Third International SPES Workshop

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Laboratori Nazionali di Legnaro (Padova), Italy

Survey of the main experimental setups for low energy ISOL physics

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CENBG

CENTRE D'ETUDES NUCLEAIRES DE BORDEAUX GRADIGNAN

cnrs IN2P3 Les deux infinis

Survey of the main experimental setups for low energy ISOL physics

1. Beta decay spectroscopy
   - general motivations
   - experimental requirements
   - examples

2. Laser assisted spectroscopy
   - general motivations
   - experimental requirements
   - examples

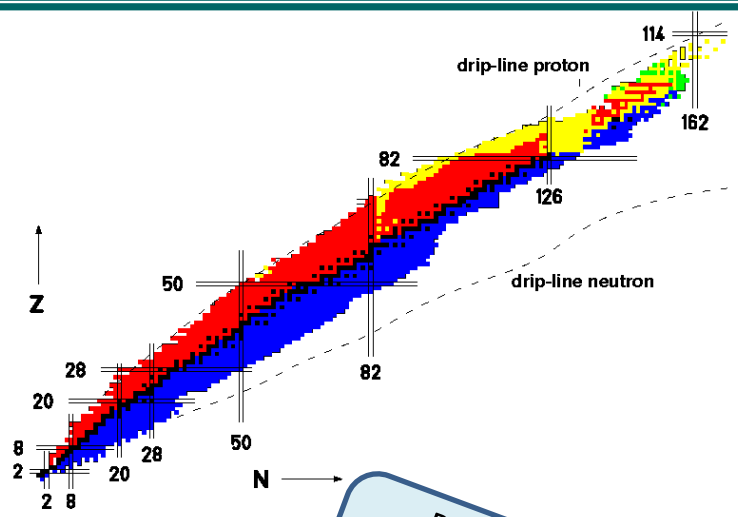
3. Trap assisted spectroscopy
   - general motivations
   - experimental requirements
   - examples

Survey of the main experimental setups for low energy ISOL physics

1. Beta decay spectroscopy
   - general motivations
   - experimental requirements
   - examples

1- Beta decay studies : general motivations

- most of the nuclei decay by β^+ or β^-
  - ~260 stable
  - ~3000 → 6000 β-decay
  - ~100 fission



- often the primary source of information about newly identified nucleus
  - $T_{1/2}$, P_n, Q_β value → few decays per day
  - Spin, excited states → few decays per second
  - Full spectroscopy → 100/1000 decays per second

Relatively simple measurements but giving important clues about the nuclear structure

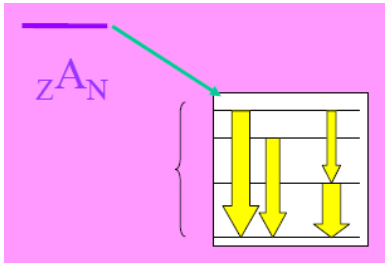
- understanding of the creation of the heaviest elements in explosive stellar processes

- study of fundamental interactions

- important for applications
  - for nuclear reactors : 7-8% of the heat is generated by radioactive decay of fission products

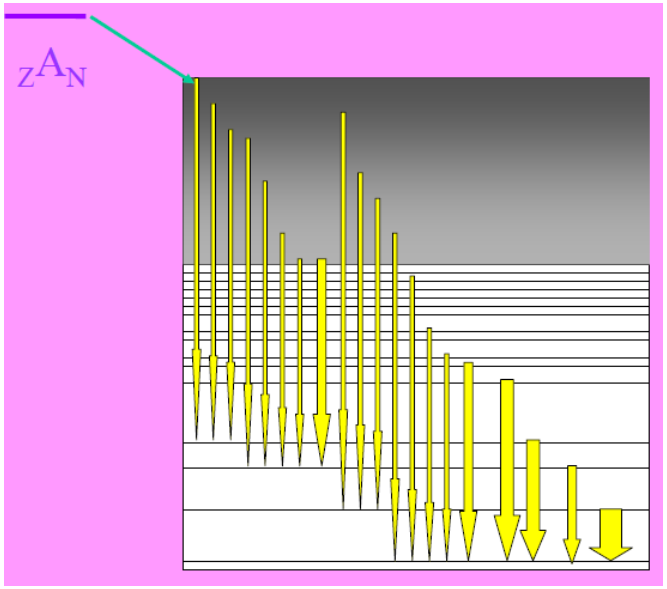
Beta decay pattern

Near the stability → small Q_β-values → decay schemes simple, few states are populated



→ experiments are "easy"

In exotic nuclei → large Q_β-values → wider range of states can be populated
→ can access to a "large" fraction of the GT strength



→ constraints on the detection system

→ need for complementary and sophisticated experimental setups

Detectors

Spectroscopy of low lying discrete states :

- charged particles (β's, e^-, p…)
  → PI; Si
- γ-rays
  → Ge array for energy resolution
  → Fast scintillators for timing properties
- delayed neutrons
  → ^{3}He counters, Liquid scintillators, Plastics…

Measurement of the GT strength :

- Total Absorption Spectrometer
  → use of large scintillator crystals viewed by PM's

Ancillary systems

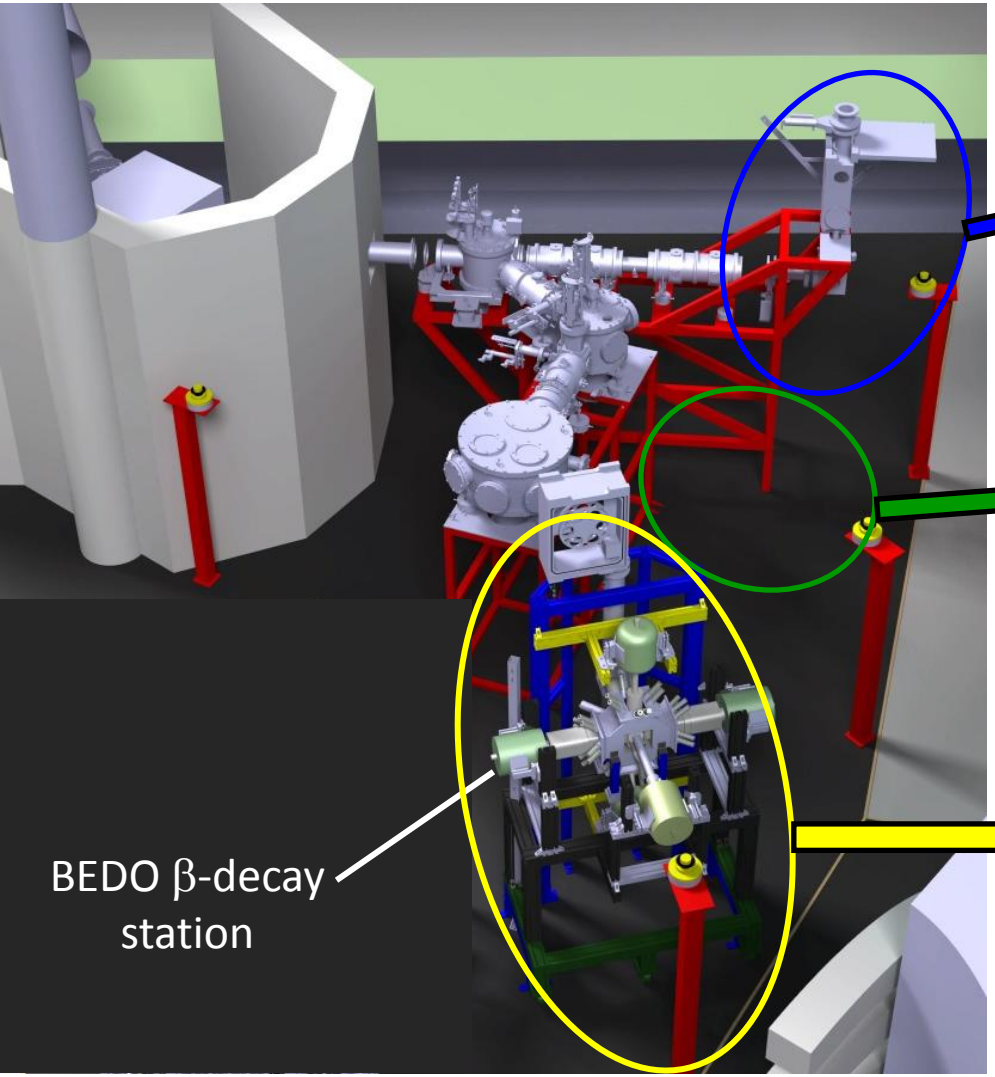
- Fast tape system
  → measurement of $T_{1/2}$
  → removal of daughter activities
- Purification devices
  → magnetic separators (HRS), Penning traps, MR-TOF-MS

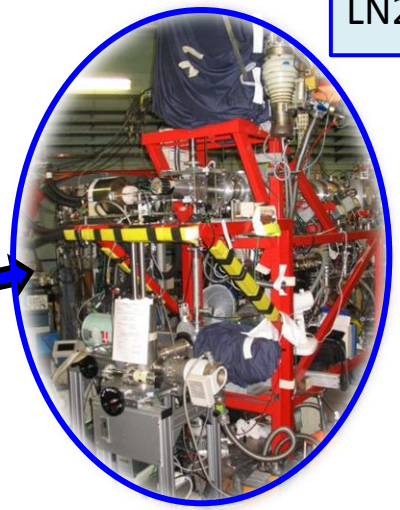
BEDO/TETRA setups @ ALTO/IPN Orsay

↳ ISOL installation based on photofission

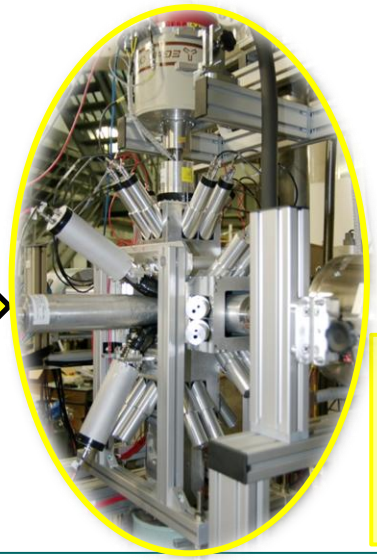
→ 10^{11} fission/sec in the target

Identification Station
β-delayed CE and γ
LN2-cooled SiLi detector





TETRA n-detector
3He counters



BEDO β-decay station
2 CLOVERS
2 coax
1 big LaBr3

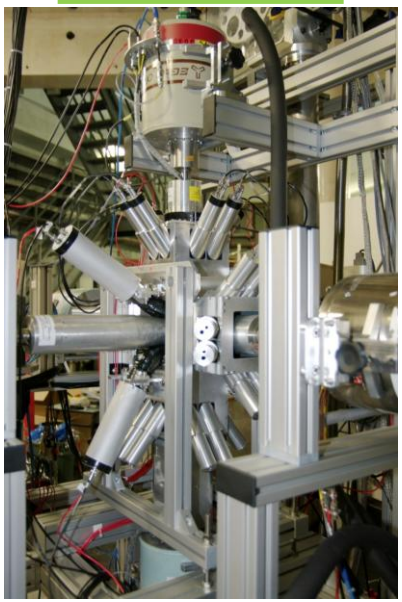
BEDO/TETRA setups @ ALTO/IPN Orsay

courtesy of D. Verney

↳ ISOL installation based on photo fission

→ 10^{11} fission/sec in the target

BEDO setup in gamma mode
4 small EXOGAM clovers

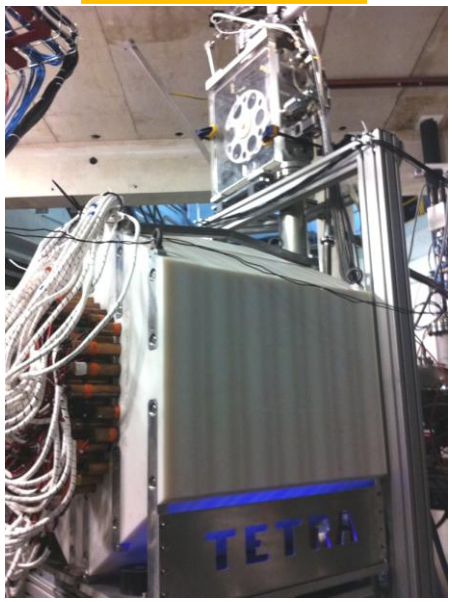


IPN, coll. CSNSM, IPHC

PhD: A. Etilé (CSNSM)

PRC 91, 064317 (2015)

BEDO setup in neutron mode
Dubna neutron detector TETRA

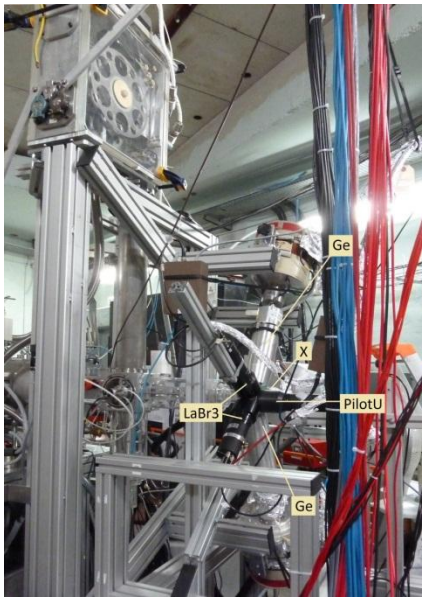


IPN, coll. JINR (Russia), IPHC

PhD: D. Testov (IPN)

NIM A815, 96 (2016)

BEDO setup fast timing mode
LaBr3



IPN, coll. CSNSM, TANDAR (Argentina), INRNE (Bulgaria)

M.A.Cardona, D.Hojman, B.Roussière, I.Deloncle et al.

to be submitted

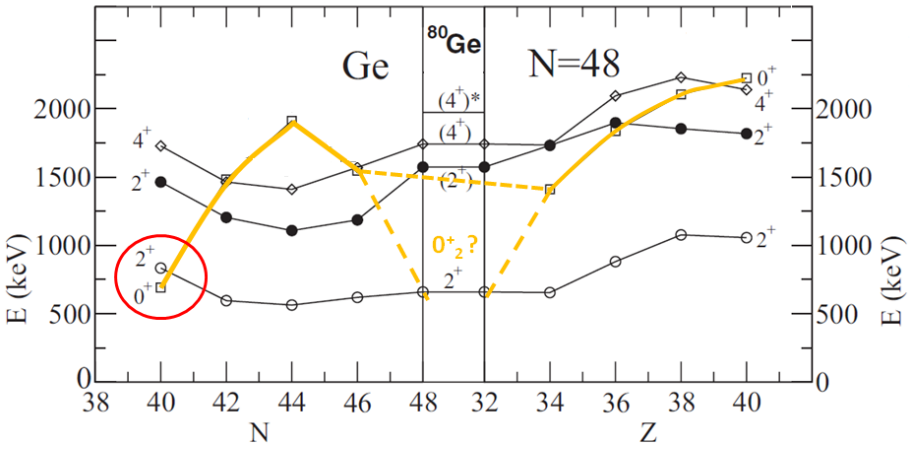
1- Beta decay studies : recent results

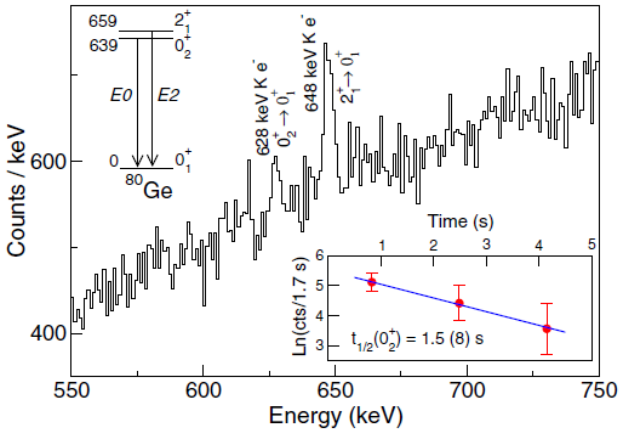
PRL 116, 182501 (2016) PHYSICAL REVIEW LETTERS week ending 6 MAY 2016

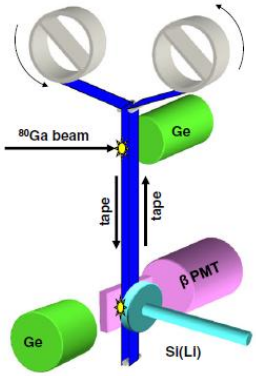
First Evidence of Shape Coexistence in the ^{78}Ni Region: Intruder 0_2^+ State in ^{80}Ge

A. Gottardo *et al*, ALTO

Verney et al. PRC **87** 054307 (2013)



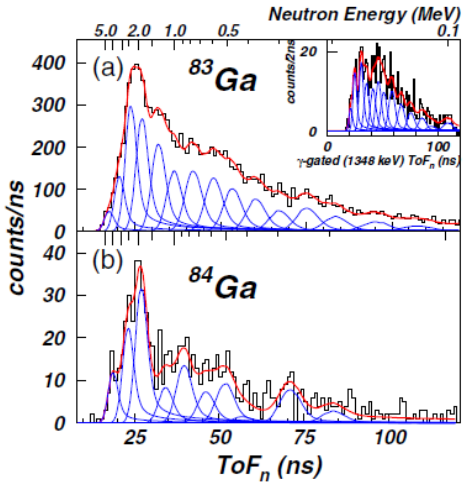


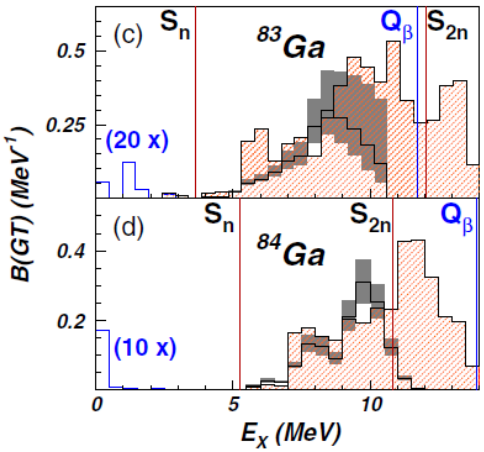


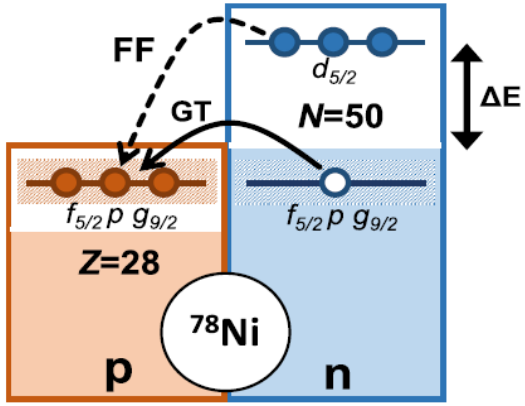
PRL 117, 092502 (2016) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2016

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

M. Madurga *et al*, Oak-Ridge U. of Tennessee







1- Beta decay studies : LoI's@SPES

LoIs Presentation 1

Convener: Giovanni Pollarolo (University of Torino)

17:00 **Studies of pair transfer processes with the SPES beams PRISMA** *13'*
Speaker: Lorenzo Corradi (INFN LNL)

17:13 **Sub-barrier fusion of exotic neutron-rich nuclei** *13'*
Speaker: Alberto Stefanini (INFN LNL)

17:26 **Pre-equilibrium processes and exotic systems as a tool to study clustering structure effects on nuclear dynamics** *13'*
Speaker: Tommaso Marchi (KU Leuven)

17:39 **Study of the population of heavy neutron-rich nuclei in the A~200 mass region via multinucleon transfer reactions** *13'*
Speaker: Enrico Fioretto (INFN LNL)

17:52 **Neutron-rich heavy nuclei explored via multinucleon transfers** *13'*
Speaker: Dr. Suzana Szilner (Ruder Boskovic Institute)

18:05 **Dissipative collisions with n-rich SPES beams** *13'*
Speaker: Giovanni Casini (INFN Firenze)

18:18 **Transfer studies in neutron-deficient nuclei with the neutron detector array NEDA** *13'*
Speaker: Jose' Javier Valiente Dobon (INFN LNL)

18:31 **Electromagnetic moment measurements with radioactive ion beams using GALILEO Gamma-ray array** *13'*
Speaker: Asli Kusoglu (Istanbul University)

09:00 **Compound Nucleus Decay with light beams provided by SPES** *13'*
Speaker: Mauro Bruno (Bologna University)

09:13 **A Dedicated Gas Jet Target for Radioactive Ion Beam Studies at SPES** *13'*
Speaker: Steven Pain (Oak Ridge National Laboratory)

09:26 **Measurement of the decay characteristics of nuclei around A=90 relevant to the r-process nucleosynthesis** *13'*
Speaker: Teresa Kurtukian Nieto (CENBG)

09:39 **Isospin dependence of compound nucleus formation and decay** *13'*
Speaker: Giuseppe Politi (Catania University)

09:52 **Study of proton-neutron balance of quadrupole-collective states of even-even neutron rich Te, Xe and Ba isotopes** *13'*
Speaker: Christian Stahl (IKP, TU Darmstadt)

10:05 **Nuclear structure of neutron-rich nuclei determined through beta decay spectroscopy of fission fragments** *13'*
Speaker: K.P. Rykaczewski (Oak Ridge National Laboratory)

10:18 **Shape coexistence in Kr isotopes towards N = 60** *13'*
Speaker: Victor Modamio Hoybjor (Oslo University)

10:31 **Set-up for Coulomb-excitation measurements of Radioactive Ions** *13'*
Speaker: Adriana Nannini (INFN Firenze)

10:44 **Low-lying dipole excitations via nuclear probes in exotic nuclei** *13'*
Speaker: Fabio Celso Luigi Crespi (Milano University)

10:57 **Pygmy Dipole States in Neutron-rich Zr and Kr Isotopes Investigated with Beta Decay** *13'*
Speaker: Fabio Celso Luigi Crespi (Milano University)

11:10 **Dynamical Dipole Resonance with SPES** *13'*
Speaker: Silvia Piantelli (INFN Firenze)

11:40 **Measurement of astrophysical relevant reactions induced by alpha, protons and neutrons at the Gamow peak using the Trojan Horse method** *13'*
Speaker: Sara Palmerini (Perugia University)

11:53 **Shape coexistence and N=50 gap: transfer reactions on ground and isomeric states** *13'*
Speaker: Andrea Gottardo (IPN-Orsay/IN2P3)

12:06 **Shell structure and collective excitations and resonances at and beyond N=50 with decay spectroscopy** *13'*
Speaker: Andrea Gottardo (IPN-Orsay/IN2P3)

LoIs Presentation 4

Convener: Krzysztof Rusek (University of Warsaw)

14:40 **Search for deformed structures in 96Y and 97Y by gamma spectroscopy andcluster transfer reactions with a 95Sr SPES beam** *13'*
Speaker: Lukasz Iskra (Institute of Nuclear Physics PAN)

14:53 **Search for structures built on the isomeric 0+ state in 96Sr** *13'*
Speaker: Silvia Leoni (Milano University)

15:06 **Structure of Sb nuclei around 132Sn as a testing ground for realistic shell model interactions** *13'*
Speaker: Silvia Leoni (Milano University)

15:19 **Heavy-ion binary reactions as a tool for detailed gamma spectroscopy in exotic regions** *13'*
Speaker: Silvia Leoni (Milano University)

15:32 **Exploring shape coexistence, triaxiality and configuration mixing in 90,92Kr** *13'*
Speaker: Katarzyna Hadynska-Klek (INFN LNL)

15:45 **Study of beta-decay properties of neutron-rich isotopes approaching the r-process path** *13'*
Speaker: Dmitry Testov (Padova University)

15:58 **Study of the Dynamical Dipole mode with the SPES radioactive ion beams** *13'*
Speaker: Concetta Parascandolo (INFN Napoli)

16:11 **Electron conversion measurements at SPES 1+ beam line: measurement of E0 transitions in 96Sr** *13'*
Speaker: Barbara Melon (INFN Firenze)

16:44 **Measurements at SPES on beta-decay properties of nuclei belonging to the s-process path** *13'*
Speaker: S. Cristallo (INAF)

16:57 **Exploring the Z=32 triaxiality corridor towards N=50 via safe Coulomb excitation at SPES** *13'*
Speaker: Magda Zielinska (CEA Saclay)

17:10 **Study of the shell structure and order-to-chaos transition in warm rotating nuclei with the radioactive beams of SPES** *13'*
Speaker: Giovanna Benzoni (INFN Milano)

17:23 **Beta-decay studies at SPES** *13'*
Speaker: Giovanna Benzoni (INFN Milano)

17:36 **Probing the Island of Stability with SPES beams** *13'*
Speaker: Emanuele Vardaci (Napoli University)

17:49 **Studies of Proton-Rich Nuclei Using Fusion-Evaporation Reactions with 7Be Beams and NEDA** *13'*
Speaker: Johan Nyberg (Uppsala University)

18:02 **Collectivity vs spin using direct reactions** *13'*
Speaker: Francesco Recchia (Padova University)

18:15 **Shell structure in the vicinity of 132Sn with an active target** *13'*
Speaker: Tommaso Marchi (KU Leuven)

12:19 **Coulomb-excitation measurements in nuclei around 132Sn** *13'*
Speaker: Marco Rocchini (INFN Firenze)

12:32 **Direct Reactions at SPES: Shell Evolution and Nuclear Astrophysics around Z~50 and N~82** *13'*
Speaker: Daniele Mengoni (Padova University)

12:45 **Transfer reaction measurements at SPES for r-process nucleosynthesis** *13'*
Speaker: Steven Pain (Oak Ridge National Laboratory)

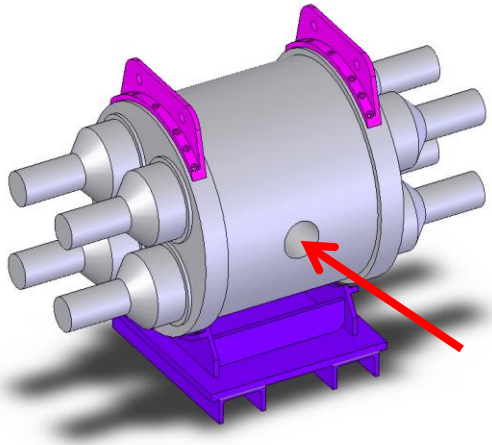
12:58 **Measurements at SPES of n-capture cross sections on radioactive nuclei interesting for s-process nucleosynthesis** *13'*
Speaker: Oscar Trippella (Perugia University)

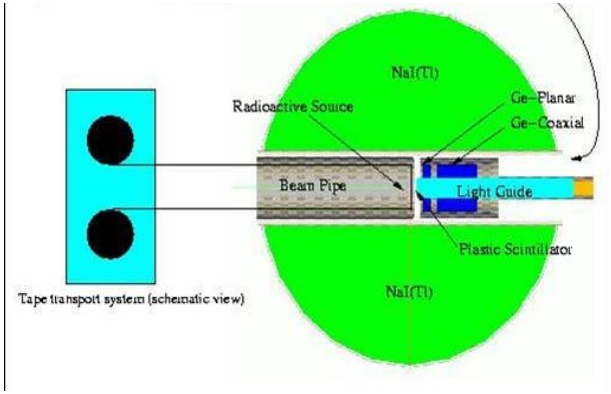
TAS setup Lucrecia @ ISOLDE/CERN

courtesy of B. Rubio

Lucrecia at ISOLDE/CERN

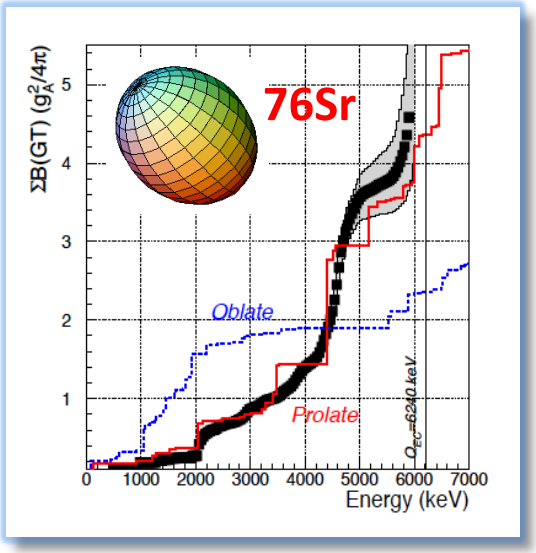
collaboration : Valencia-Surrey-Strasbourg



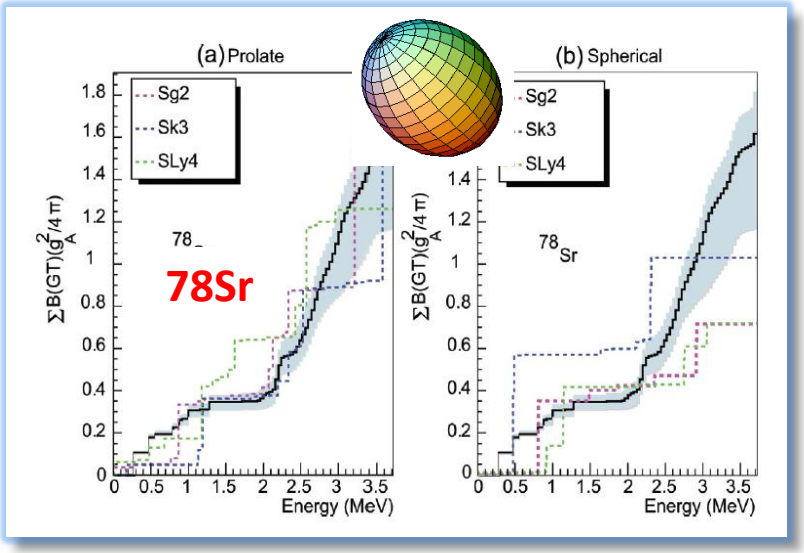


NaI single-crystal Φ38cm x 38cm
(+ ancillary detectors)Ge for X-rays
and plastic for β particles

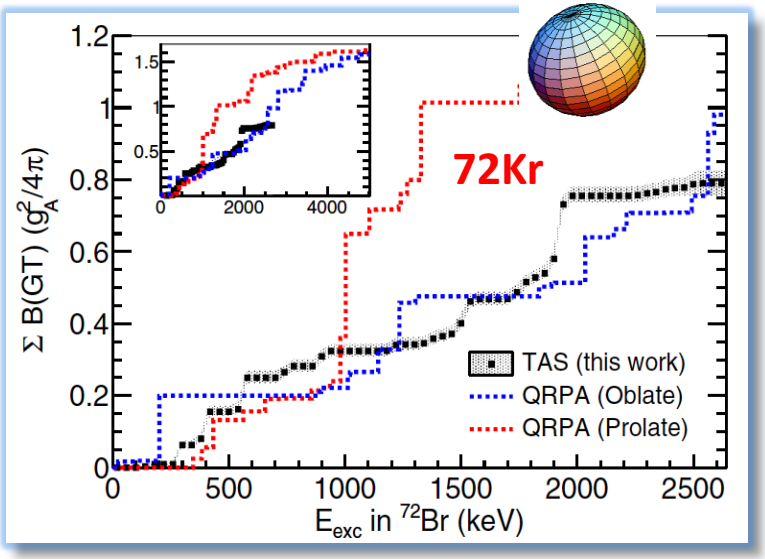
TAS setup Lucrecia @ ISOLDE/CERN



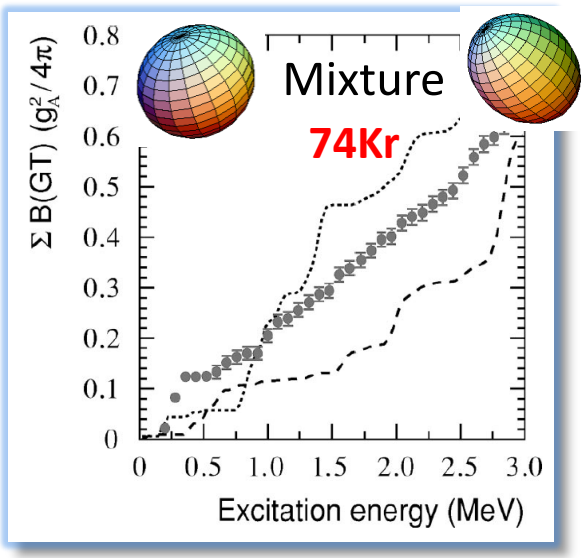
E. Nacher *et al., PRL.92, 232501 (2004)*



A. Pérez-Cerdán et al. PRC88 (2013) 014324



J. Briz et al, PRC 92(2016) 054326

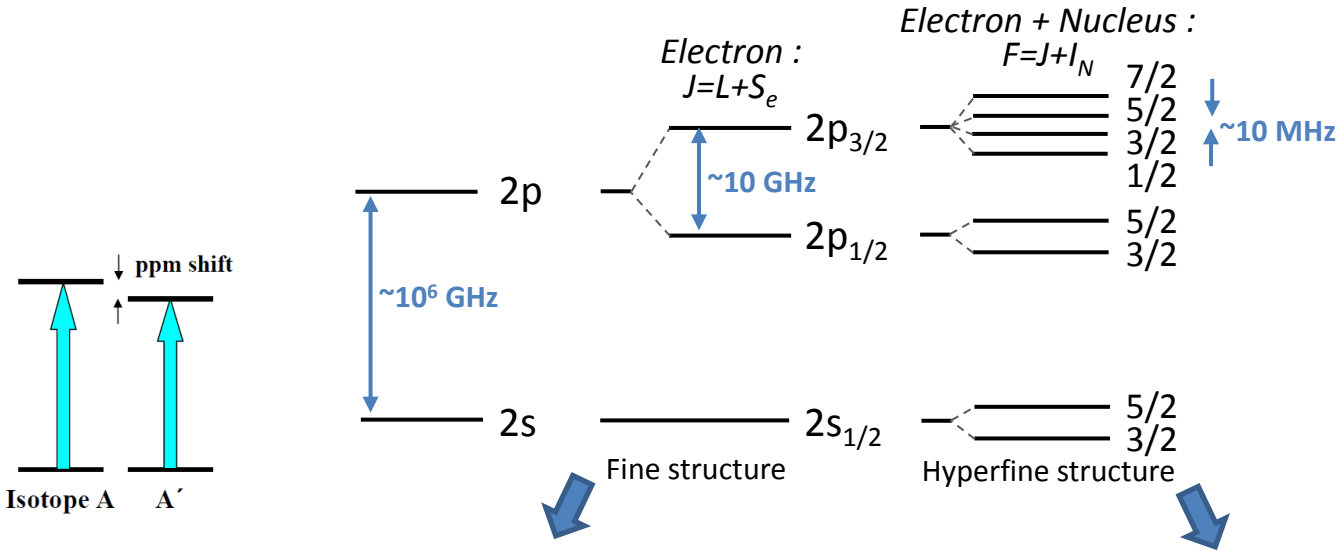


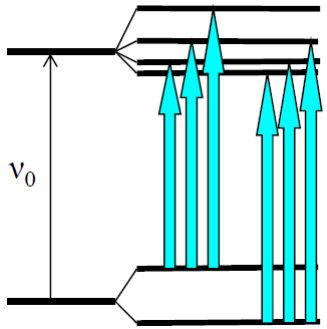
E. Poirier *et al., PRC 69, 034307 (2004)*

Survey of the main experimental setups for low energy ISOL physics

2. Laser assisted spectroscopy
   - general motivations
   - experimental requirements
   - examples

Laser spectroscopy allows to determine fundamental properties of nuclei (gs or long lived isomers) from the knowledge of the energy of the atomic levels.





Isotope shift of an atomic transition

→ yields the *change in* nuclear mean square charge radius

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

Hyperfine factors

→ give access to the nuclear spin I, magnetic (μ) and quadrupole (Q) moments

$$\Delta E_{hfs} = \frac{1}{2} A_{hfs} K + B_{hfs} \frac{\frac{3}{2}K(K+1) - 2I_N(I_N+1)J(J+1)}{2I_N(2I_N-1)2J(2J-1)}$$

$$A_{hfs} = \frac{\mu_I \langle H_e(0) \rangle}{IJ}$$

$$B_{hfs} = eQ\langle V_{zz}(0) \rangle$$

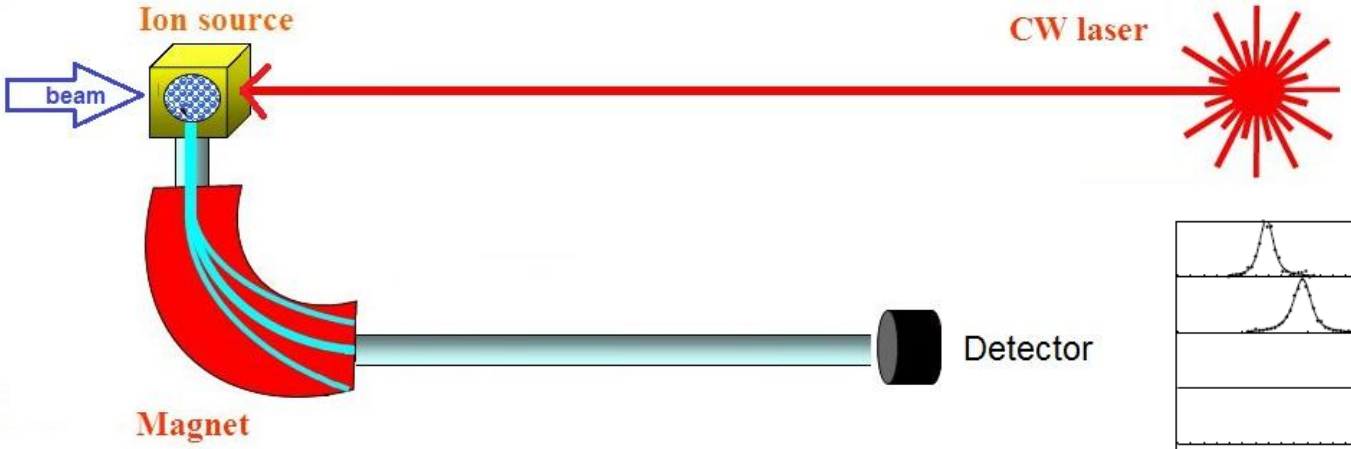
nuclear shape/deformation in ground and isomeric states

NB: the laser spectroscopy methods are well suited for nuclear states with $T_{1/2}$ in the range of msec to sec

→ particularly well suited for ISOL facilities

Two main laser spectroscopy methods :

- In source laser spectroscopy

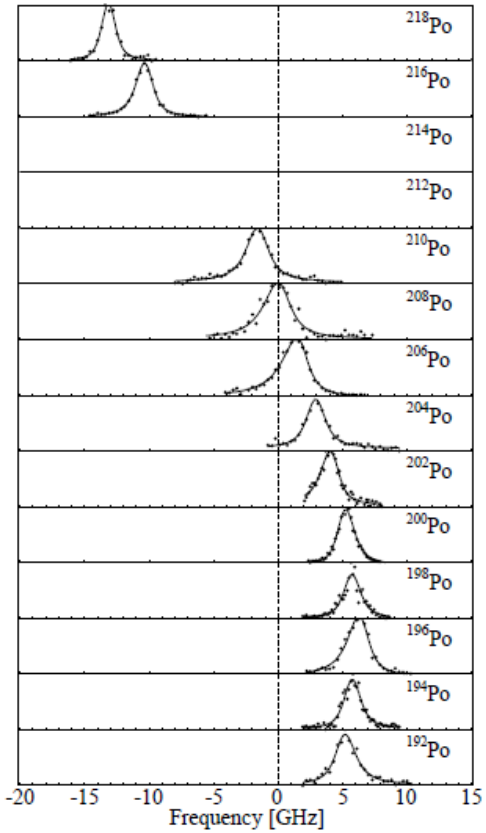


Gaussian velocity distribution
Laser Spread
} resolution ~GHz

→ isotope shifs measurements

→ beam purification (Z selection)

→ isomeric beam production

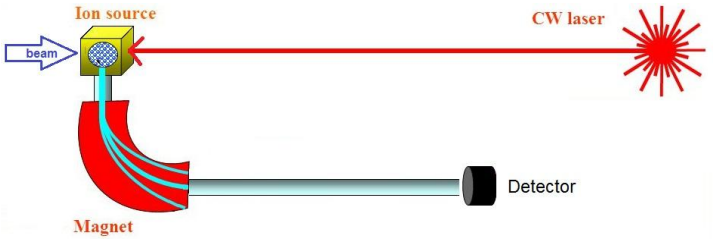


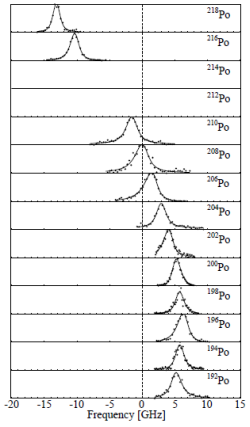
T. Cocolios et al.

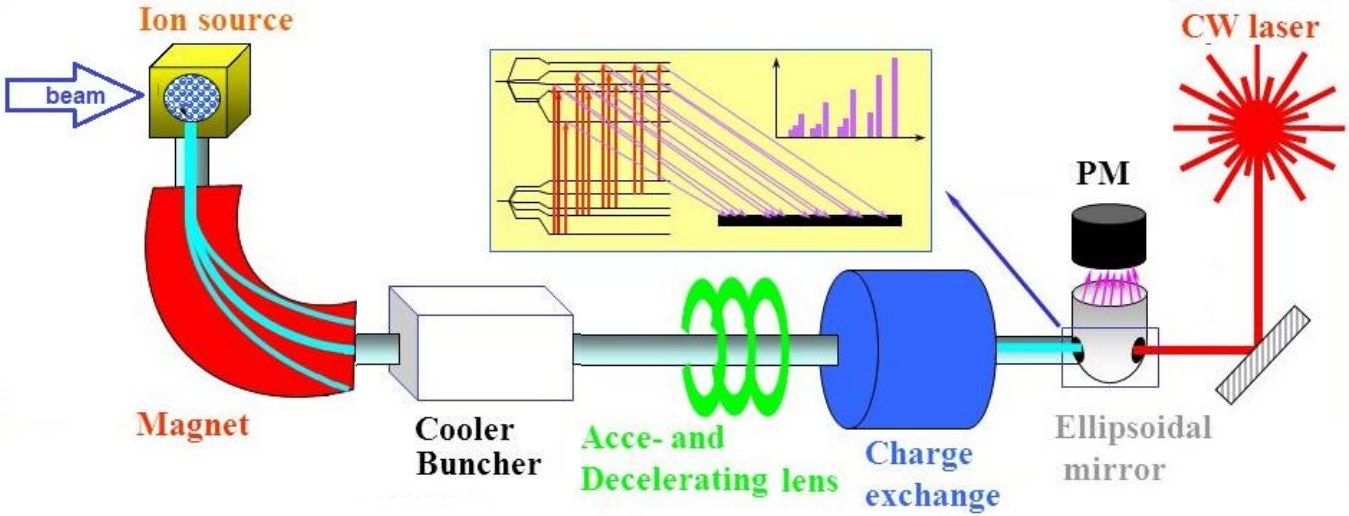
Development of the "in jet laser spectroscopy" , resolution around 150 MHz (S3-LEB)

Two main laser spectroscopy methods :

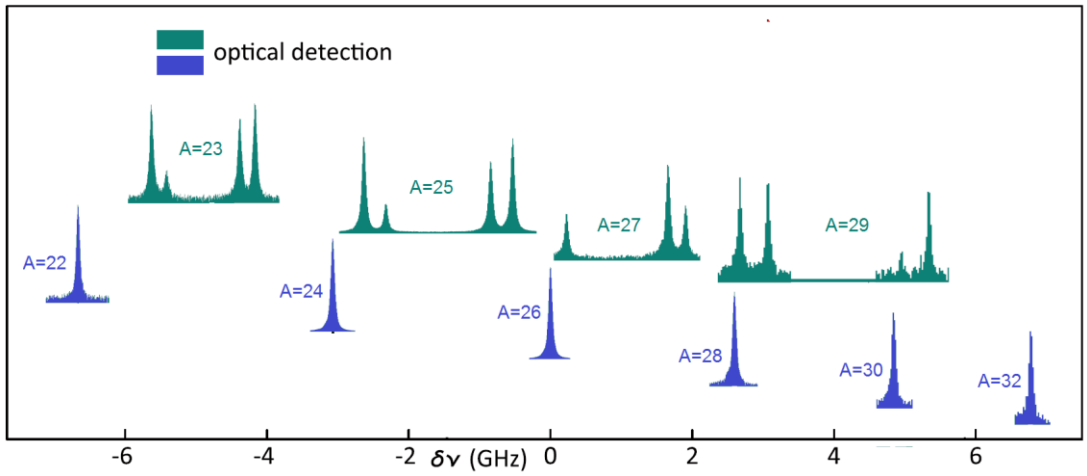
- In source laser spectroscopy
- Collinear laser spectroscopy







Spectral lines of Mg isotopes (A=22 to 32)

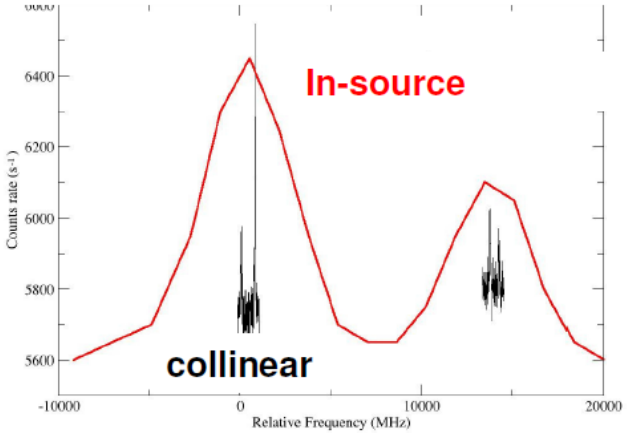


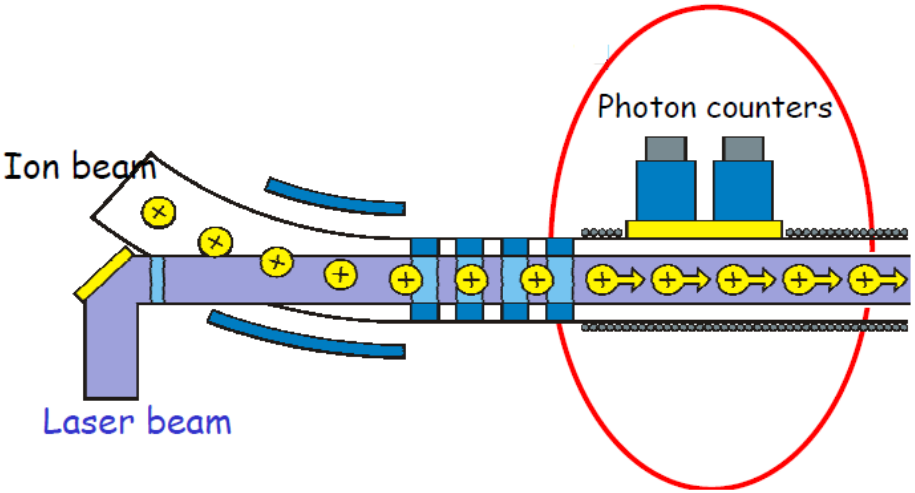
COLLAPS set-up at ISOLDE:

- collinear laser spectroscopy **with optical detection**

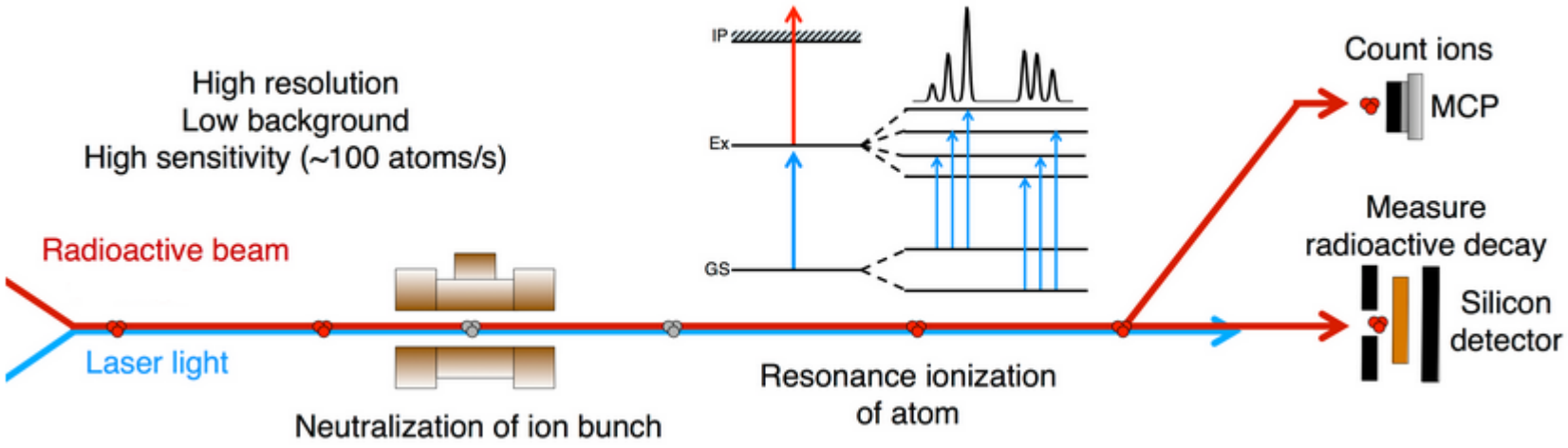
→ spin, magnetic moment, quadrupole moment, charge radii

Advantages: high resolution, no upper limit on lifetime
Disadvantage: need 10^{6-7} ions/μC





Collinear Resonance Ionization Spectroscopy



COLLAPS set-up at ISOLDE:

- collinear laser spectroscopy **with β-asymmetry detection**

on an optically polarized radioactive beam ($t_{1/2}$ < few s)

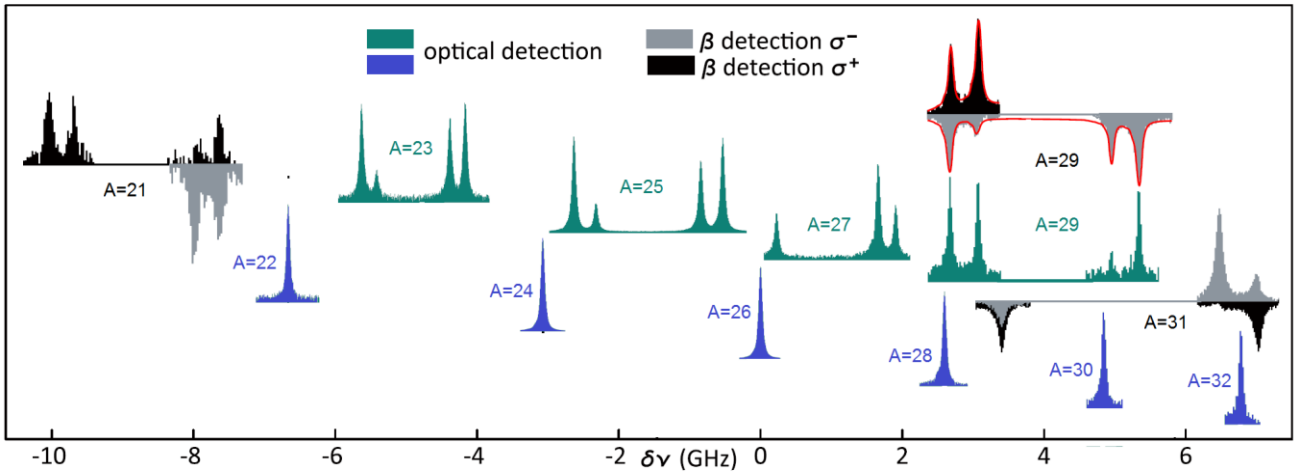
→ spin, magnetic moment, quadrupole moment

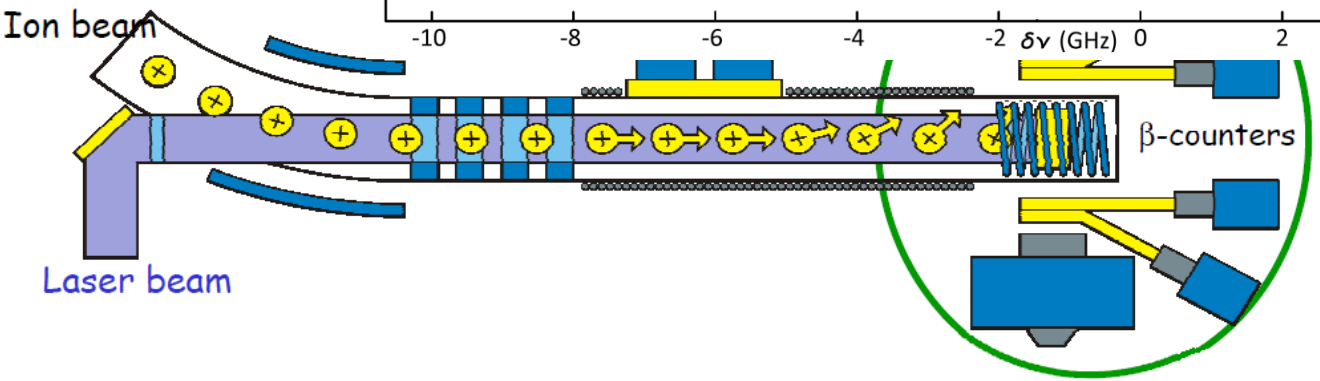
→ understand line shapes to extract charge radii !!

Advantages: need only few 10^3 ions/μC!

Disadvantage: upper lifetime limit (~ few seconds)

Spectral lines of Mg isotopes (A=22 to 32)





COLLAPS set-up at ISOLDE:

- β-nuclear magnetic resonance **with β-asymmetry detection**

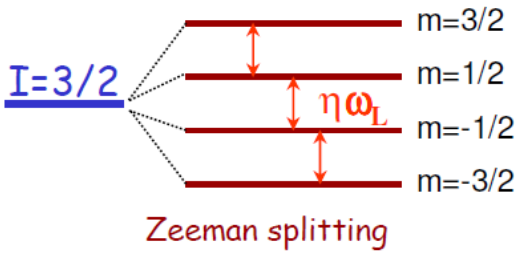
on an optically polarized radioactive beam ($t_{1/2}$ < few s)

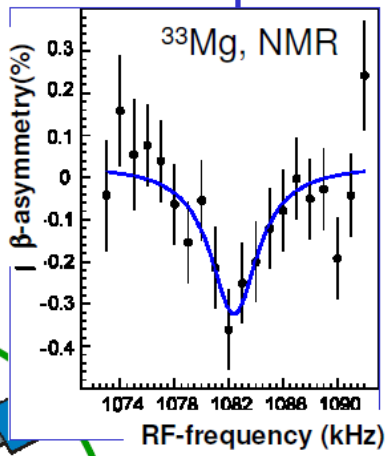
→ implanted in a crystal, immersed in a magnetic field

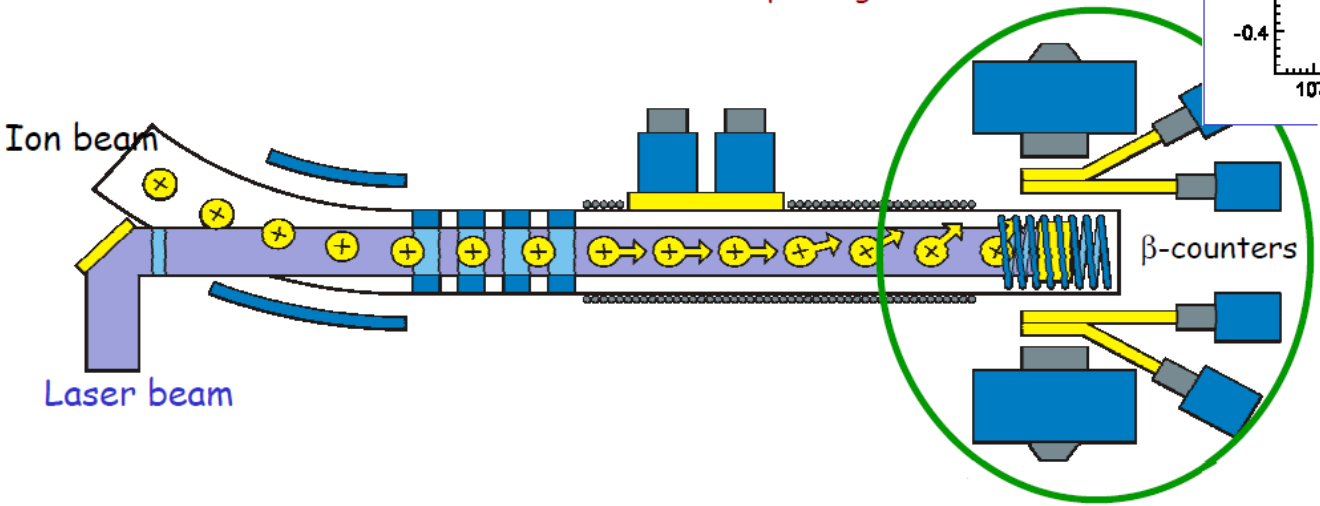
g-factor, quadrupole moment

Advantages: need only few 10^3 ions/μC, very high precision (< 10^{-3}) !

Disadvantage: upper lifetime limit (~ few seconds)







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ARTICLES
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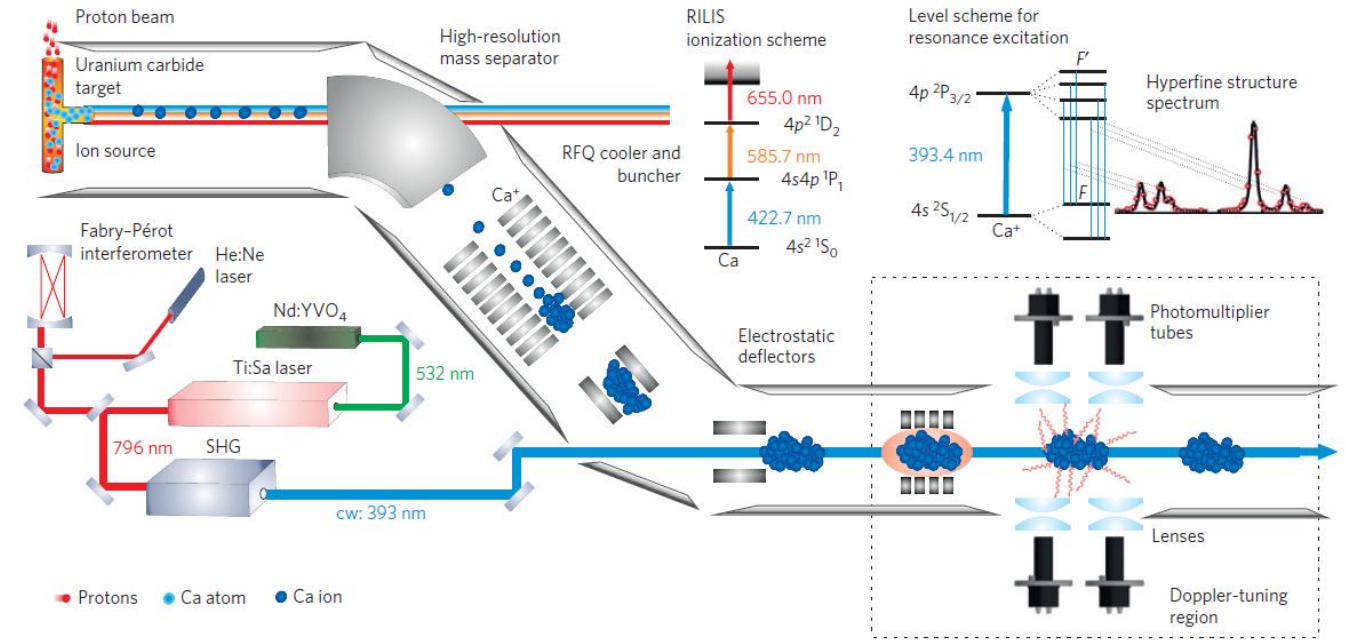
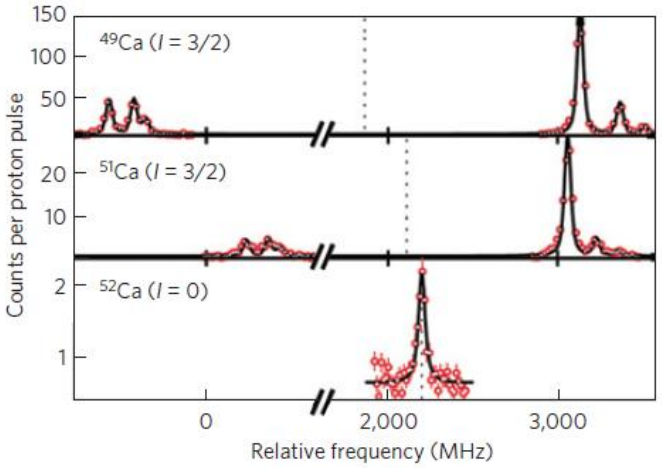
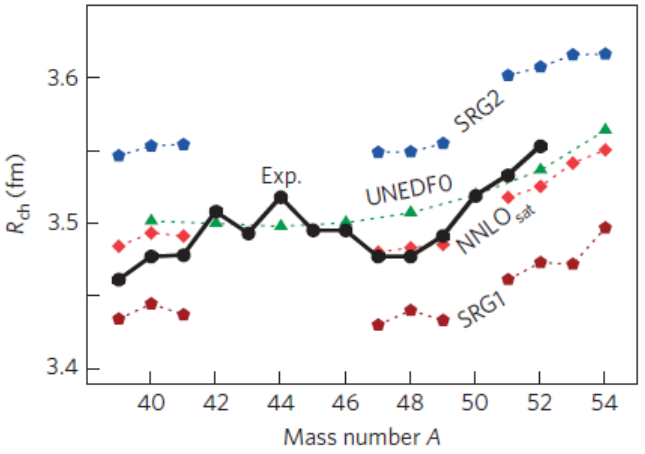
R. F. Garcia Ruiz[1*], M. L. Bissell[1,2], K. Blaum[3], A. Ekström[4,5], N. Frömmgen[6], G. Hagen[4], M. Hammen[6], K. Hebeler[7,8], J. D. Holt[9], G. R. Jansen[4,5], M. Kowalska[10], K. Kreim[3], W. Nazarewicz[4,11,12], R. Neugart[3,6], G. Neyens[1], W. Nörtershäuser[6,7], T. Papenbrock[4,5], J. Papuga[1], A. Schwenk[3,7,8], J. Simonis[7,8], K. A. Wendt[4,5] and D. T. Yordanov[3,13]

Unexpectedly large charge radii of neutron-rich calcium isotopes







LINO - Laser Induced Nuclear Orientation at ALTO

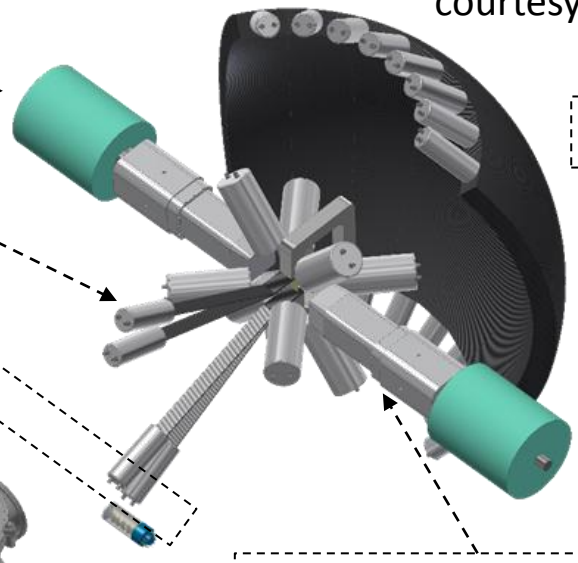
courtesy of D. Yordanov

γ detection

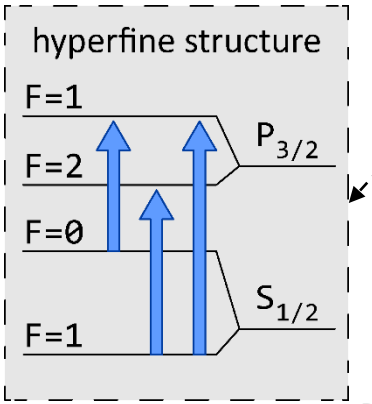
n detection

β detection

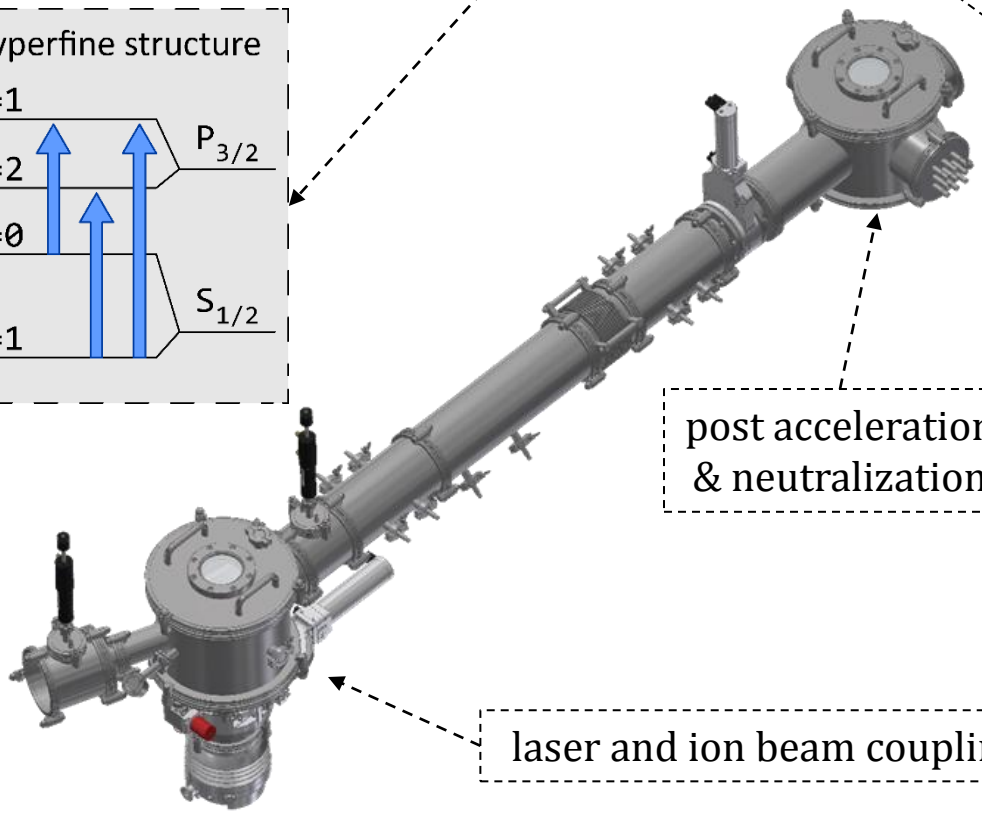
fluorescence detection



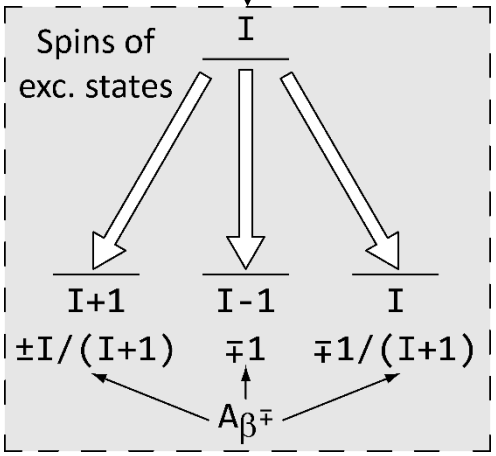
hyperfine structure



β-delayed spectroscopy of polarized beams



post acceleration & neutralization



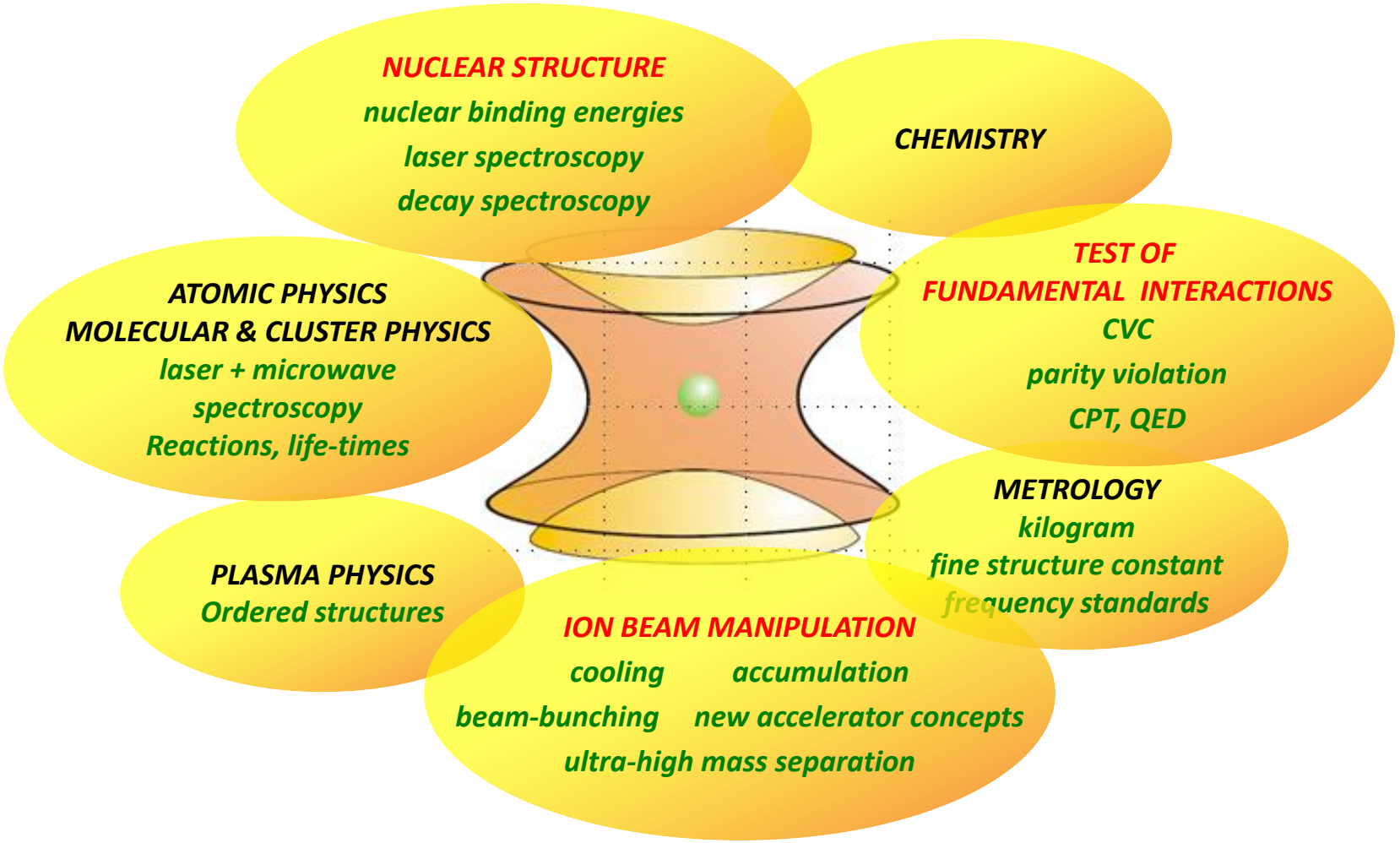
laser and ion beam coupling

Survey of the main experimental setups for low energy ISOL physics

3. Trap assisted spectroscopy
   - general motivations
   - experimental requirements
   - examples

Traps are used in many domains of physics and in particular :

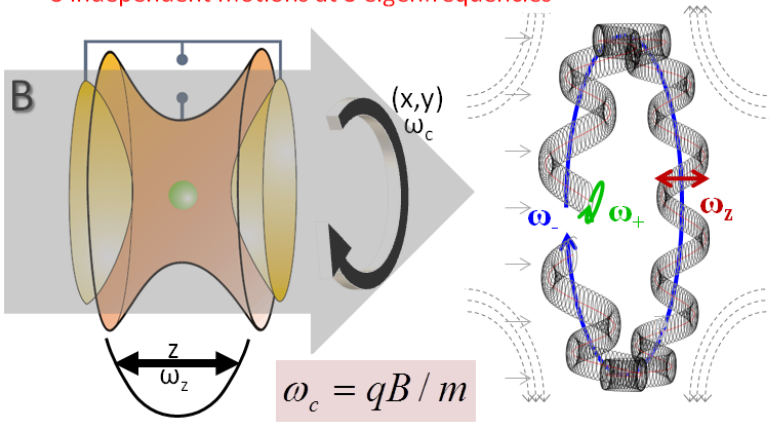
- nuclear structure → precision measurements
- test of fundamental interactions
- ion beam manipulation → RFQ's and ultra high mass separation



Traps in nuclear physics

Penning trap

3 independent motions at 3 eigenfrequencies



$$\omega_c = qB/m$$

axial motion

$$\omega_z = \sqrt{\frac{qU_{dc}}{md^2}}$$

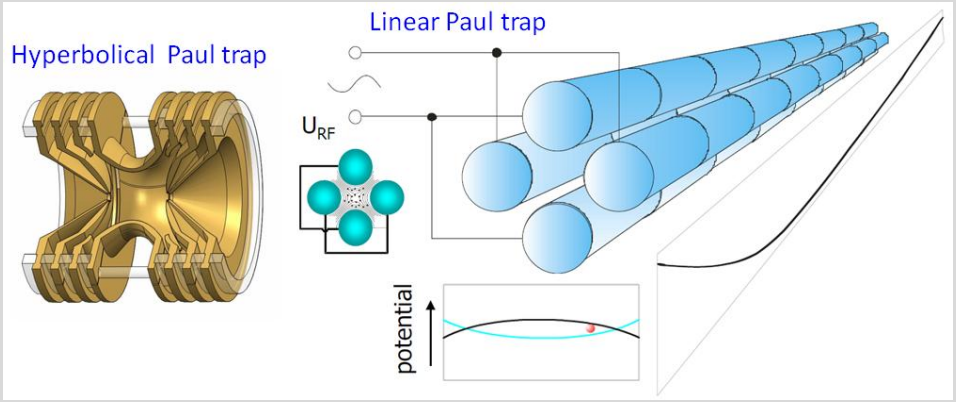
magnetron motion

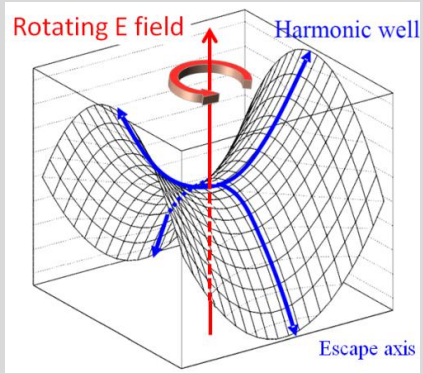
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

modified cyclotron motion

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

Paul trap

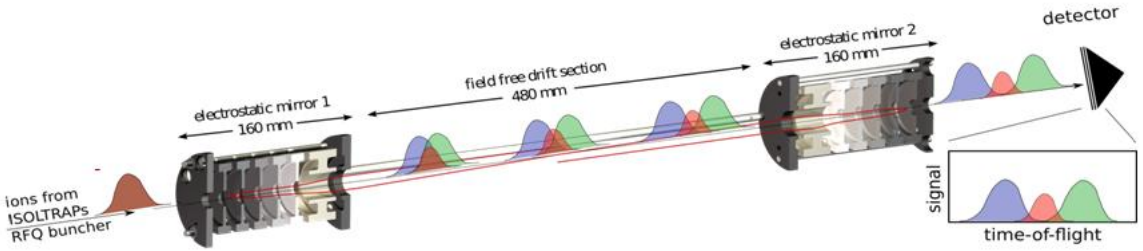




$$\Phi = \frac{U_0}{2d_0^2}(\rho^2 - 2z^2)$$

$$U_0 \rightarrow U_0 + V_0 \cos\Omega t$$

MR-TOF-MS



Complex systems : need for cooled and bunched beams

- mass measurements

- Penning trap ISOLTRAP
  JYFLTrap
  SHIPTrap
  MLLTrap@ALTO
  …
- MR-TOF-MS ISOLTRAP
  In development everywhere !

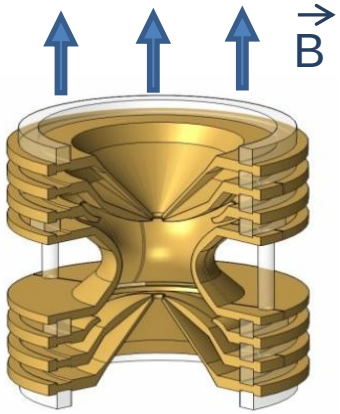
doi:10.1038/nature12226

LETTER

Masses of exotic calcium isotopes pin down nuclear forces

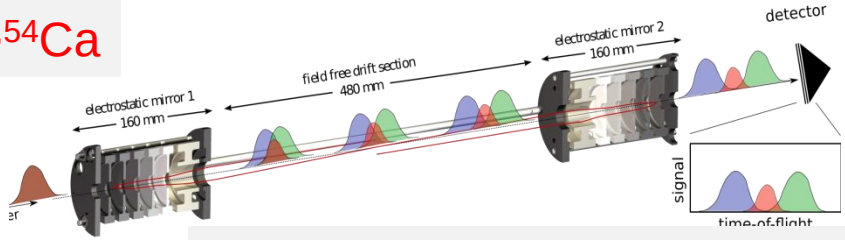
F. Wienholtz[1], D. Beck[2], K. Blaum[3], Ch. Borgmann[3], M. Breitenfeldt[4], R. B. Cakirli[3,5], S. George[1], F. Herfurth[2], J. D. Holt[6,7], M. Kowalska[8], S. Kreim[3,8], D. Lunney[9], V. Manea[9], J. Menéndez[6,7], D. Neidherr[2], M. Rosenbusch[1], L. Schweikhard[1], A. Schwenk[2,6], J. Simonis[6,7], J. Stanja[10], R. N. Wolf[1] & K. Zuber[10]

^{51,52}Ca



- Production rates of ~10 ions/s
- Mass measurements via S_{2n} establish new magic number at $N = 32$
- Correct prediction from 3N-forces (A. Schwenk *et al.*, TUD)

^{53,54}Ca



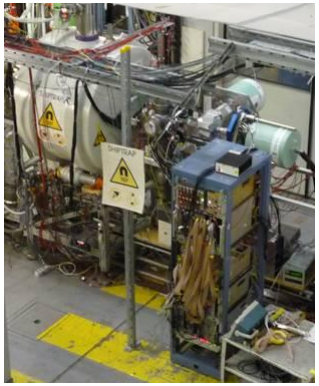
R. Wolf *et al.*, Int. J. Mass Spec. 349, 123 (2013)
T. Dickel *et al.*, Nucl. Instrum. Meth. B 317, 779 (2013)

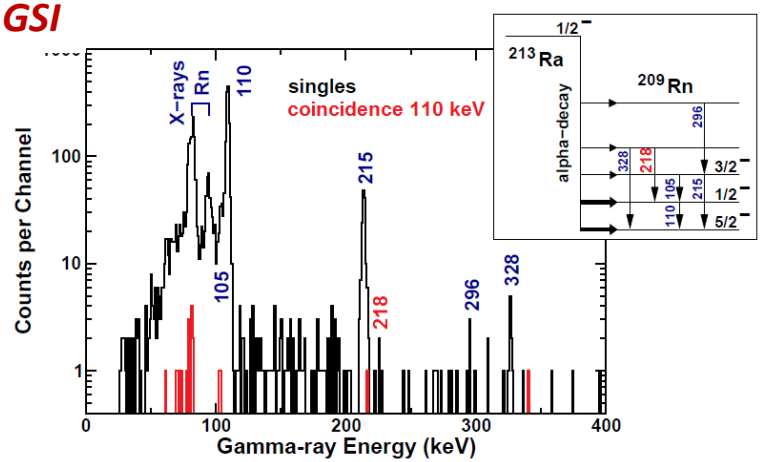
- trap assisted spectroscopy and purification devices

→ Penning trap as high-resolution mass separator to prepare state-selected pure sample

Pionner work @ JYFLTrap

TASISpec with SHIPTRAP @ GSI





- Clean spectra
- Detailed nuclear structure information

PIPERADE @ SPIRAL2

➢ **Mass resolution > 10^5** (Isobaric and isomeric cleaning)

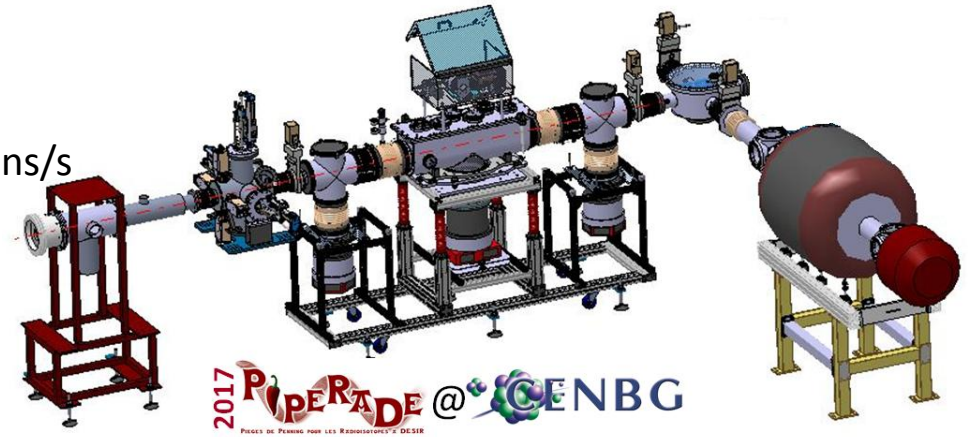
↳ totally pure samples

➢ **Purify very large samples of ions**

↳ > 10^5 ions/bunch; ~10Hz → > 10^6 ions/s

(Large ratio contamination/ions of interest)

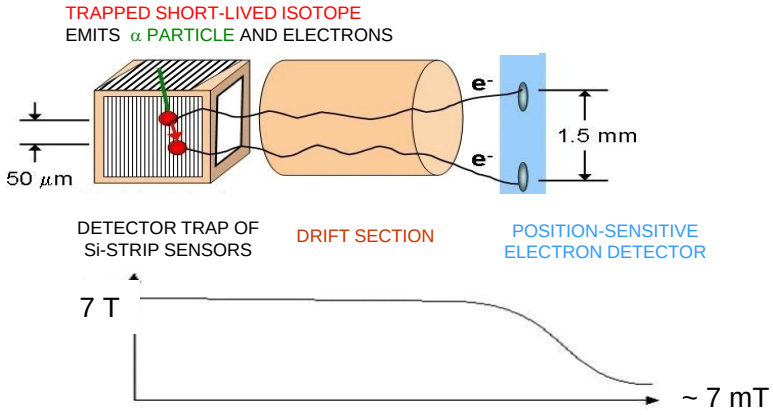
➢ "**Fast**" cleaning process (50 – 500 ms)



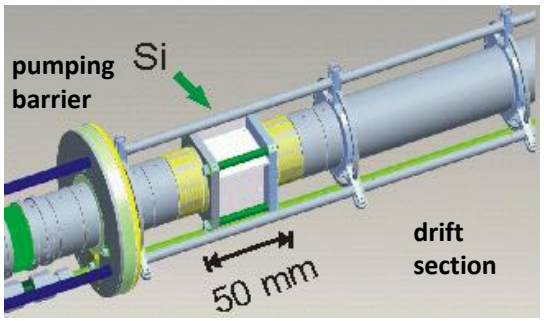
↳**Double Penning trap system** ⇄ selection / accumulation

- in-trap spectroscopy

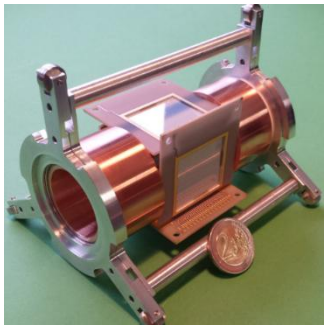
MLLTrap courtesy E. Minaya



C. Weber et al., Int. J. Mass Spectrom. 349-350, 270 (2013)
C. Weber et al., Nucl. Instr. Meth. B 317, 532 (2013)



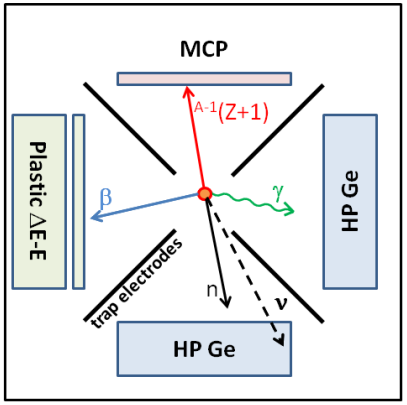
Conceptual layout



Detector trap

- "detector trap": α-detectors act as trap electrodes
- Customized α-detectors were developed and characterized for the cryogenic and UHV-conditions (Si-strip detector, 30x30 mm², 30 strips, α resolution ~ 20 keV)

Beta delayed neutron using a transparent Paul trap



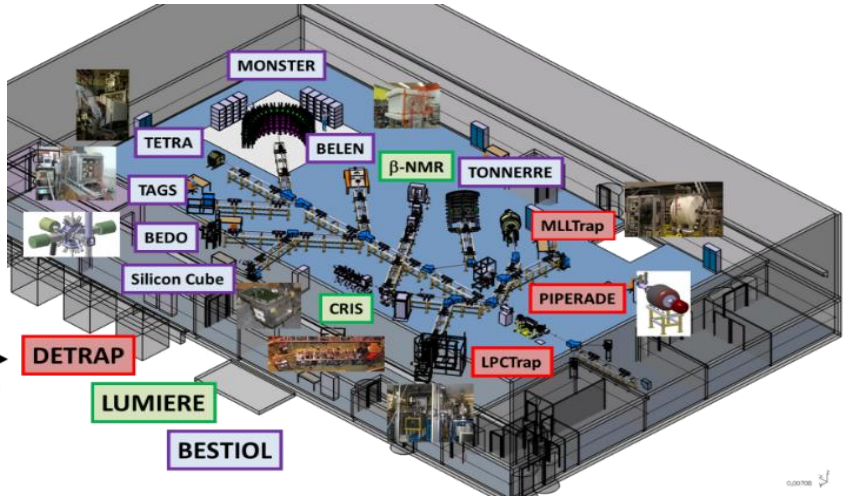
Test of fundamental interactions

LPCTrap@SPIRAL...

Conclusions

Survey of the main experimental setups for low energy ISOL physics

1. Beta decay setups
2. Laser setups
3. Trap setups



- **BESTIOL** : **BEta decay STudies at the SPIRAL2 IsOL facility**
- **LUMIERE** : **Laser Utilization for Measurement and Ionization of Exotic Radioactive Elements**
  Collinear laser spectroscopy (CRIS-Like), Optical pumping line (LINO project at ALTO) and Laser spectroscopy with ConeTrap
- **DETRAP** **DESIR-TRAP**
  In-trap decay studies, mass measurements and trap-assisted spectroscopy

Grazie per la vostra attenzione

Thank you for your attention

Merci pour votre attention