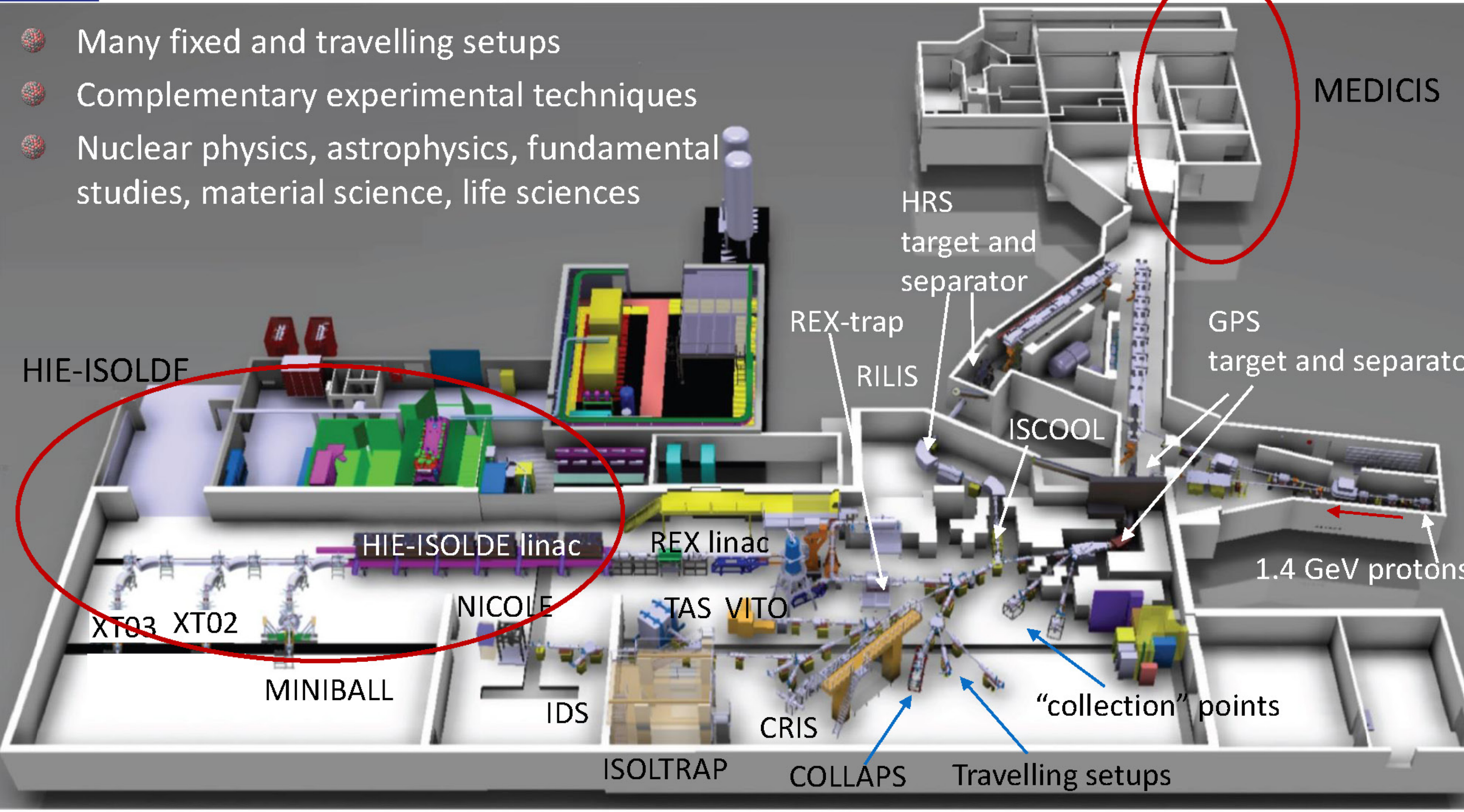
Polarization of exotic beams

Outline

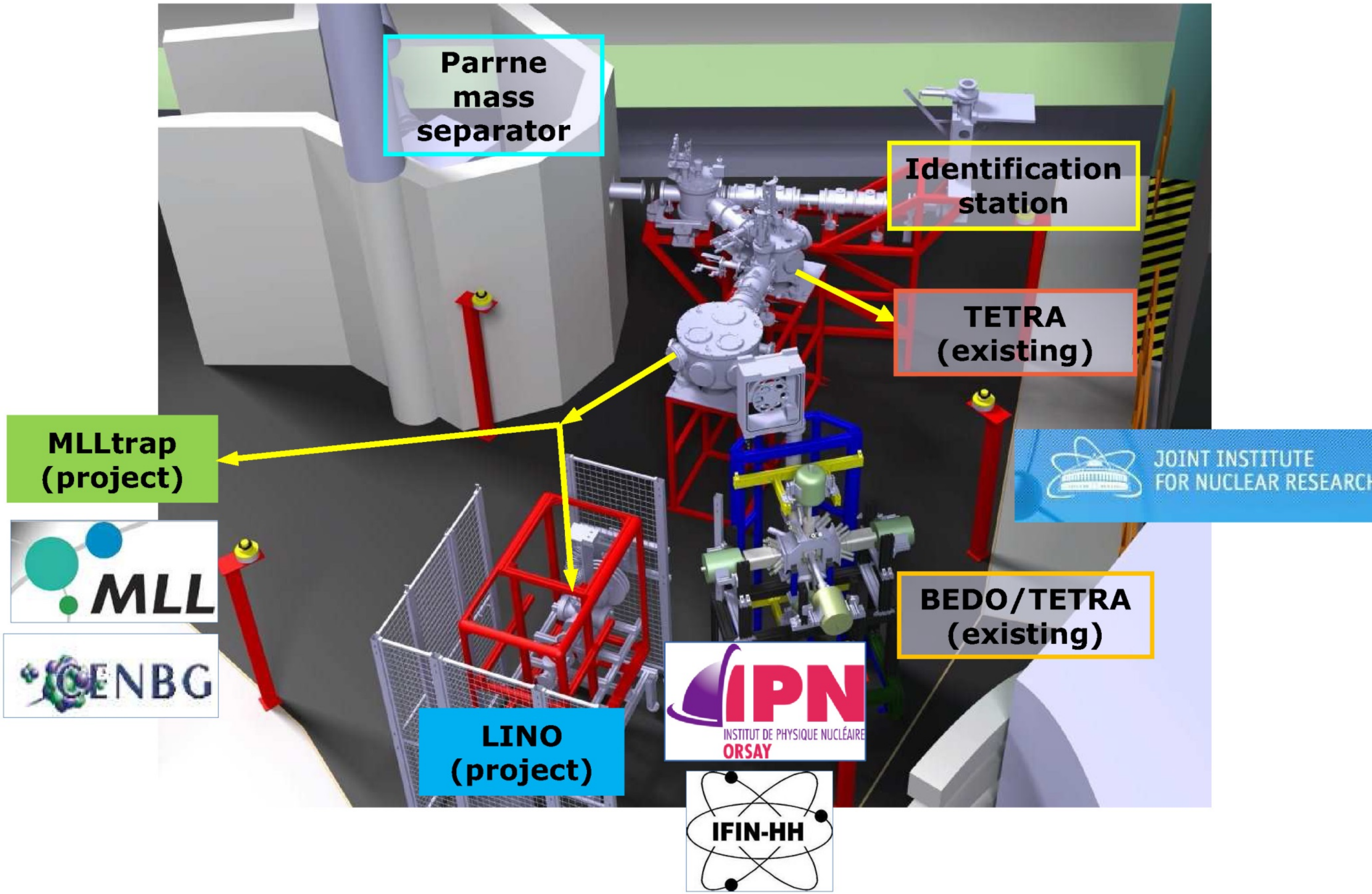
- ISOL facilites in the world
- 1^+ exotic beams: instrumentation
- OLNP: PolarEx and Nicole
- Laser Polarization ?
- Polarization for EDM searches

1^+ @ ISOLDE

- Many fixed and travelling setups
- Complementary experimental techniques
- Nuclear physics, astrophysics, fundamental studies, material science, life sciences

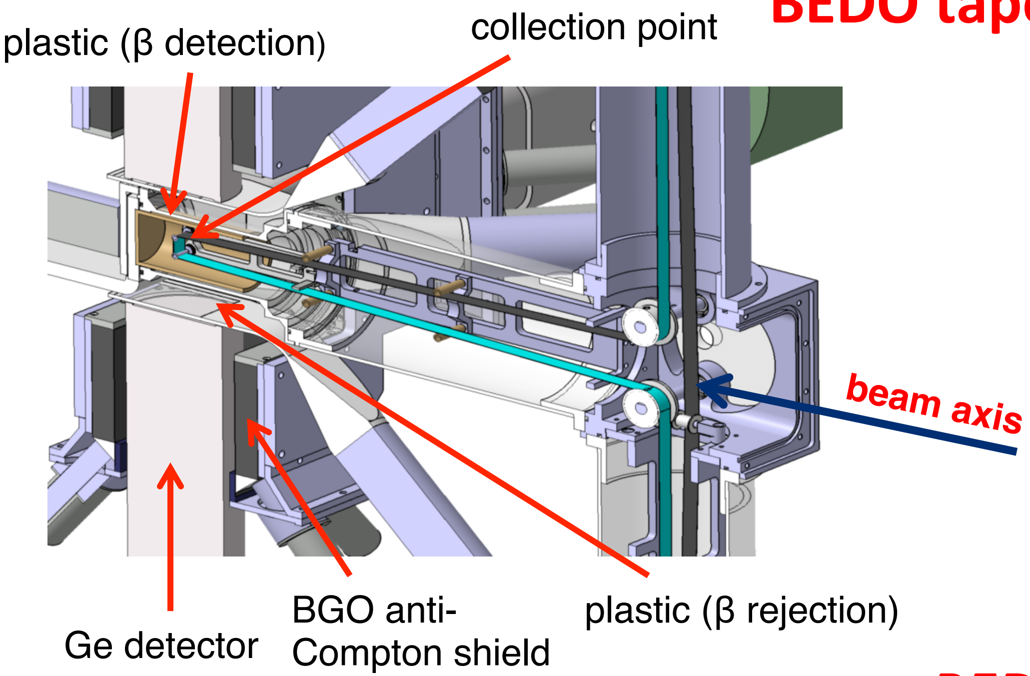


1^+ @ALTO



Parrne mass separator
Identification station
TETRA (existing)
MLLtrap (project)
JOINT INSTITUTE FOR NUCLEAR RESEARCH
MLL
CENBG
BEDO/TETRA (existing)
LINO (project)
IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY
IFIN-HH

Typical β-decay measurement



BEDO tape station

- Up to 5 Ge detectors
- Compton BGO shielding
- Plastic veto detector
- > 50 % β efficiency

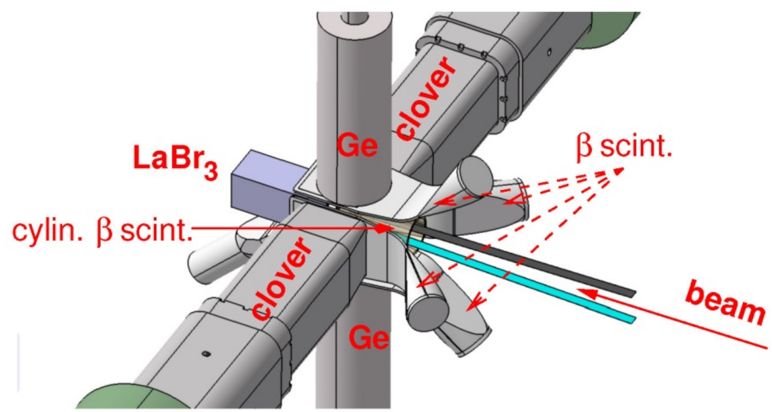
Optimal configurations:

- 4 clovers (~ 3.5 - 4% eff. @ 1 MeV)
- 1 planar Ge for X rays

OR

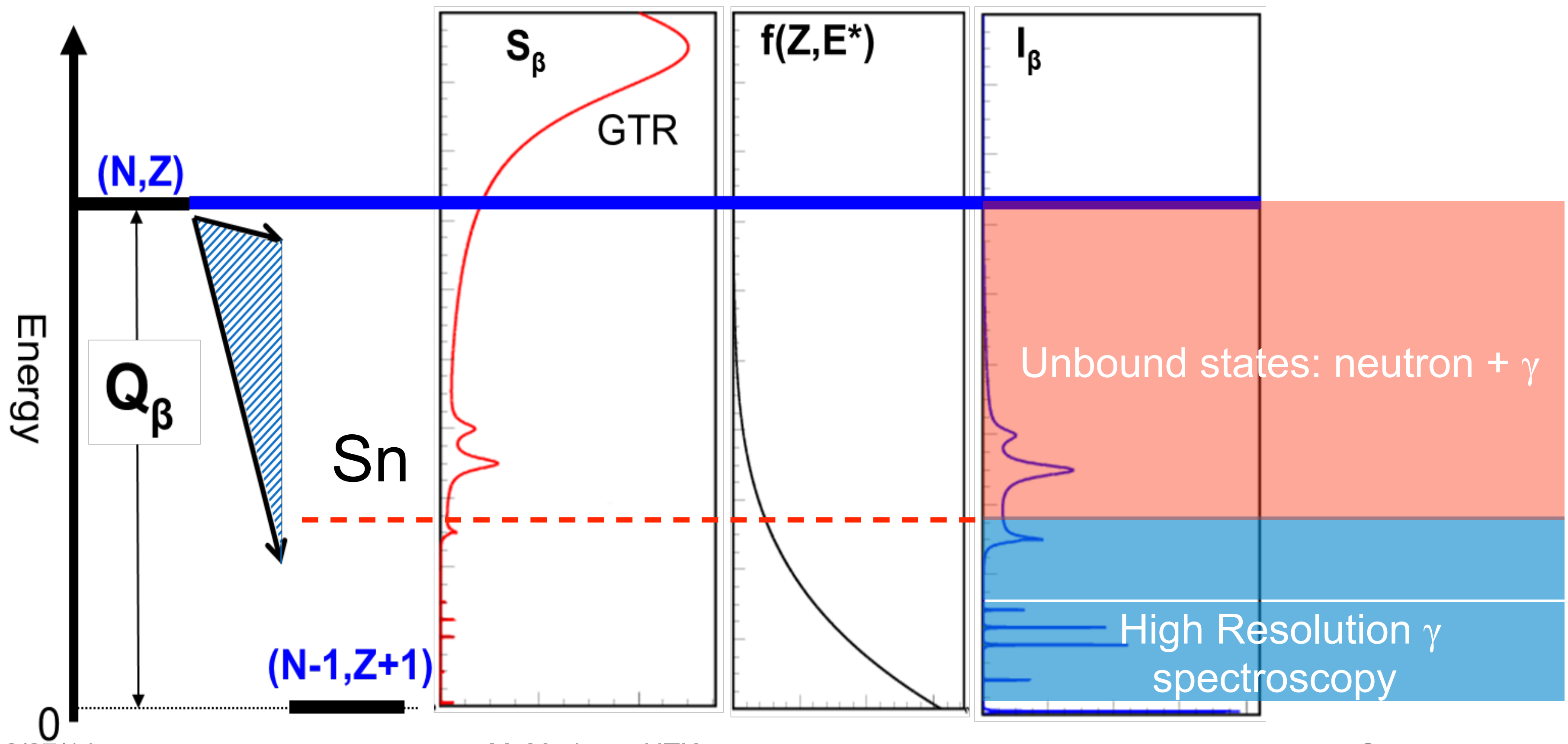
- FAST timing configuration (2 LaBr + 2 Ge)

BEDO setup with large $LaBr_3$



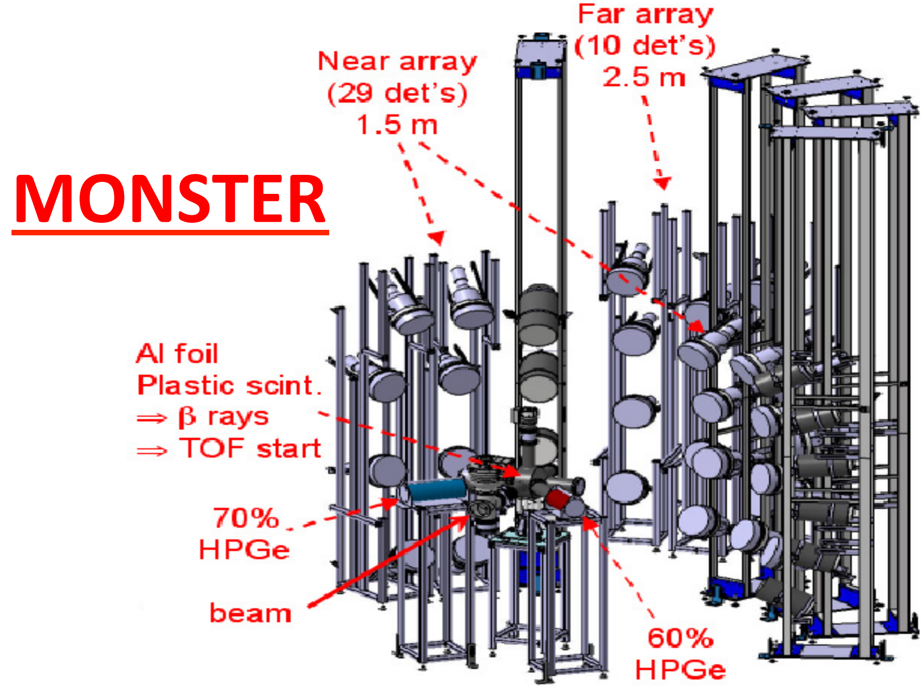
β-delayed neutron spectroscopy

High Q-value beta decays



Courtesy of M. Madurga, CERN

β-delayed neutron detectors



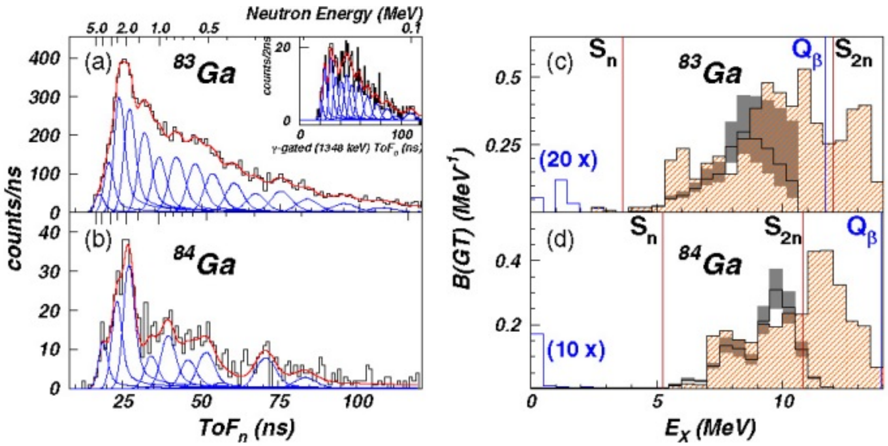
- Dedicated TOF detectors
- Efficiency 10 %
- Energy FWHM 80-100 keV @ 1 MeV
- 2n detection challanging

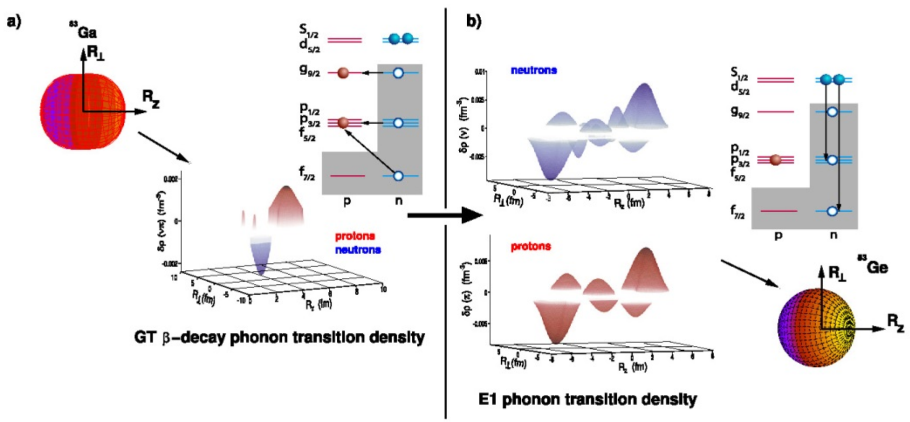
Recent highlights: core decay

PRL 117, 092502 (2016) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2016

Evidence for Gamow-Teller Decay of ^{78}Ni Core from Beta-Delayed Neutron Emission Studies

M. Madurga,[1,2] S. V. Paulauskas,[1] R. Grzywacz,[1,3] D. Miller,[1] D. W. Bardayan,[3] J. C. Batchelder,[4] N. T. Brewer,[3]





Physics Letters B 772 (2017) 359–362

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www.elsevier.com/locate/physletb

Unexpected high-energy γ emission from decaying exotic nuclei

A. Gottardo[a,*], D. Verney[a], I. Deloncle[b], S. Péru[c], C. Delafosse[a], S. Roccia[b], I. Matea[a],

Old hypothesis from Hardy that high-energy β decay is featurless is refuted

Polarizing 1^+ beams

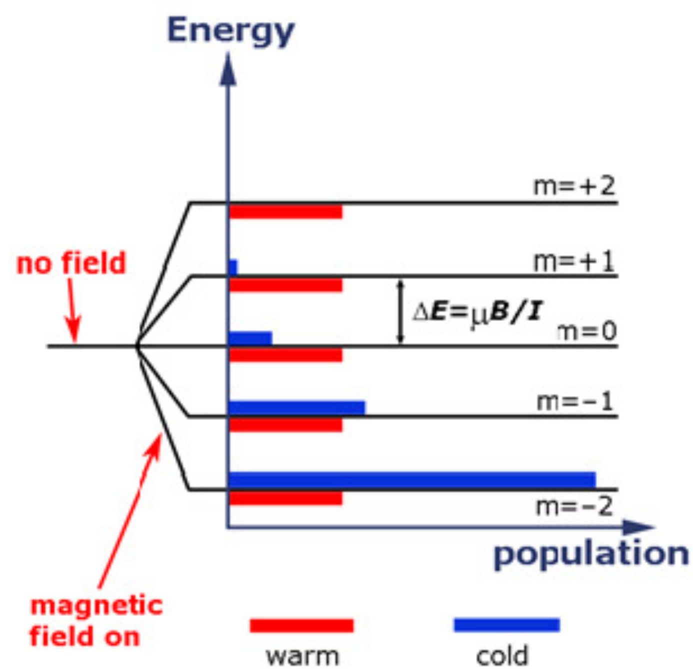
What does it mean to polarize ?

- Degeneracy of nuclear spin I is removed by magnetic field

- One magnetic substate has to be preferentially occupied

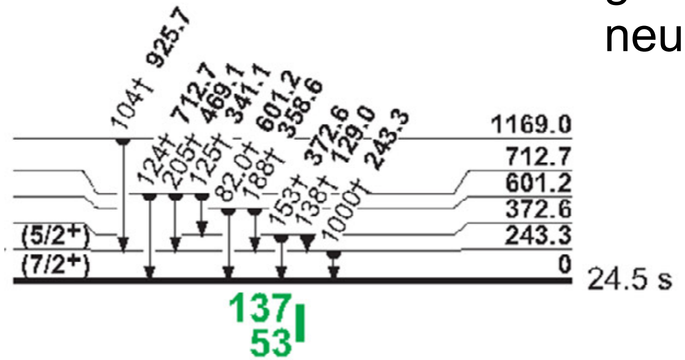
Lower energy
Lower temperature

Laser transitions among the substates



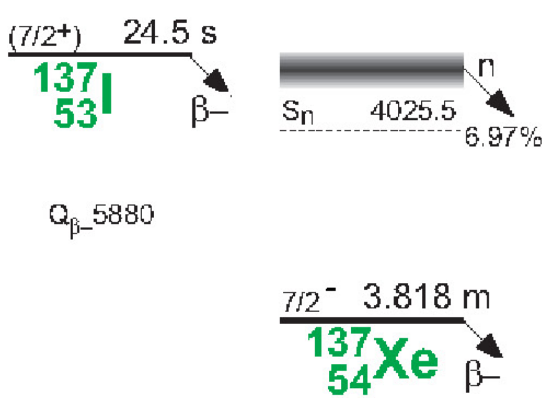
What physics ?

β-delayed γ and neutron spectroscopy:
spin assignments,
g-factor measurements,
neutron wave functions



- Measurement of magnetic moment of the odd proton $7/2^+$ state

γ-decay of $^{137}Xe^*$ and β-delayed neutron emission from ^{137}Xe



- Anisotropy of γ emission
  High density of $7/2^+$ and $7/2^-$ states in ^{137}Xe
  ⇒ strong parity admixture

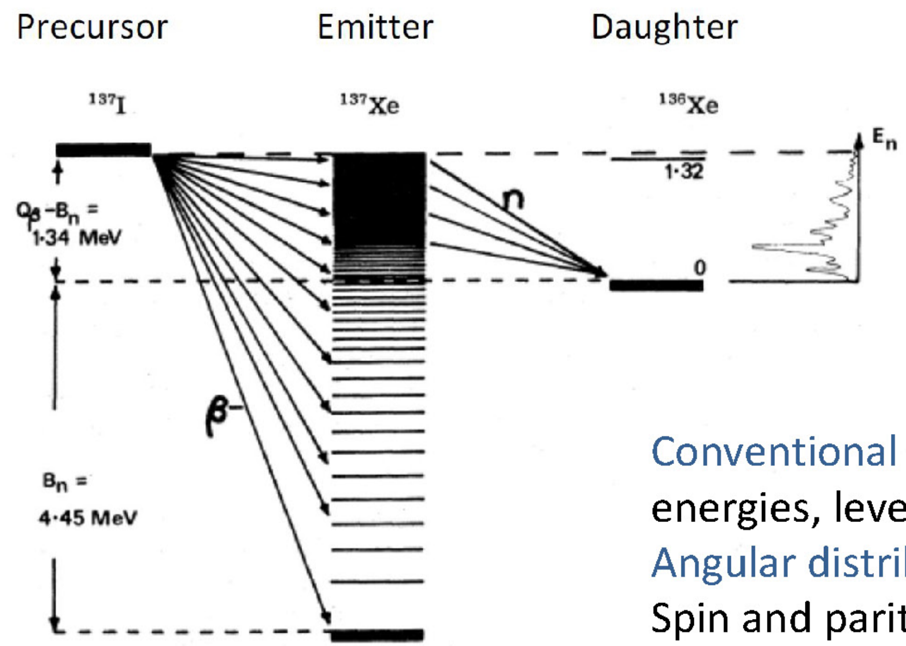
- Anisotropy of β-delayed neutron emission
  ⇒ access to quantum barrier penetration studies
  ⇒ neutron wave function

World first experiment

NICOLE @ ISOLDE

Beta-delayed neutrons from oriented ^{137,139}I and ^{87,89}Br nuclei

VANDLE@NICOLE Versatile Array of Neutron Detectors at Low Energy



Conventional spectroscopy:
energies, level structures intensities,
Angular distribution:
Spin and parity of the levels
and the angular momenta (partial waves)

Particle emission: physics at the drip--lines
r--process nuclei are delayed neutron emitters
power plant modeling

OLNO-LTNO thechnique

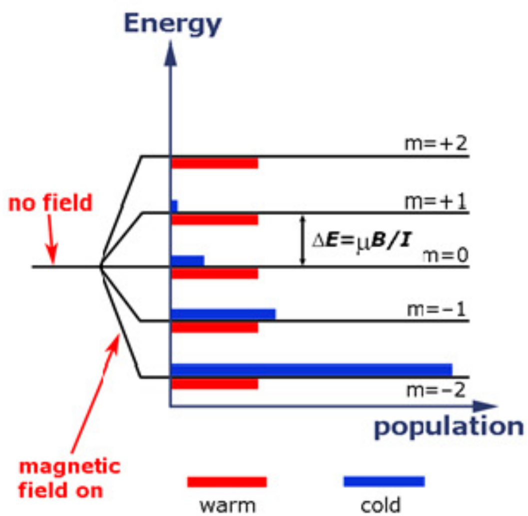
- On-line nuclear orientation

Low-temperature nuclear orientation (LNTO)

On-line: implantation of radioactive beams produced by an ISOL source

POLAREX @ ALTO

Polarizing with temperature



Polarex in numbers

B_{ext} = 1.5 T

B_{tot} = 10-100 T

T = 6-20 mK

Lowest temperature possibile to shift the Boltzmann distribution towards the lowest substate

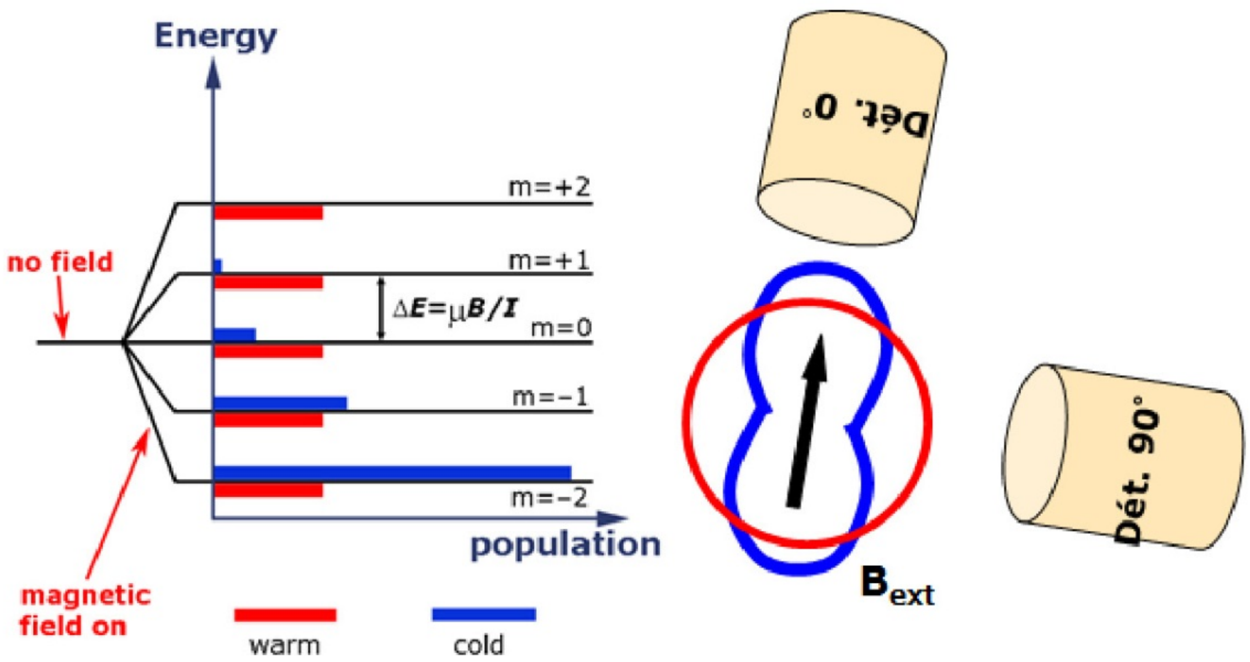
A *caveat*: time to reach thermal equilibrium not small (spin-lattice relaxation time)

A non negligible requirement for an exotic beam (i.e. $T_{1/2}$>> s) !

Courtesy of C. Gaulard

POLAREX @ ALTO

Once the nucleus is orientes, β-delayed γ (and neutron!) emission is anysotropic

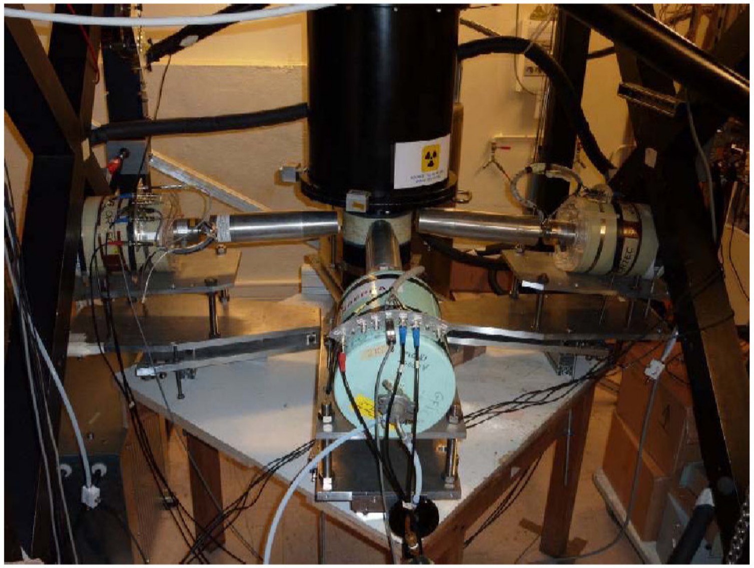


Courtesy of C. Gaulard

POLAREX @ ALTO: ingredients

- Low temperature (< 15 mK): ^{3}He-^{4}He refrigerator
- Strong **B** field (1.5 T): superconduting magnet in a cryostat
- Ferromagnetic foil to host exotic nuclei (hyperfine **B** ≈ 10 T – 100 T)

Anisotropic gamma emission
→ 4 germanium detectors
(1@0°, 2@90°, 1@180°)



^{60}Co as nuclear thermomether

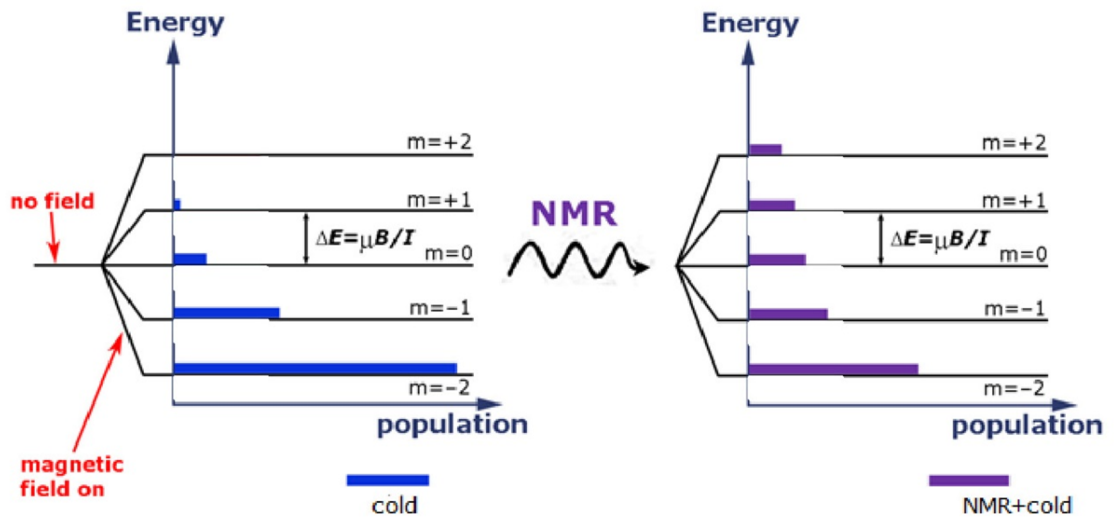
- Detectors for gamma rays and neutrons

- NMR: nuclear magnetic resonance: radiofrequency applied

Courtesy of C. Gaulard

POLAREX @ ALTO: NRM

Application of a radiofrequency



By destroying the alignment we can get the nuclear magnetic moment, provide we know the magnetic field and the temperature precisely

Courtesy of C. Gaulard

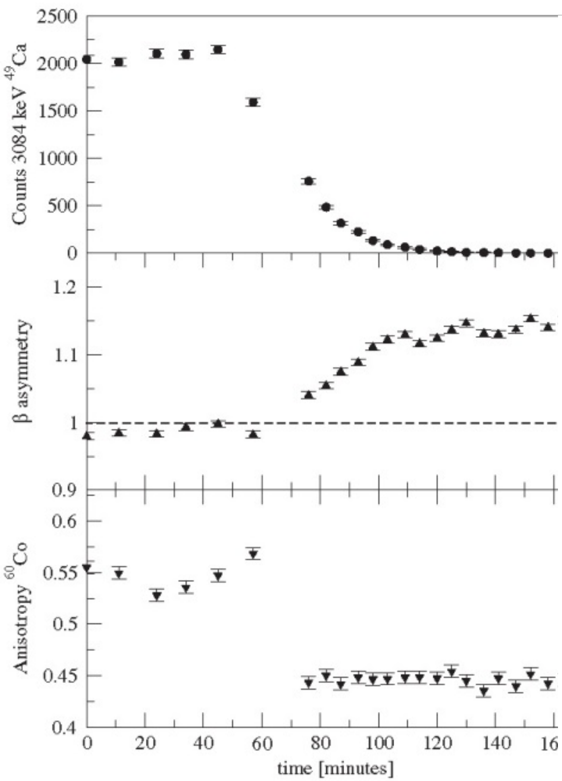
NICOLE @ ISOLDE

^{49}Sc experiment

PRL 109, 032504 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

Magnetic Dipole Moment of the Doubly-Closed-Shell Plus One Proton Nucleus ^{49}Sc

T. Ohtsubo,[1] N. J. Stone,[2,3] J. R. Stone,[2,3] I. S. Towner,[4] C. R. Bingham,[2] C. Gaulard,[5] U. Köster,[6] S. Muto,[7] J. Nikolov,[8]



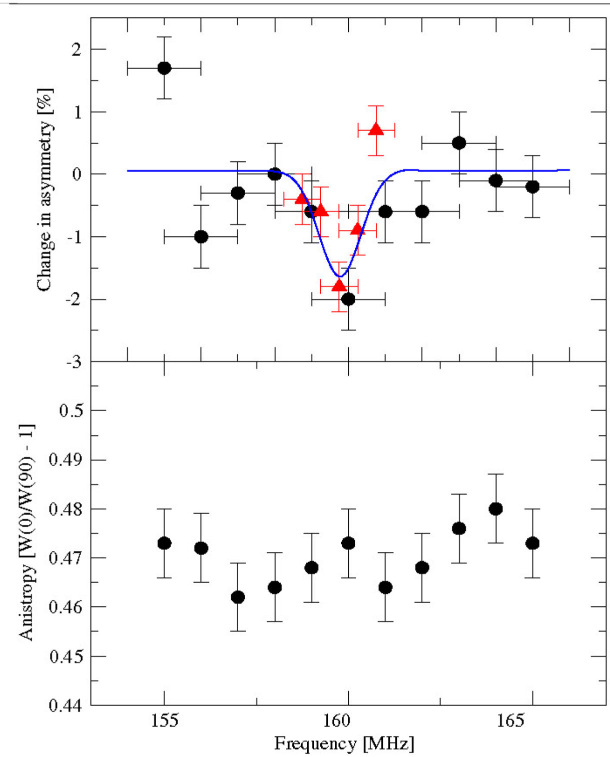


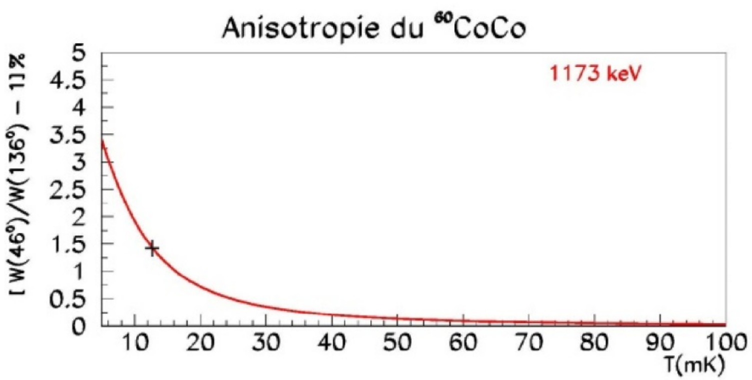
TABLE I. Magnetic dipole moments of odd-A Sc isotopes and $N = 28$ isotones.

A	Scandium Neutrons	Moment (μ_N)	Reference
^{41}Sc	0	5.431(2)	[5]
^{43}Sc	2	4.62(4)	[6]
^{45}Sc	4	4.756 487(2)	[7]
^{47}Sc	6	5.34(2)	[4]
^{49}Sc	8	5.616(25)	This work
B	$N = 28$ Protons	Moment (μ_N)	Reference
^{49}Sc	1	5.616(25)	This work
^{51}V	3	5.148 705 7(2)	[8]
^{53}Mn	5	5.024(7)	[9]
^{55}Co	7	4.822(3)	[10]

POLAREX @ ALTO: results and perspectives

- **^{60}CoCo (Done)**

  Absolute temperature ⇒ **11 mK**

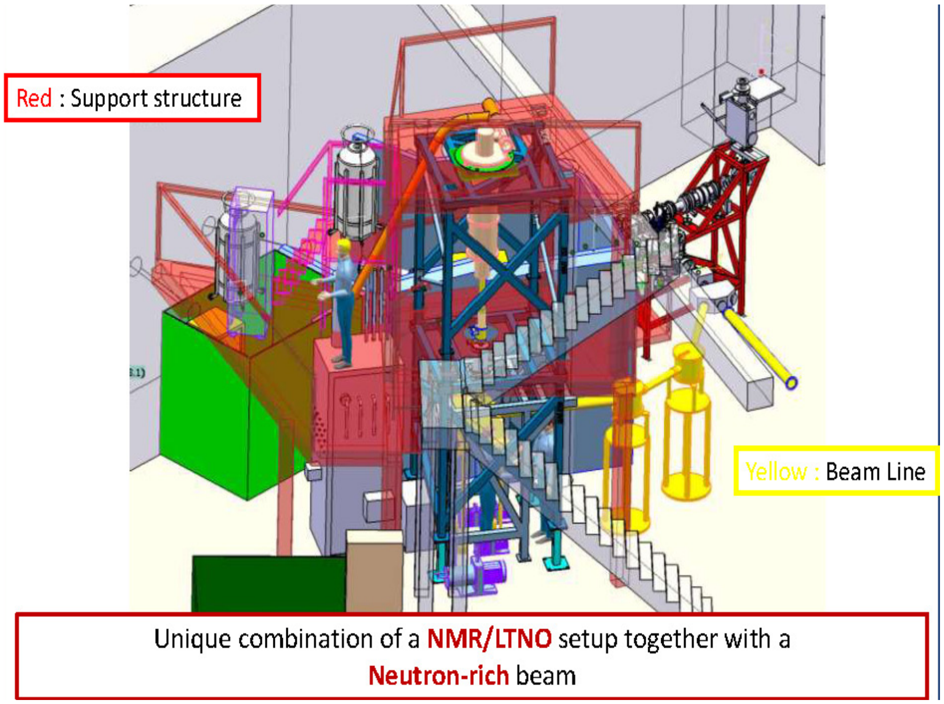


- **^{125}SbFe + ^{60}CoCo (on going)**

  Ph.D. of A. Etilé

Nuclear thermomether

POLAREX now installated at ALTO



Courtesy of C. Gaulard

POLAREX @ ALTO

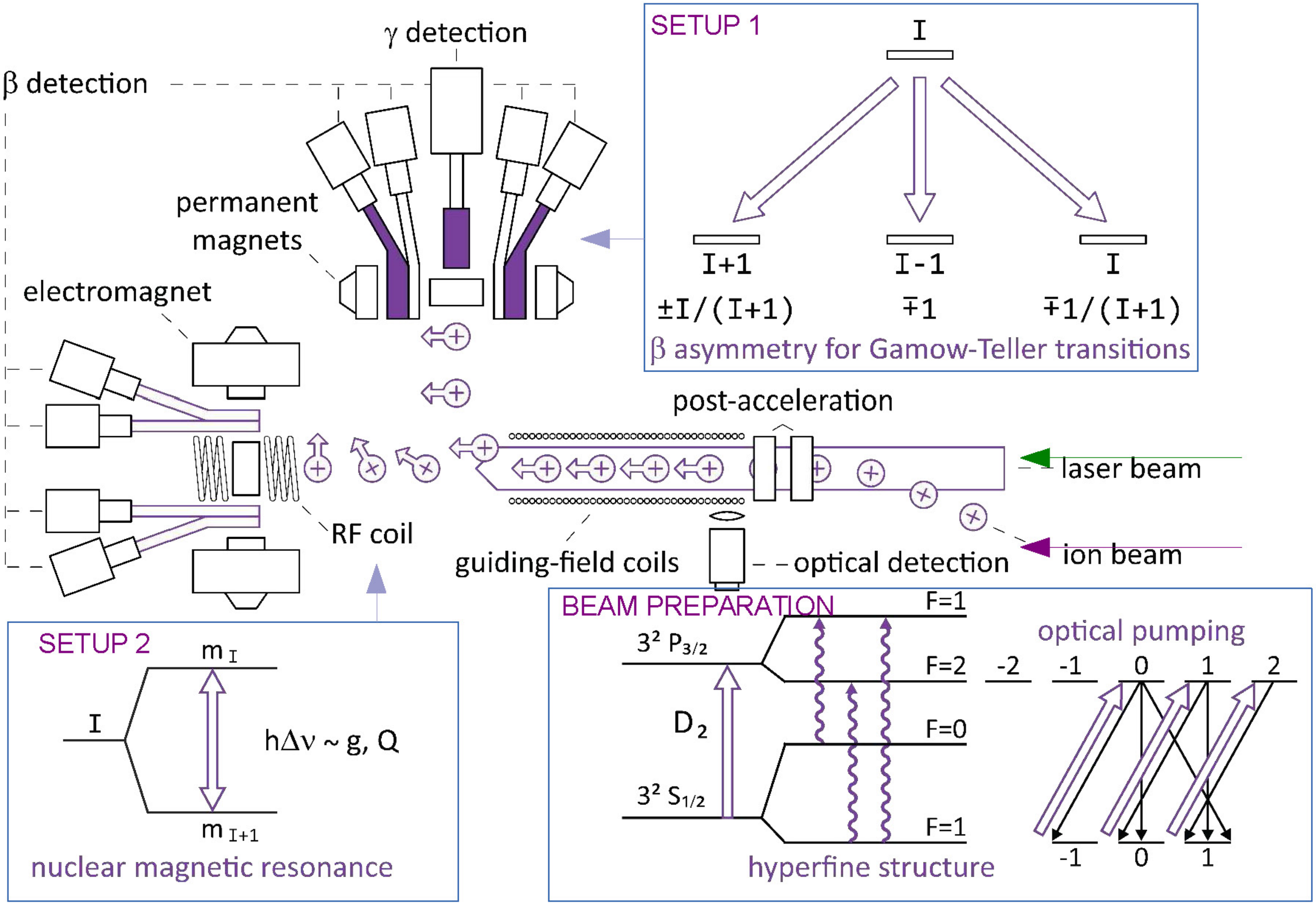
Element		Accessible A range		Number of nuclei accessible
Z	X			
5	B	10	11	2
6	C	13	13	1
8	O	15	17	2
9	F	17	19	3
10	Ne	21	21	1
13	Al	26	29	4
15	P	30	33	4
19	K	39	44	6
20	Ca	41	49	5
21	Sc	43	49	7
22	Ti	47	51	3
23	V	47	52	6
24	Cr	51	53	2
25	Mn	50	60	11
26	Fe	55	59	3
27	Co	55	66	12
28	Ni	57	67	6
29	Cu	59	73	15
30	Zn	63	71	5
31	Ga	65	75	11
32	Ge	67	77	6
33	As	67	83	17
34	Se	69	85	9
35	Br	71	89	19
36	Kr	75	89	8
37	Rb	78	89	12
38	Sr	79	95	9
39	Y	85	95	11
40	Zr	83	99	9
51	Nb	83	101	19
52	Mo	91	101	6
43	Tc	88	110	23
44	Ru	95	105	6
45	Rh	91	116	26
46	Pd	97	113	9
47	Ag	95	113	19
48	Cd	101	119	10
49	In	101	125	25
50	Sn	109	127	10
51	Sb	111	133	23
52	Te	113	133	11
53	I	110	145	36
54	Xe	115	139	13
55	Cs	114	141	28
56	Ba	129	139	6
57	La	123	149	27
58	Ce	127	145	10
59	Pr	123	155	33
60	Nd	125	157	17
61	Pm	126	163	38
62	Sm	129	157	15
63	Eu	130	165	36
64	Gd	141	159	10
65	Tb	137	171	35
66	Dy	139	173	18
68	Er	143	177	18
69	Tm	146	179	34
70	Yb	149	181	17
71	Lu	161	185	25
72	Hf	161	187	14
73	Ta	159	192	34
74	W	167	191	13
75	Re	163	195	33
76	Os	171	197	14
77	Ir	167	202	36
78	Pt	177	203	14
79	Au	175	207	33
80	Hg	181	207	14
81	Tl	183	213	31
82	Pb	189	215	14
83	Bi	188	224	37
84	Po	193	209	9
85	At	191	229	39
86	Rn	199	211	7
88	Ra	213	213	1
90	Th	225	237	7
92	U	227	243	9
94	Pu	229	247	10

Figure 2: Range of accessible nuclei in mass unit. The color code is a comparison with reference [2]: the filling in green/orange/red means that this study predicts more/equal/less accessible nuclei than the previous one. No filling indicates that this element was not studied before. The last column presents the number of accessible nuclei within the range and takes into account that even-even nuclei can not be ori-

Courtesy of PolarEx collaboration
NIM in preparation

LASER Polarization

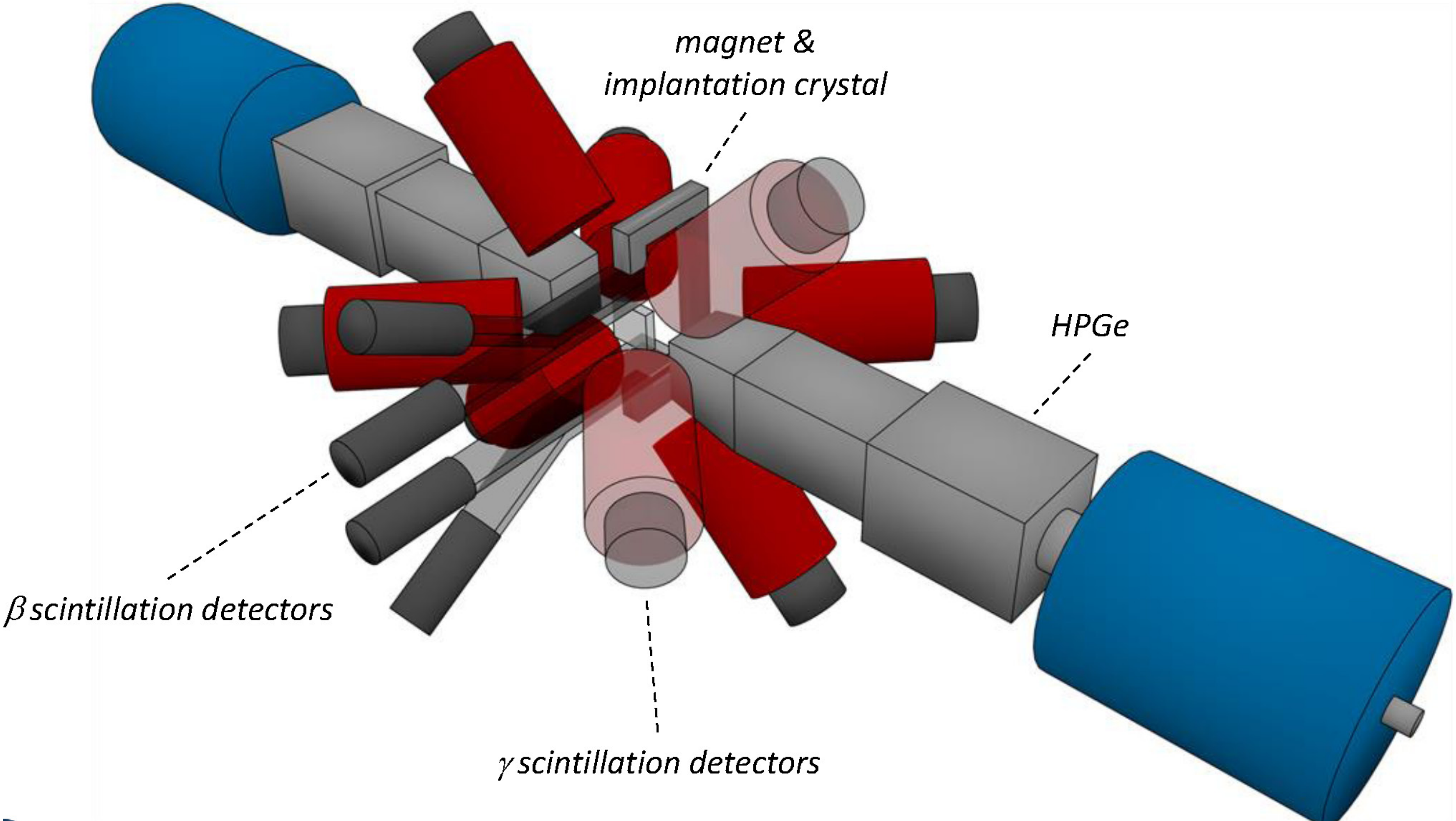
LINO: Laser-induced nuclear orientation at Orsay



Courtesy of S. Franchoo

LINO @ ALTO: decay station

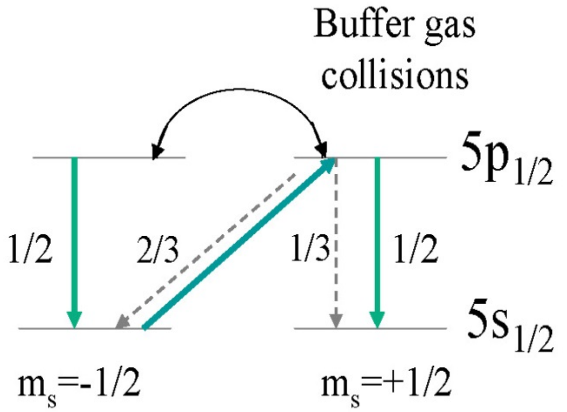
Sketch of a possible layout for β - delayed γ detection

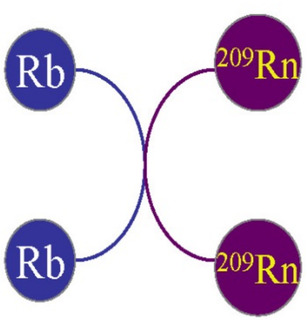


Courtesy of D. Yordanov

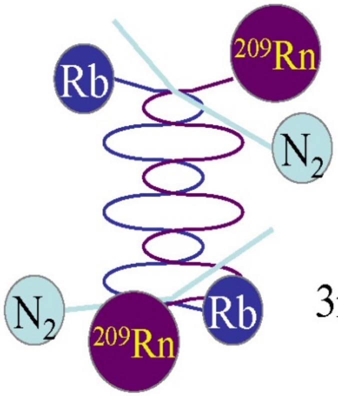
Polarizing for EDM: ^{223}Rn @ TRIUMF
Spin-Exchange Optical Pumping

- Optically pump the Rb with circularly polarized laser light.
- Spin-exchange collisions transfer the polarization to the radon nuclei.





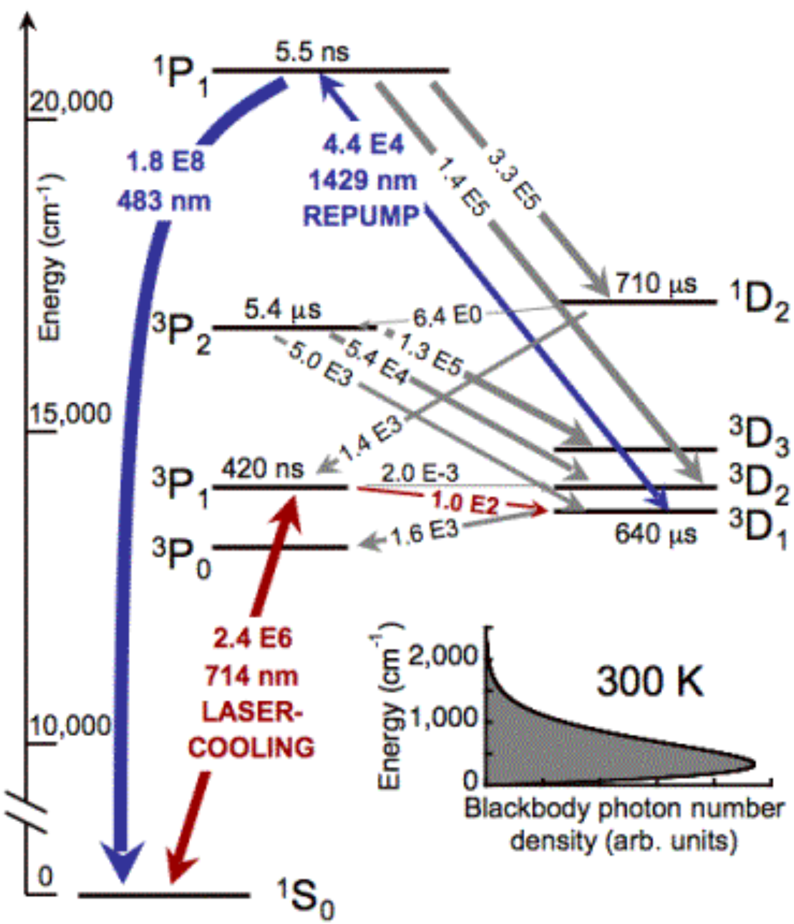
Binary Collision:
$\tau \sim 10^{-12}$ sec.



van Der Waals Molecule:
τ is dependent on 3rd body (N_2) pressure.

Polarizing for EDM: ^{225}Ra @ Argonne

Optical pumping with circularly-polarized light



Polarizing for EDM: ^{229}Pa

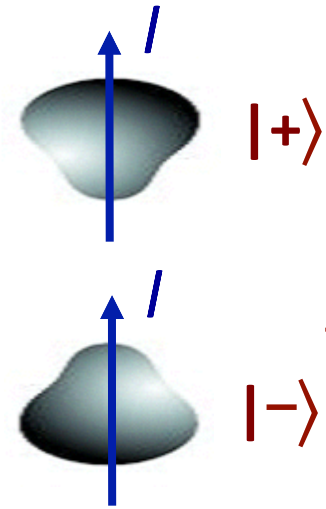
- OLNO seems possible in a PolarEx-like setup
  1. Degree of polarization achievable
  2. Mechanical compatibility
  3. Imprecision with anisotropy measurment

- Laser ionization: information on atomic transitions not sufficient to exclude, but likely poor/impossible
  1. Pa is heavy which is bad for the implantation depth if done at keV energies)
  2. Atomic/ionic ground state spin must be low
  3. Atomic transitions need to be quite strong (information missing)

- Scattering on a polarized element (like Rn): chemical reactivity ?

But…

Octupole Enhancement



$$\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$$

ΔE

$$\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$$

$\not{P}, \not{T}$ ⇒

$$\Psi^+ = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$$

$$\Psi^- = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$$

$$\alpha = \frac{\langle \Psi^- | V^{PT} | \Psi^+ \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

$S_{intr} \sim eZA\beta_2\beta_3$ $S_{lab} \sim e\,Z\,A^{2/3}\,\beta_2\,\beta_3^{\,2}/\Delta E$ $\beta_2, \beta_3 \sim 0.1$

Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel; Dobaczewski & Engel

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
Δe_{th} (keV)	37	170	47	75	49	5		
ΔE_{exp} (keV)	--	50.2	55.2	160.5	40.1	0.22		
10^5 S ($e$fm^3)	1000	400	300	500	900	**12000**	-1.4	1.75
10^{28} d_A (e cm)	**2000**	**2700**	**2100**	**2800**			-5.6	0.8

Polarizing for EDM: neutrons @ SNS Oak-Ridge

1. Load collection volume with polarized ^3He atoms
2. Transfer polarized ^3He atoms into the measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced polarization ^3He atoms from measurement cell
7. Go to 1.