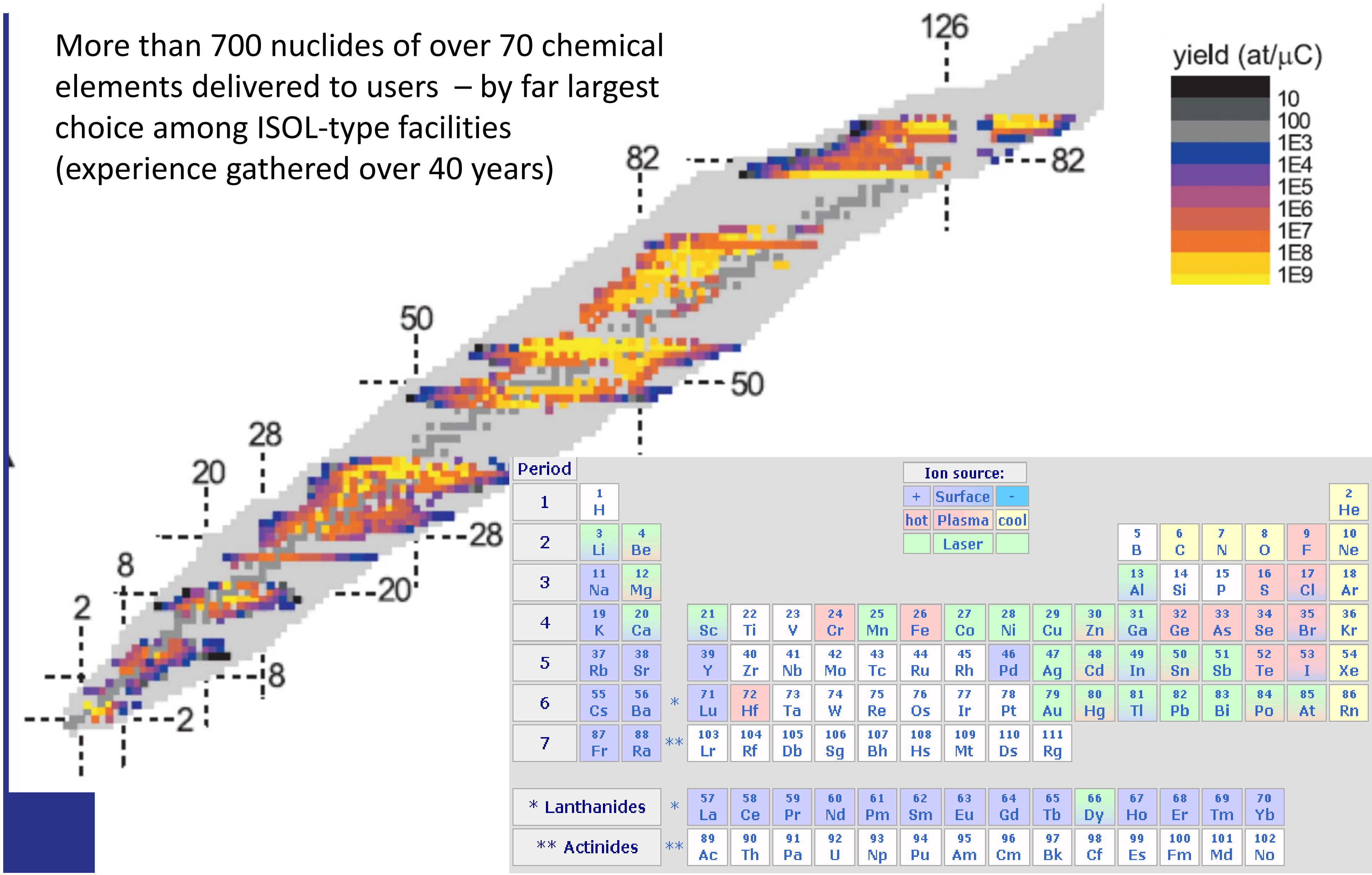
^{9}Li

p

d

Extracted nuclides

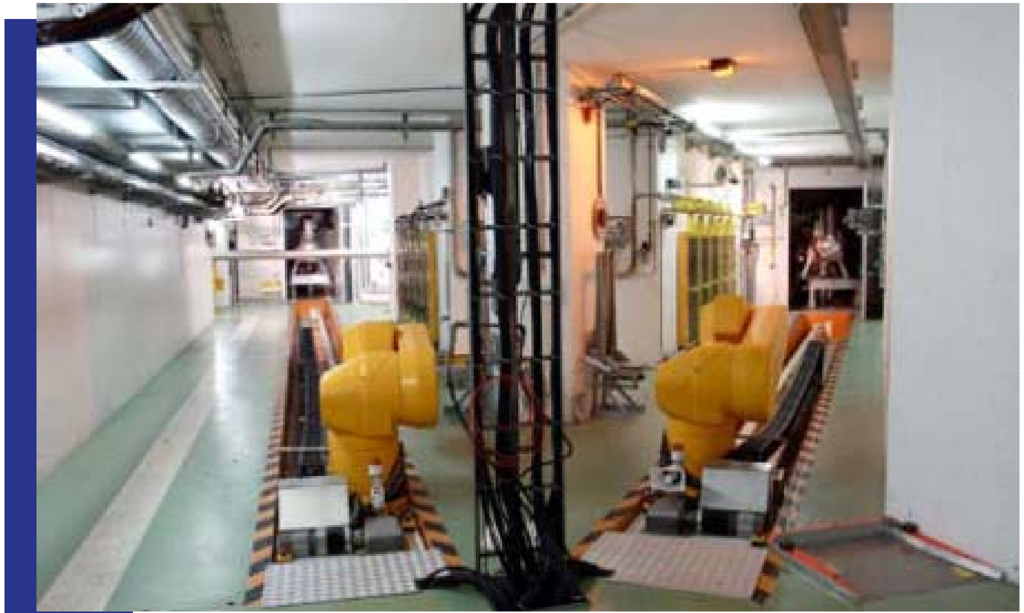
More than 700 nuclides of over 70 chemical elements delivered to users – by far largest choice among ISOL-type facilities (experience gathered over 40 years)

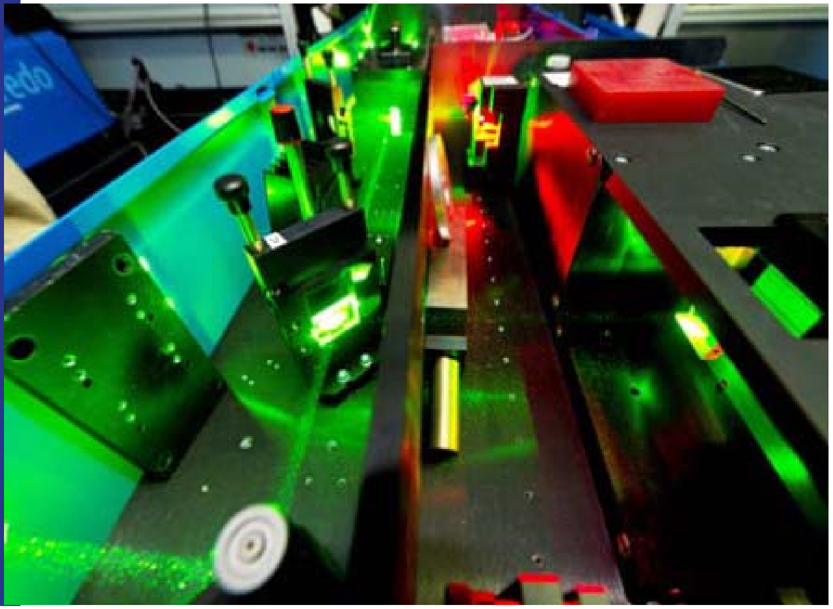


Ion source:
+ Surface -
hot Plasma cool
Laser

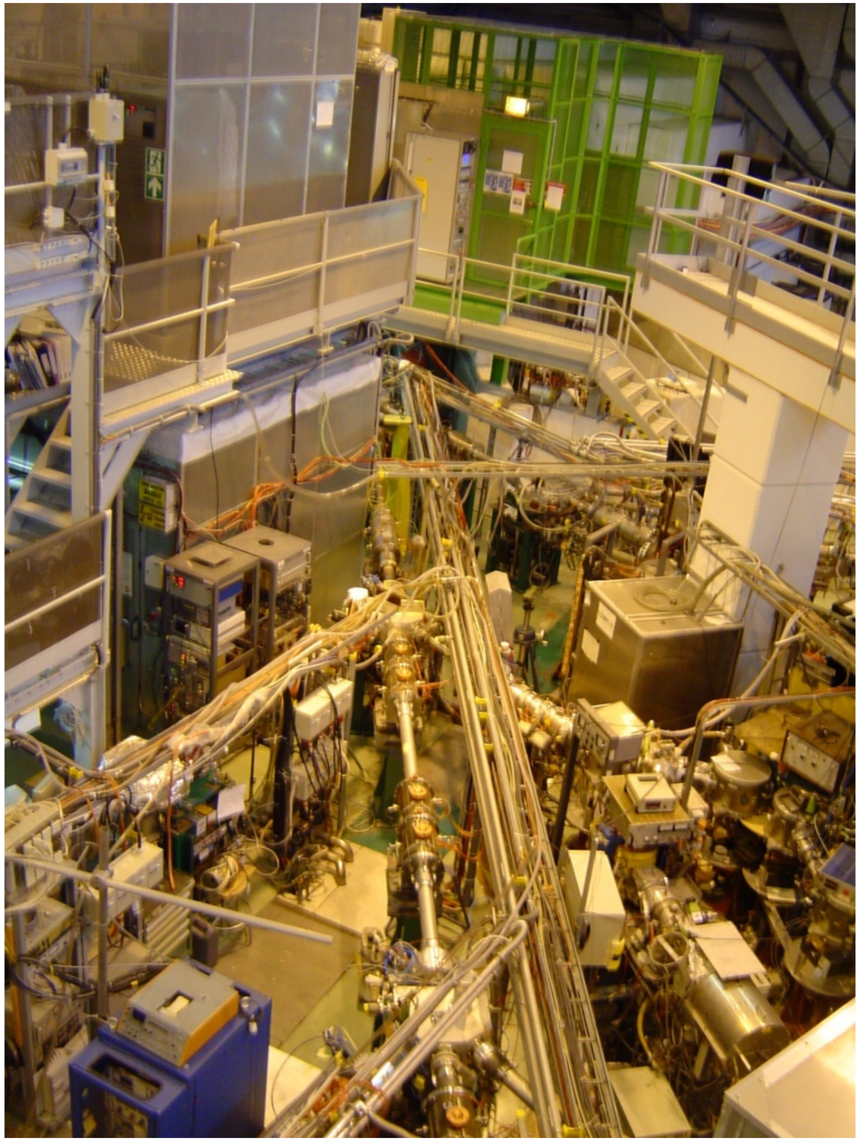
Period																			
1	1 H																		2 He
2	3 Li	4 Be													5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg													13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg							
* Lanthanides			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
** Actinides			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Facility photos





Experimental beamlines



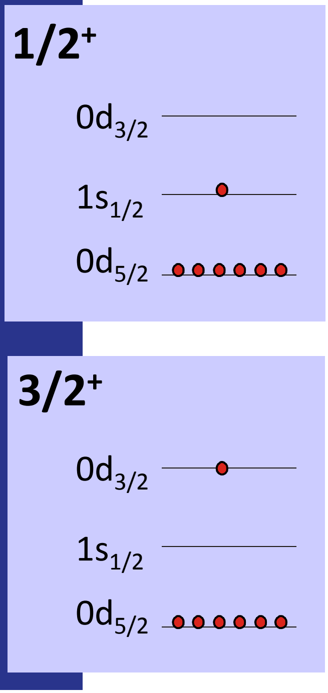
Laser spectroscopy and nuclear physics

- **Spin** (orbital+intrinsic angular momentum), **parity** (I^{π})
- Nuclear ***g*-factor** and **magnetic** dipole **moment** (g_I and μ_I)
- Electric quadrupole moment (Q)
-**Charge radius** ($\langle r^2 \rangle$)

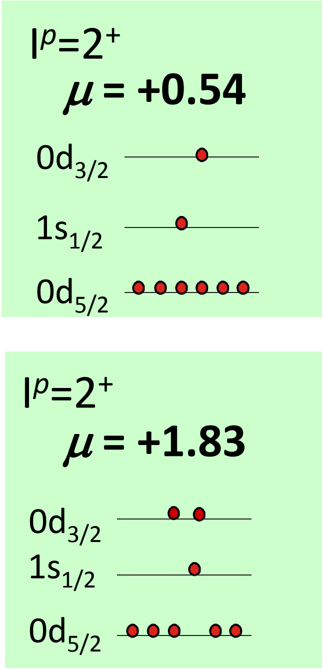
Give information on:

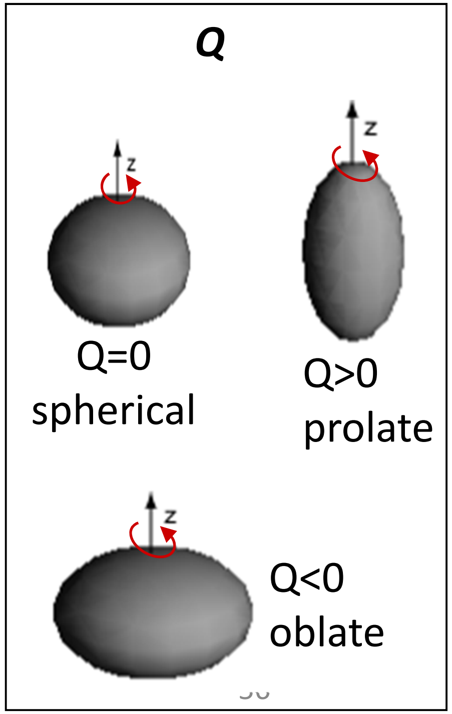
- Configuration of neutrons and protons in the nucleus
- Size and form of the nucleus

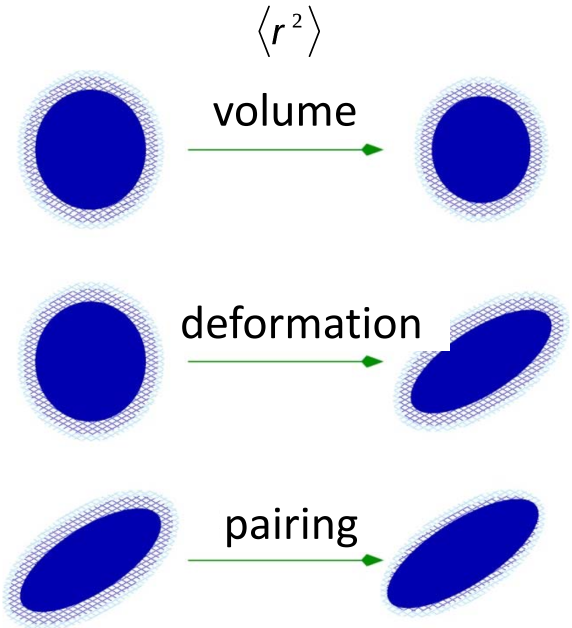
I^{π}



g_I and μ_I







Laser spectroscopy

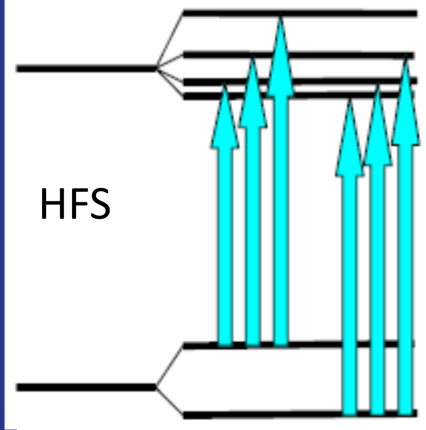
Atomic **hyperfine structure**

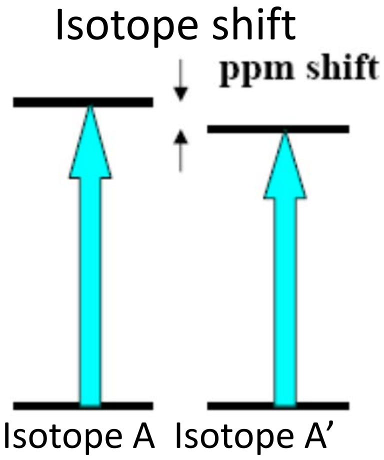
(interaction of nuclear and atomic spins)

$$\Delta E_{HFS} = \frac{A}{2}K + B\frac{\frac{3}{4}K(K+1) - I(I+1)J(J+1)}{2(2I-1)(2J-1)I\cdot J}$$

$$\text{where } K = F(F+1) - I(I+1) - J(J+1)$$

$$A = \frac{\mu_I H_e(0)}{I\cdot J} \qquad B = eQV_{zz}(0)$$





Isotope shifts in atomic transitions

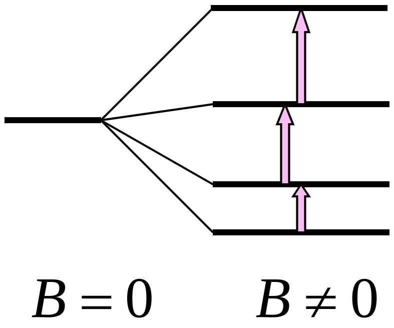
(change in mass and size of different isotopes of the same chemical element)

$$\delta\nu^{A,A'} = (K_{NMS} + K_{SMS}) \times \frac{A' - A}{A'A} + F \times \delta\langle r^2\rangle^{A,A'}$$

Nuclear Magnetic Resonance – NMR

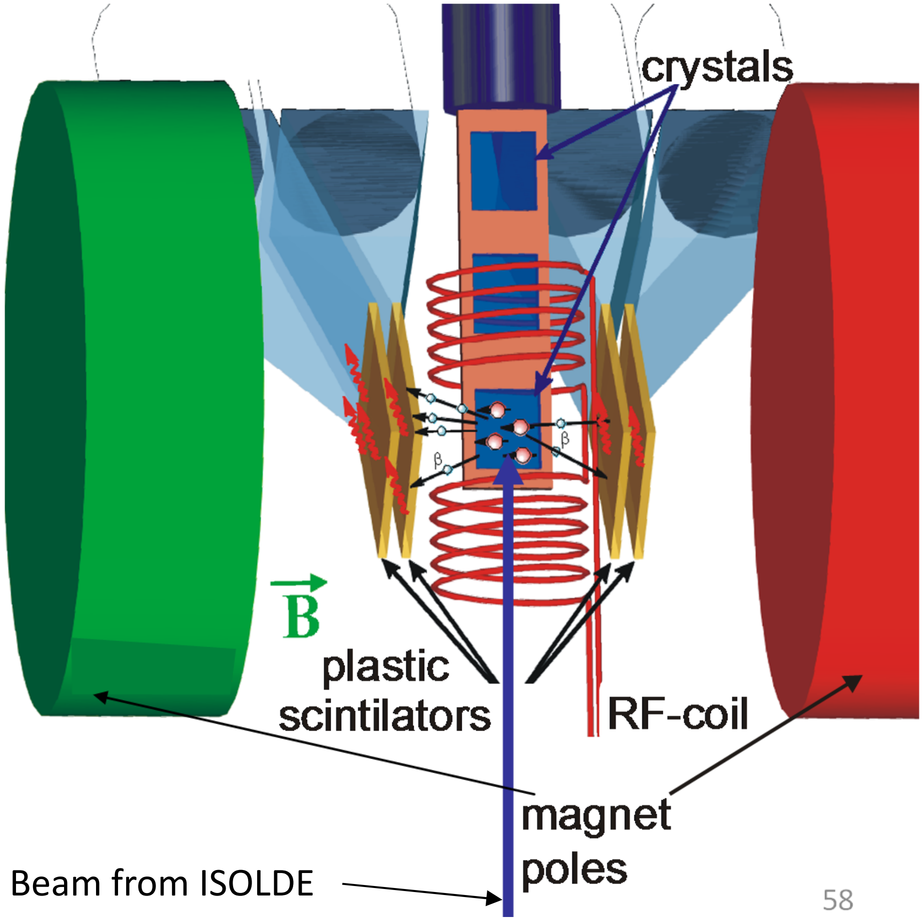
(Zeeman splitting of nuclear levels)

$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2}Q \cdot V_{zz}$$



Beta-detected NMR

Beta particles (e-,e+) can be used as a detection tool, instead of rf absorption
(beams down to 1000 ions/s can be studied)

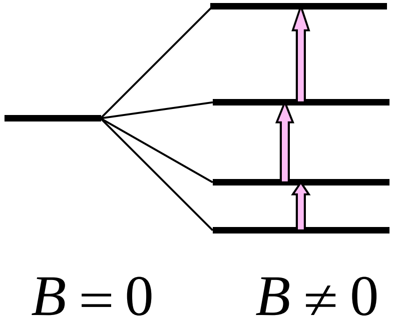


Measured asymmetry:

$$A = \frac{N(0°) - N(180°)}{N(0°) + N(180°)}$$

Nuclear Magnetic Resonance – NMR
(Zeeman splitting of nuclear levels)

$$\Delta E_{mag} = |g_I| \cdot \mu_N \cdot B + \frac{1}{2} Q \cdot V_{zz}$$



Results:
Magnetic and electric moments of nuclei
(position of last nucleons, shapes)