Karl Johnston
Karl.johnston@cern.ch

What is ISOLDE?

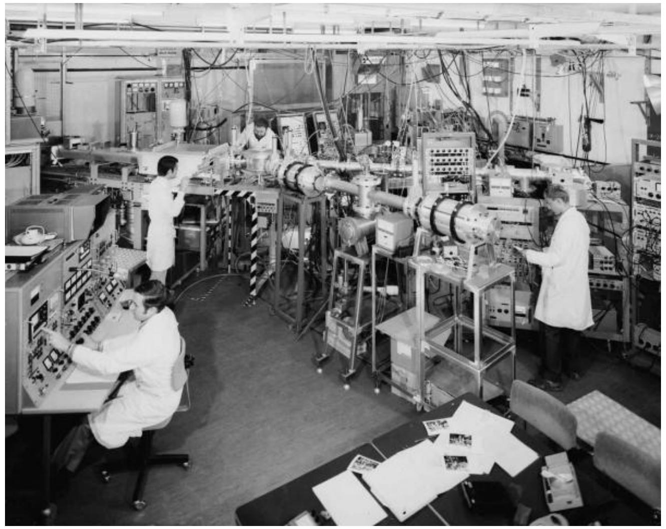
The On-Line Isotope Mass Separator ISOLDE is a facility dedicated to the production of a large variety of radioactive ion beams (RIBs)

Isolde history

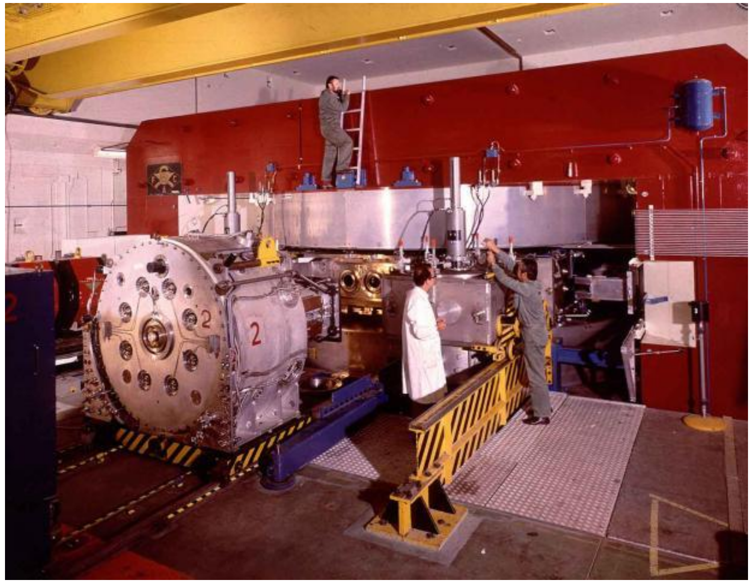
Dec 1964: CERN approves the online separator project

May 1966: SynchroCyclotron shuts down for the construction of ISOLDE

Oct 1967: First proton beams at ISOLDE



1972: SC Improvement Program – doubles the intensity
(now quite a nice museum)

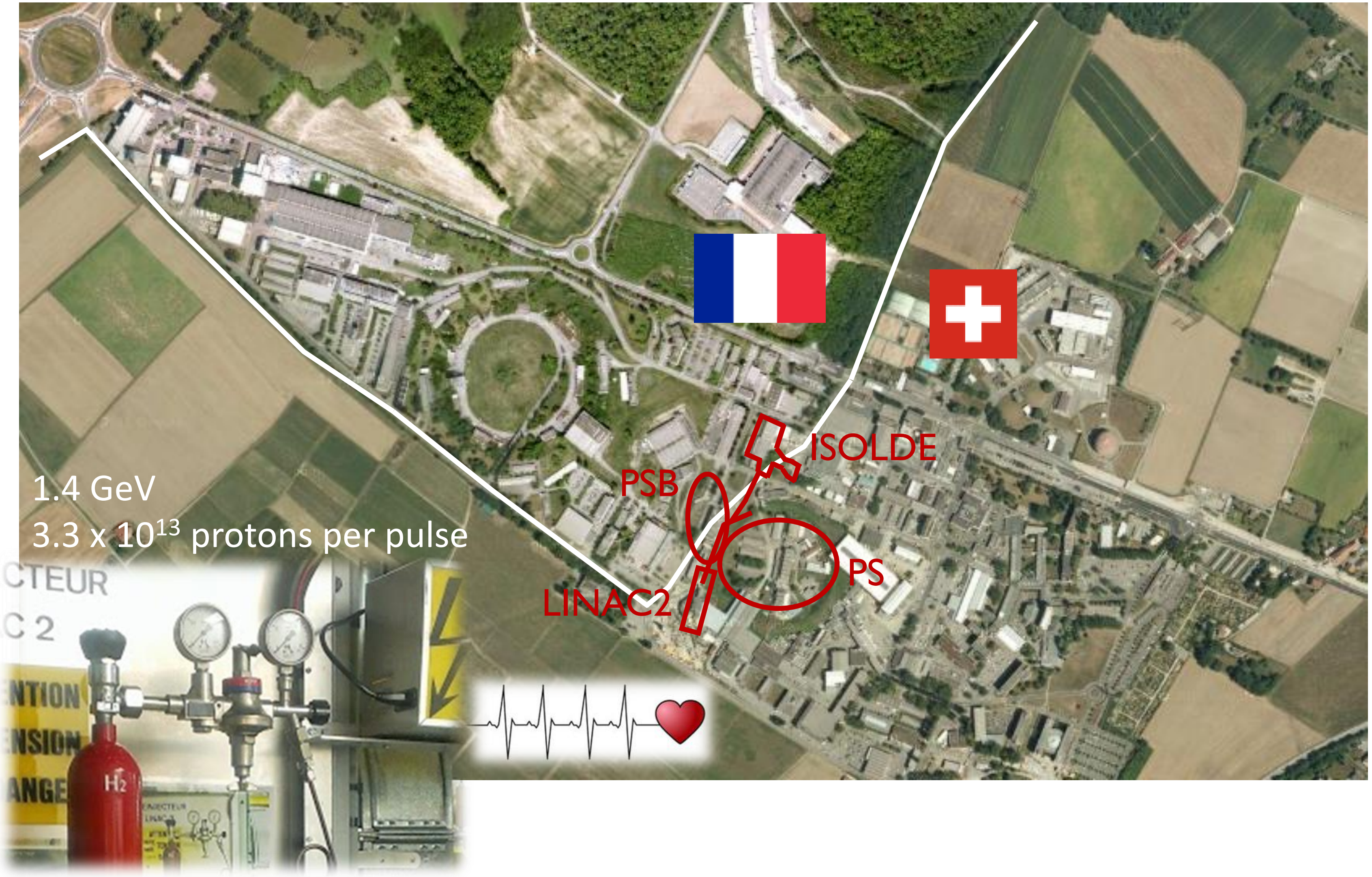


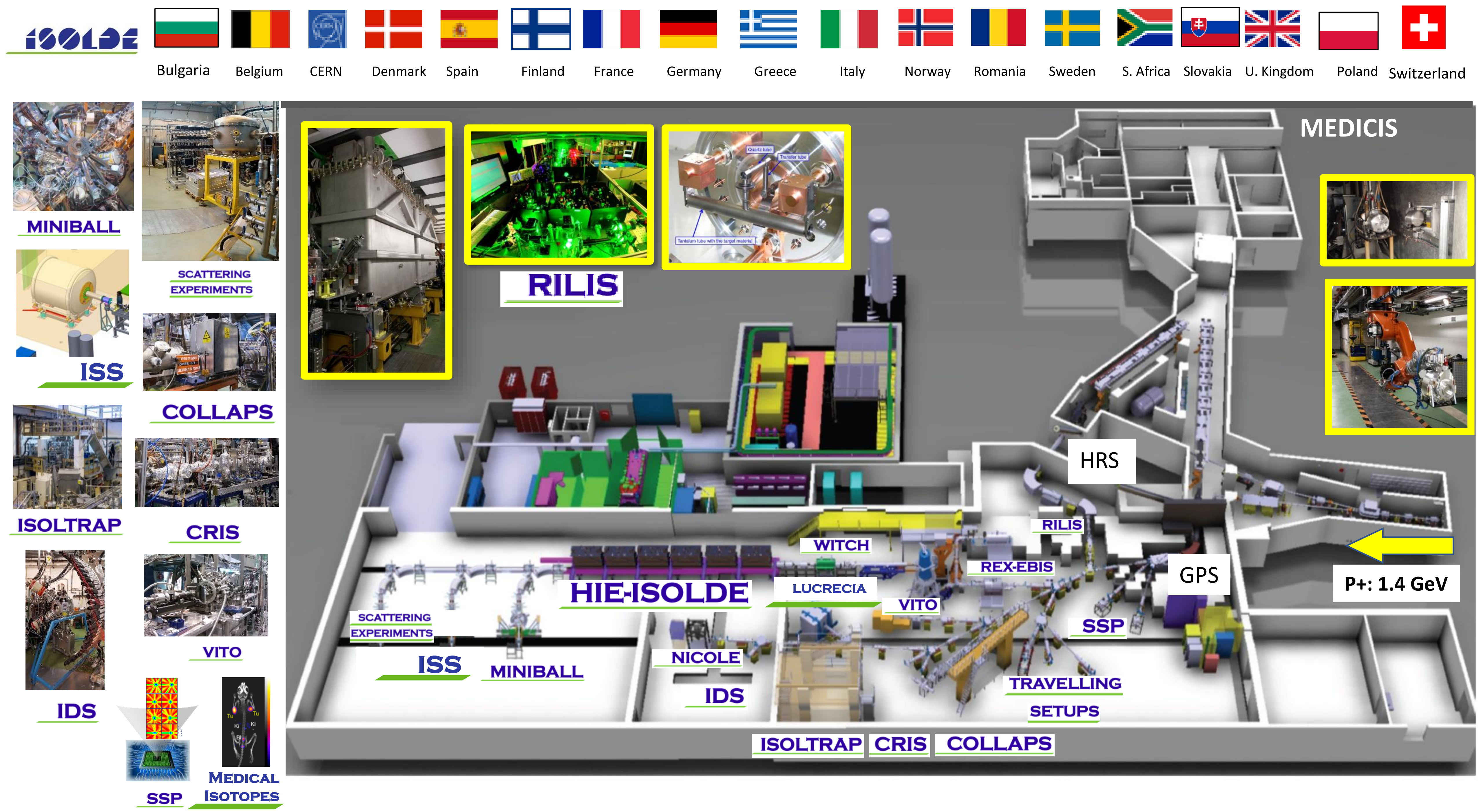
1976: New experiments in ISOLDE II

June 1983: ISOLDE III approved –
two-stage high resolution separation using two magnets

Dec 1990: The Synchrocyclotron beam ends
ISOLDE moves to PS booster to utilize CERN's spare proton capacity…

Why at CERN?

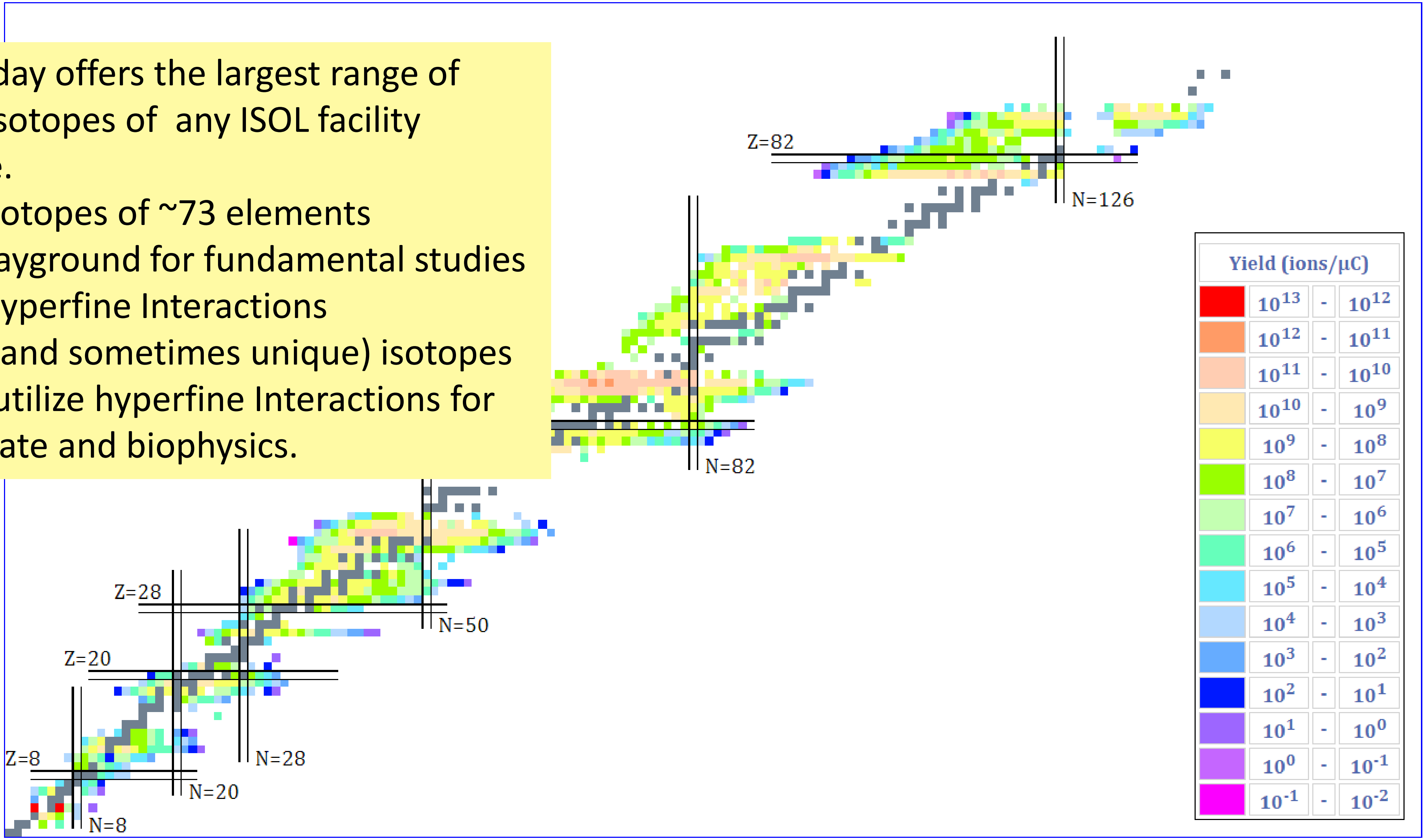



ISOLDE
Bulgaria
Belgium
CERN
Denmark
Spain
Finland
France
Germany
Greece
Italy
Norway
Romania
Sweden
S. Africa
Slovakia
U. Kingdom
Poland
Switzerland
MINIBALL
SCATTERING EXPERIMENTS
ISS
COLLAPS
ISOLTRAP
CRIS
IDS
VITO
SSP
MEDICAL ISOTOPES
RILIS
MEDICIS
HRS
GPS
P+: 1.4 GeV
RILIS
WITCH
REX-EBIS
HIE-ISOLDE
LUCRECIA
VITO
SSP
SCATTERING EXPERIMENTS
ISS
MINIBALL
NICOLE
IDS
TRAVELLING SETUPS
ISOLTRAP
CRIS
COLLAPS

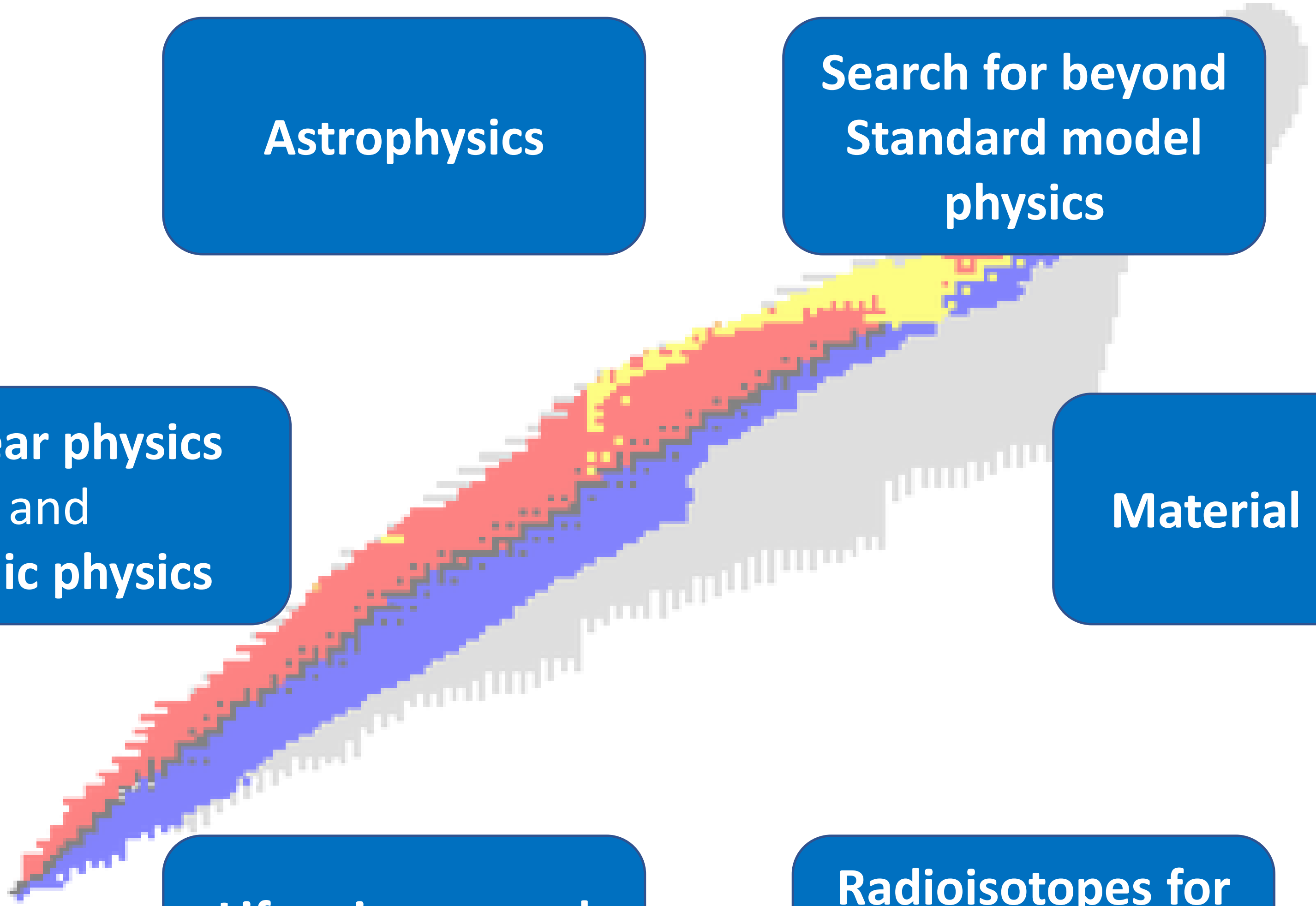
Nuclear chart for ISOLDE

ISOLDE today offers the largest range of available isotopes of any ISOL facility worldwide.

- 1200 isotopes of ~73 elements
- Rich playground for fundamental studies using hyperfine Interactions
- Novel (and sometimes unique) isotopes which utilize hyperfine Interactions for solid state and biophysics.



Research with radioactive beams at ISOLDE



Astrophysics

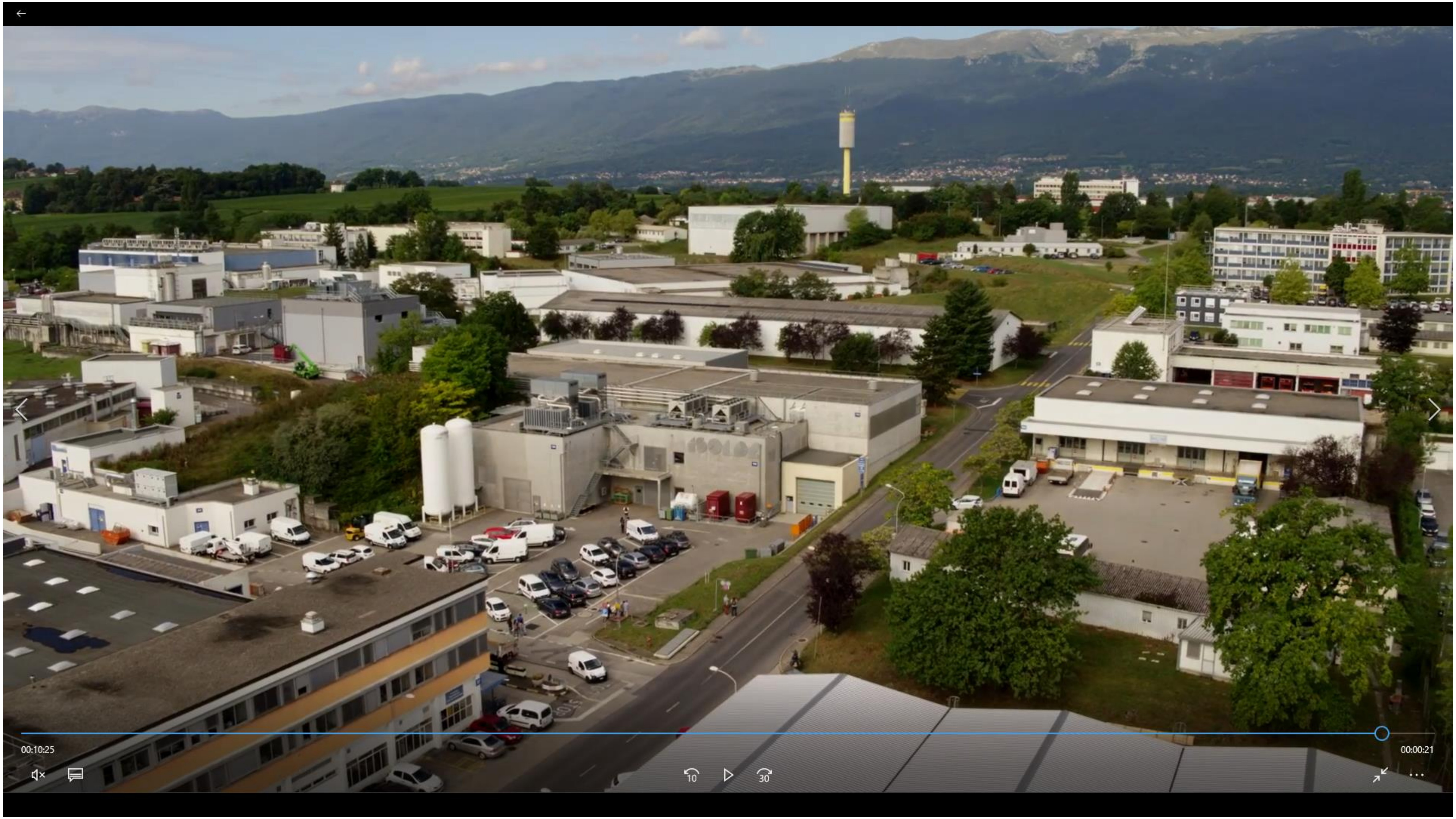
Search for beyond Standard model physics

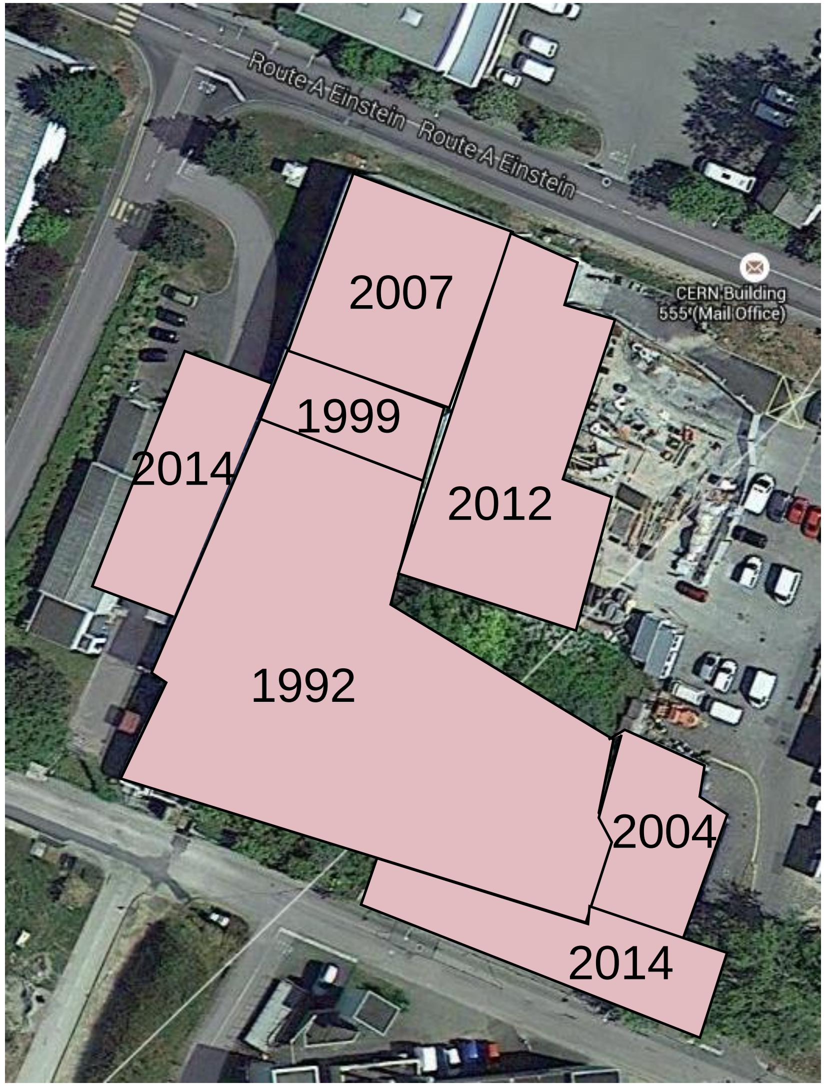
Nuclear physics and atomic physics

Material science

Life sciences and biophysics

Radioisotopes for medical applications


00:10:25
00:00:21



User and Operations facility building

Groundbreaking MEDICIS building

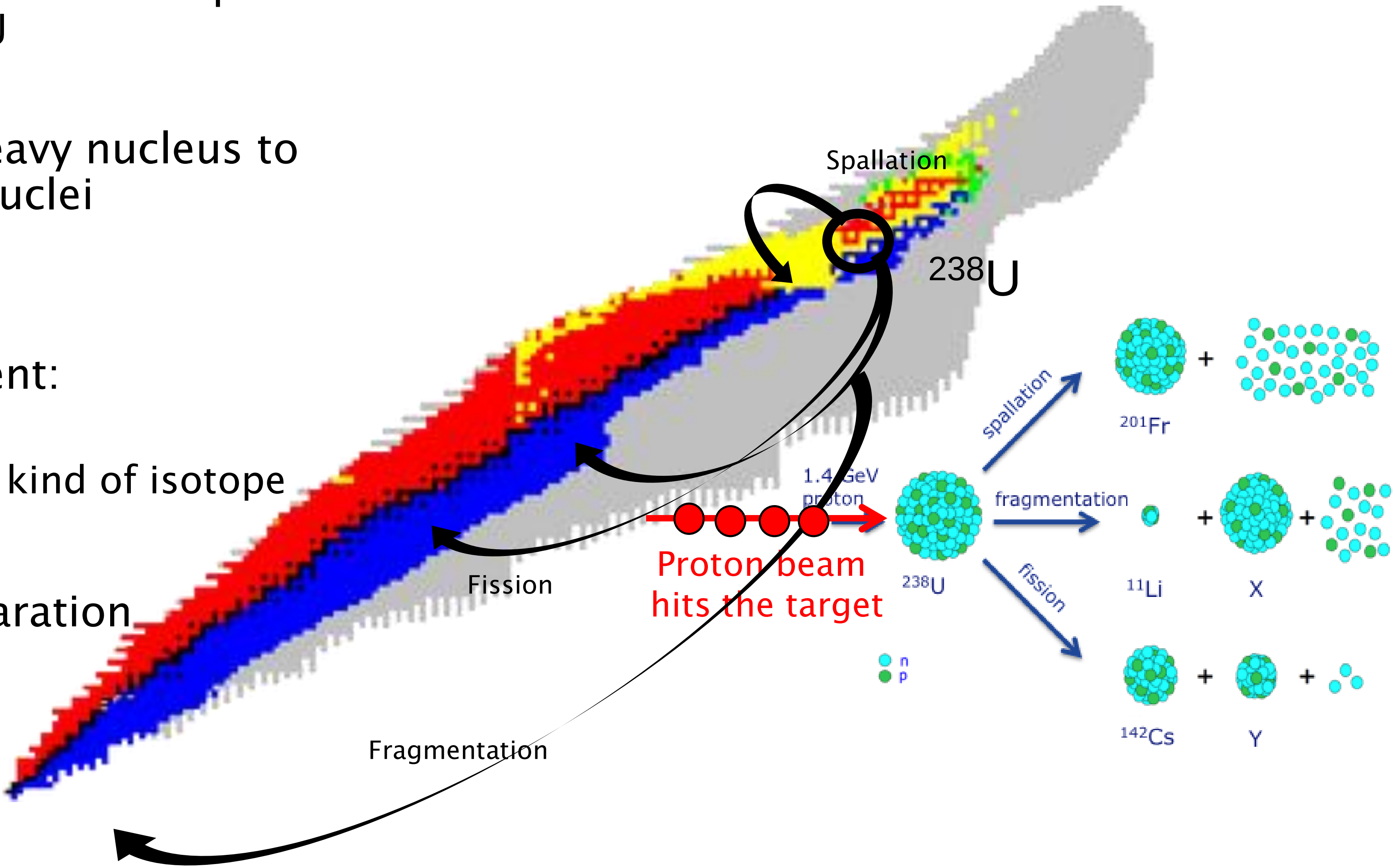
Production: Modern-day alchemy

- High energy (1.4 GeV) protons are impacted onto a thick target e.g. ^{238}U

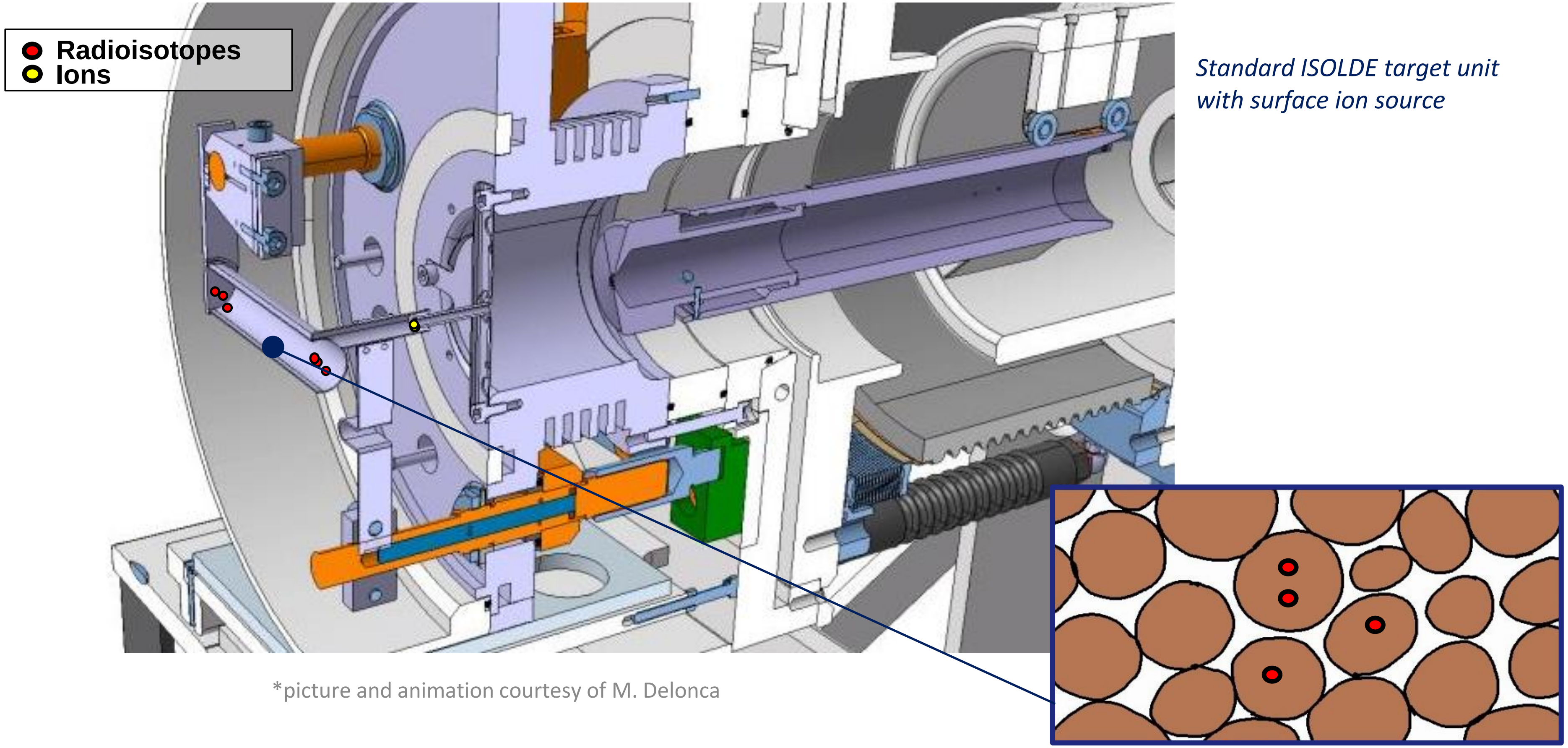
- The protons split up the heavy nucleus to produce a wide variety of nuclei simultaneously

- Requirements for experiment:
  - High production
  - Pure radioactive beams: 1 kind of isotope

- There are 3 stages of preparation
  - Production
  - Ionization
  - Separation



Production: Targets

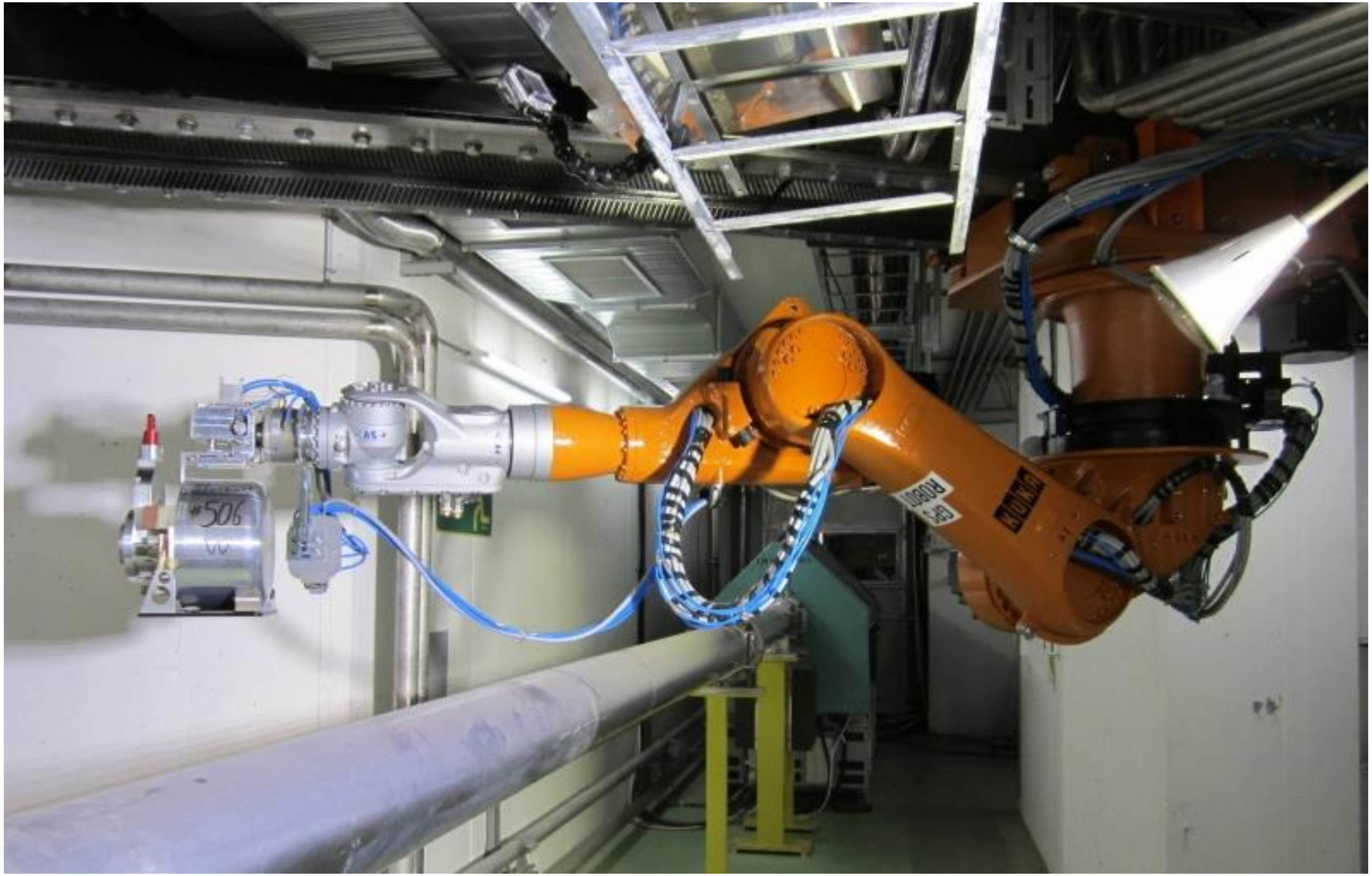


Standard ISOLDE target unit with surface ion source

*picture and animation courtesy of M. Delonca

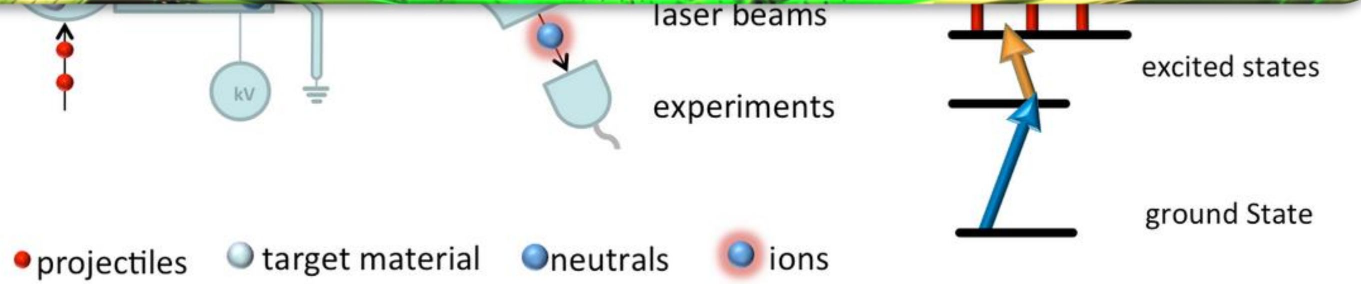
- ◆Over 120 materials have been tested and/or used as ISOL targets
  - ◆ Choice of target material and ionizer dependent on radioactive beam of interest
- ◆Target material and transfer tube heated to 1500 – 2000 degrees
- ◆Operated by robots due to radiation

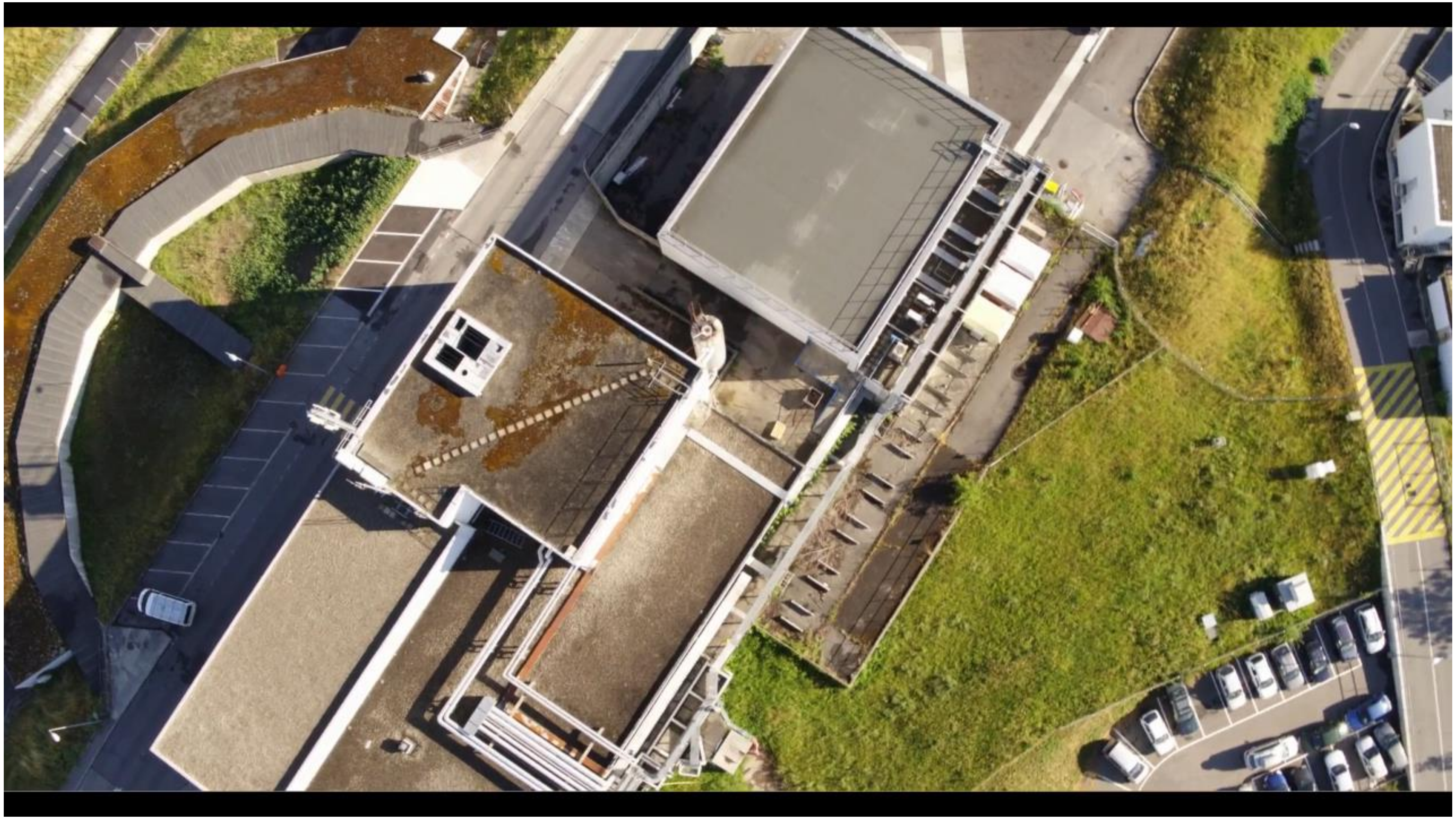
ISOLDE Robots



Ion Sources

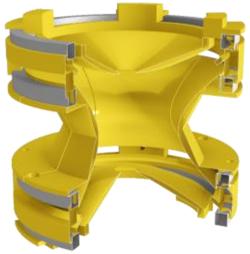
- **Hot-cavity**
    - W heated at > 2000 C
    - High ionization efficiencies for some nuclei
- **Plasma**





Experiments with low-energy RIB's

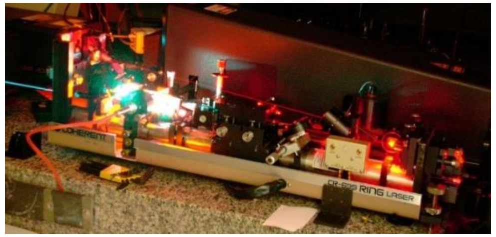
- **Masses**
  - **ISOLTRAP** (Penning trap + MR-TOF-MS)



- **Decay spectroscopy**
  - **Modular and versatile**

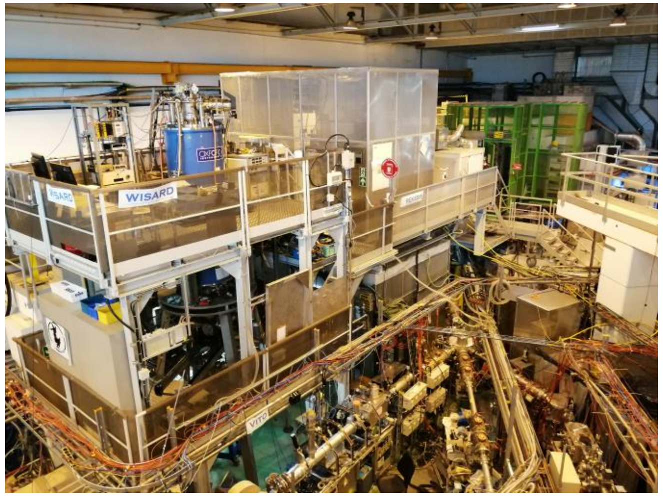
    Isolde Decay Station (IDS) since 2015

- **Moments, radii and spins**
  - **LASER SPECTROSCOPY (COLLAPS, CRIS, RILIS)**

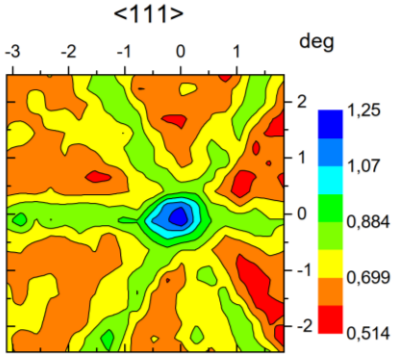


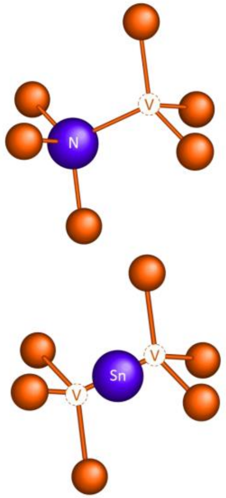
Experiments with low-energy RIB's

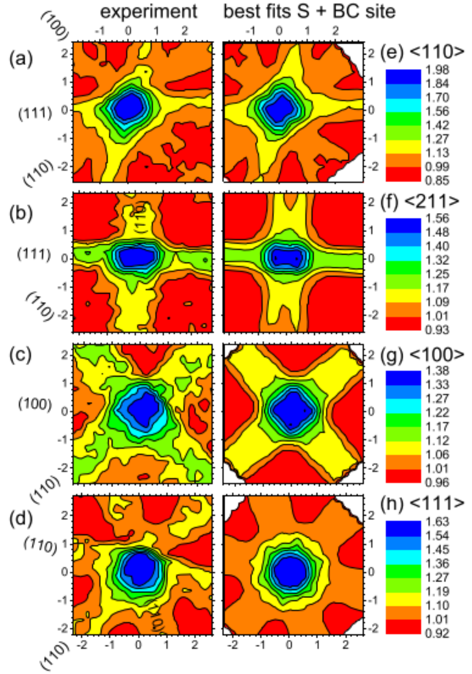
- **Fundamental Interaction Studies**
  - **WISArD experiment**



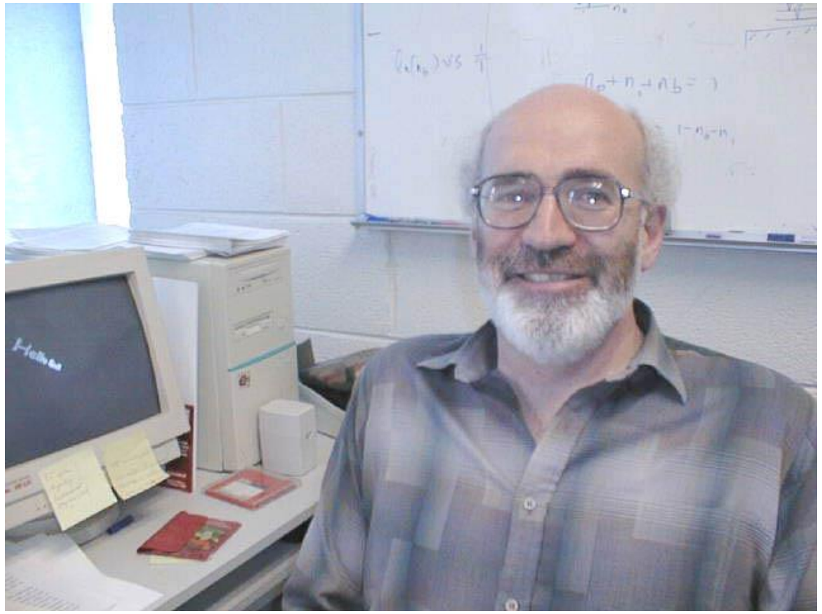
- **Material research with short lived isotopes**
  - **Emission channeling, PAC, β-NMR, Mossbauer**







Martin Henry
Defects in Semiconductors and Radioactivity: The early years



J. Phys.: Condens. Matter 6 (1994) L643–L650. Printed in the UK

LETTER TO THE EDITOR

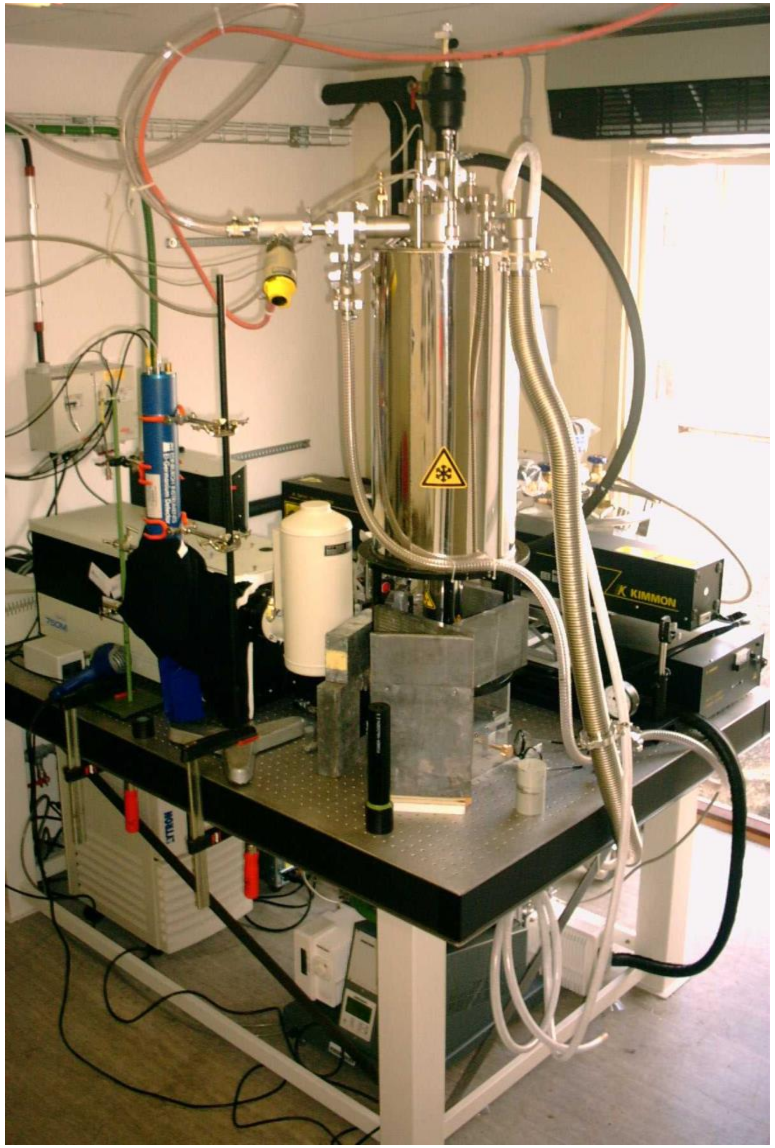
Radioactive isotopes for photoluminescence spectroscopy—^{111}In in silicon

S E Daly†, M O Henry†, K Freitag‡ and R Vianden‡

† School of Physical Sciences, Dublin City University, Collins Avenue, Dublin 9, The Republic of Ireland

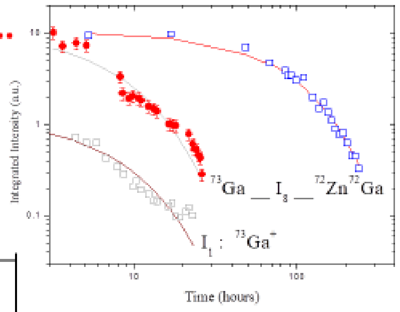
‡ Institut für Strahlen und Kernphysik der Universität Bonn, Nussallee 14-16, D 53115 Bonn, Germany

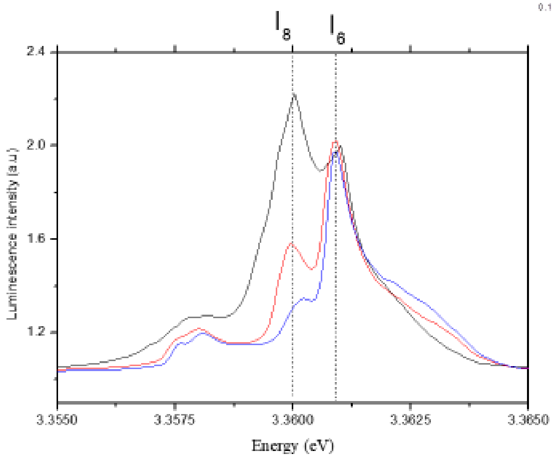
DCU

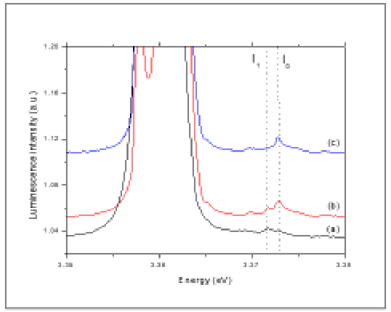


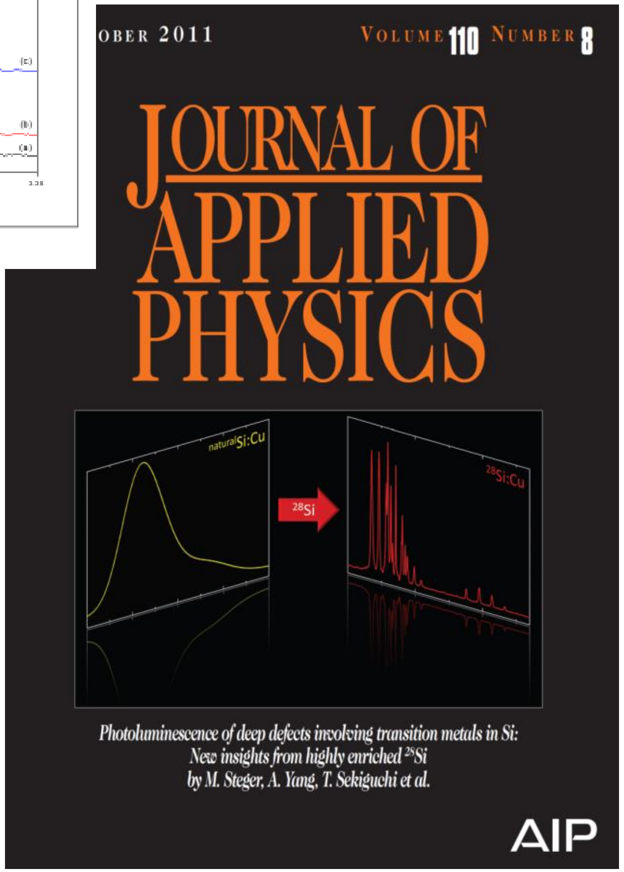
Ga identified as a donor in ZnO….

K. Johnston *et al* Phys Rev B **73** 165212 (2006).









REX-ISOLDE + MINIBALL : Octupole deformation in 220Rn and 224Ra

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

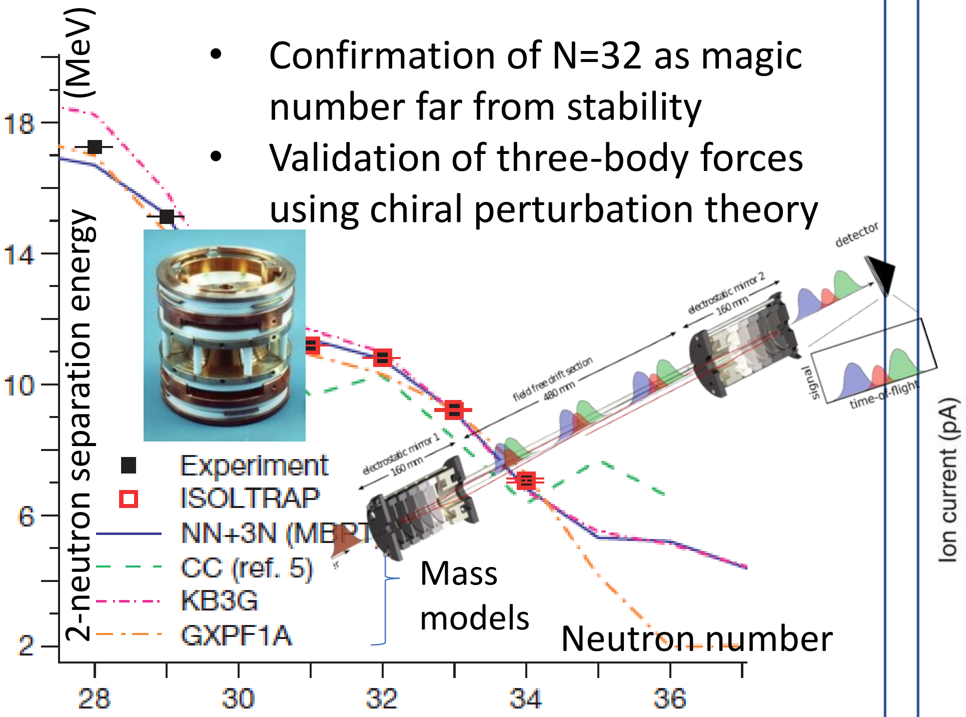
Candidates for searches for permanent EDMs:

- Radon-221 not suitable
- Radiums-223 and 225 - promising

ISOLTRAP: Mass of 54Ca and 3-body forces

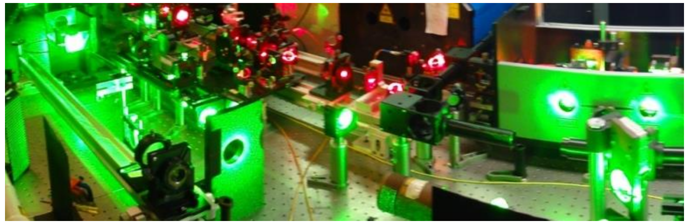
F. Wienholtz et al, **Nature** 498 (2013), 346

- Confirmation of N=32 as magic number far from stability
- Validation of three-body forces using chiral perturbation theory



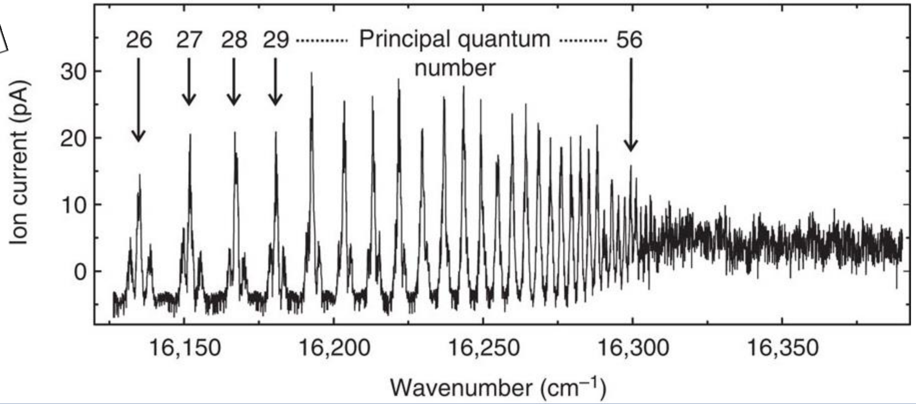
RILIS: Ionisation potential of Astatine

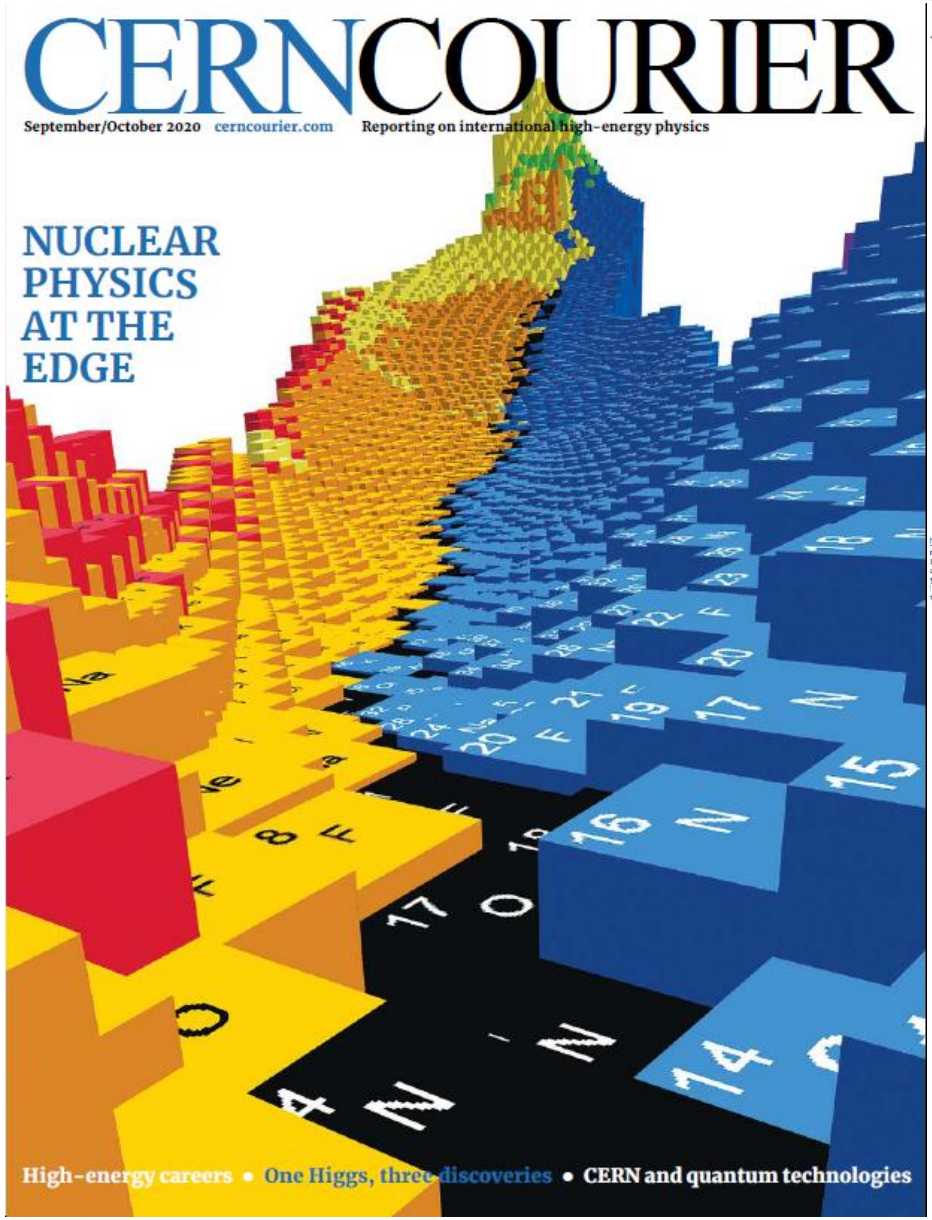
S. Rothe et al, **Nature Communications** 4 (2013), 1835



Least abundant element on Earth

High-precision study via Rydberg states





EXPLORING NUCLEI AT THE LIMITS

Recent studies of exotic nuclides using traps and lasers at CERN's ISOLDE facility are not only helping researchers understand nuclear structure, explain David Lunney and Gerda Neyens, but also offer new ways to look for physics beyond the Standard Model.

Understanding how the strong interaction binds the ingredients of atomic nuclei is the central quest of nuclear physics. Since the 1960s CERN's ISOLDE facility has been at the forefront of this quest, producing the most extreme nuclear systems for examination of their basic characteristic properties.

A chemical element is defined by the number of protons in its nucleus, with the number of neutrons defining its isotopes. Apart from a few interesting exceptions, all elements in nature have at least one stable isotope. These form the so-called valley of stability in the nuclear chart of atomic number versus neutron number (see "Nuclear landscape" figure). Adding or removing neutrons disturbs the nuclear equilibrium and creates isotopes that are generally radioactive; the greater the proton–neutron imbalance, the faster the radioactive decay.

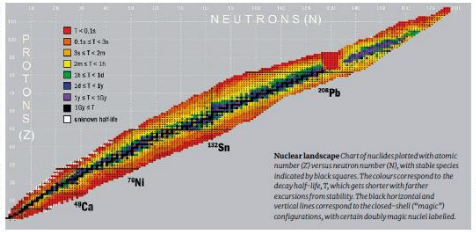
The mass of a nucleus reveals its binding energy, which reflects the interplay of all forces at work within the nucleus from the strong, weak and electromagnetic interactions. Indications of sudden changes in the nuclear shape, when adding neutrons, are often revealed first indirectly as a sudden change in the mass, and can then be probed in detail by measurements of the charge radius and electromagnetic moments. Such diagnosis – performed by ion-trapping and laser-spectroscopy experiments on short-lived (from a few milliseconds upwards) isotopes – provides the first vital signs concerning the nature of nuclides with extreme proton-to-neutron ratios.

Recent mass-spectrometry measurements and high-precision measurements of nuclear moments and radii at ISOLDE demonstrate the rapid progress being made in understanding the stubborn mysteries of the nucleus. ISOLDE's state-of-the-art laser-spectroscopy tools are also opening an era where molecular radioisotopes can be used as sensitive probes for physics beyond the Standard Model.

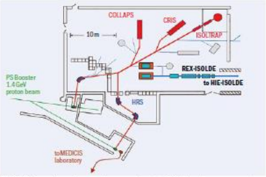
Tools of the trade

Progress in understanding the nucleus has gone hand in hand with the advancement of new techniques. Mass measurements of stable nuclei pioneered by Francis Aston nearly a century ago revealed a near-constant binding energy per nucleon. This pointed to a characteristic saturation of the nuclear force, which underlies the liquid-drop model and led to the semi-empirical mass formula for the nucleus developed by Bethe and von Weizsäcker. With the advent of particle accelerators in the 1930s, more isotopic mass data became available from reactions and decays, bringing new surprises. In particular, comparisons with the liquid drop revealed conspicuous peaks at certain so-called "magic" numbers (8, 20, 28, 50, 82, 126), analogous to the high atomic-ionisation potentials of the closed electron-shell noble-gas elements. These findings inspired the nuclear-shell model, developed by Maria Goeppert-Mayer and Hans Jensen, which is still used as an important benchmark today. The difference with the atomic system is that the force that governs the nuclear shells is poorly understood. This is because nucleons are themselves composite particles that interact through the complex interplay of three fundamental forces, rather than the single electromagnetic force governing atomic structure. The most important question in nuclear physics today is to describe these closed shells from fundamental principles (e.g. the strong interaction between quarks and gluons inside nucleons), to understand why shell structure erodes and how new shells arise far from stability.

A key to reaching a deeper understanding of nuclear structure is the ability to measure the size and shape of nuclei. This was made possible using the precision technique of laser spectroscopy, which was pioneered with tremendous success at ISOLDE in the late 1970s. While increased binding energy is a tell-tale sign of a deforming nucleus, it gives no specific information concerning nuclear size or shape. Closed-shell configurations tend to favour spherical nuclei, but since these are rather rare, a particularly important feature of nuclei is their deformation. Inspecting electromagnetic moments derived from the measured atomic hyperfine structure and the change in charge radii derived from its isotopic shift provides detailed information about nuclear shapes and deformation, beautifully complementing mass measurements.



Nuclear landscape *Chart of nuclides plotted with atomic number (Z) versus neutron number (N), with stable species indicated by black squares. The colours correspond to the decay half-life, T, which gets shorter with farther excursions from stability. The black horizontal and vertical lines correspond to the closed-shell ("magic") configurations, with certain doubly magic nuclei labelled.*



ISOLDE from above *Laser and trap experiments (red) in the low-energy section of ISOLDE (the REX-ISOLDE post-accelerator and the recent HIE-ISOLDE project produce radioactive ion beams of higher energies). A target behind that of the high-resolution separator (HRS) can be parasitically irradiated and then moved with robots to the MEDICIS facility to extract long-lived radioisotopes for medical research.*

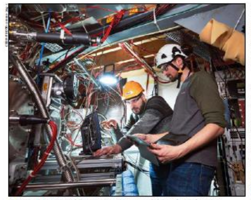
During the past half-century, nuclear science at ISOLDE has expanded beyond fundamental studies to applications involving radioactive tracers in materials (including bio-materials) and the fabrication of isotopes for medicine (with the MEDICIS facility). But the bulk of the ISOLDE physics programme, around 70%, is still devoted to the elucidation of nuclear structure and the properties of fundamental interactions. These studies are carried out through nuclear reactions, by decay spectroscopy, or by measuring the basic global properties – mass and size – of the most exotic species possible.

Half a century of history

The fabrication of extreme nuclear systems requires a driver accelerator of considerable energy, and CERN's expertise here has been instrumental. After many years receiving proton beams from a 600 MeV synchrocyclotron (the SC, now a museum piece at CERN), ISOLDE now lies just off the beam line to the Proton Synchrotron (PS), receiving 1.4 GeV beam pulses from the PS Booster (see "ISOLDE from above" figure). ISOLDE in fact receives typically 50% of the pulses in the so-called super-cycle that links the intricate complex of CERN's injectors for the LHC.

The heart of ISOLDE is a cylindrical target that can contain various different materials. The stable nuclei in the target are dissociated by the proton impact and form exotic combinations of protons and neutrons. Heating the target (up to 2000 degrees) helps these fleeting nuclides to escape into an ionisation chamber, in which they form 1^+ ions that are electrostatically accelerated to around 50 keV. Isotopes of one particular mass are selected using one of two available mass separators, and subsequently delivered to the experiments through more than a dozen beamlines. A similar number of permanent experimental setups are operated by several small international collaborations. Each year, more than 40 experiments are performed at ISOLDE by more than 500 users. More than 900 users from 26 European and 17 non-European countries around the world are registered as members of the ISOLDE collaboration.

ISOLDE sets the global standard for the production of exotic nuclear species at low energies, producing beams that



ISOLTRAPpers *CERN fellow Maxime Mougeot and PhD student Lukas Nies (University of Greifswald) tuning ISOLDE's high-precision mass spectrometer in 2019.*

CRIS collaborators *CERN research fellow Ronald Garcia Ruiz with former PhD students Adam Vernon (Manchester) and Agi Koszorus (KU Leuven), with ISOLDE group leader Gerda Neyens (standing, centre) at the Collinear Resonance Ionization Spectroscopy (CRIS) experiment, photographed in 2018.*

are particularly amenable to study using precision lasers and traps developed for atomic physics. Hence, ISOLDE is complementary to higher energy, heavy-ion facilities such as the Radioactive Isotope Beam Factory (RIBF) at RIKEN in Japan, the future Facility for Rare Isotope Beams (FRIB) in the US, and the Facility for Antiproton and Ion Research (FAIR/GSI) in Europe. These installations produce even more exotic nuclides by fragmenting heavy GeV projectiles on a thin target, and are more suitable for studying high-energy reactions such as breakup and knock-out. Since 2001, ISOLDE has also driven low-energy nuclear-reaction studies by installing a post-accelerator that enables exotic nuclides to be delivered at MeV energies for the study of more subtle nuclear reactions, such as Coulomb excitation and transfer. Post-accelerated radioactive beams have superior optical quality compared to the GeV beams from fragment separators so that the radioactive beams accelerated in the REX and more recent HIE-ISOLDE superconducting linacs enable tailored reactions to reveal novel aspects of nuclear structure.

ISOLDE's state-of-the art experimental facilities have evolved from more than 50 years of innovation from a dedicated and close-knit community, which is continuously expanding and also includes material scientists and biochemists. The pioneering experiments concerning binding energies, charge radii and moments were all performed at CERN during the 1970s. This work, spearheaded by the Orsay group of the late Robert Klapisch, saw the first use of on-line mass separation for the identification of many new exotic species, such as ^{31}Na. This particular success led to the first precision mass measurements in 1975 that hinted at the surprising disappearance of the N = 20 shell closure, eight neutrons heavier than the stable nucleus ^{23}Na. In collaboration with atomic physicists at Orsay, Klapisch's team also performed the first laser spectroscopy of ^{31}Na in 1978, revealing the unexpected large size of this exotic isotope. To reach heavier nuclides, a mass spectrometer with higher resolution was required, so the work naturally continued at the expanding ISOLDE facility in the early 1980s.

Meanwhile, another pioneering experiment was initiated by the group of the late Ernst-Wilhelm Otten. After having developed the use of optical pumping with spectral lamps in Mainz to measure charge radii, Otten's group exploited ISOLDE's first offerings of neutron-deficient Hg isotopes and discovered the unique feature of shape-staggering in 1972. Through continued technical improvements, the Mainz group established the collinear laser spectroscopy (COLLAPS) programme at ISOLDE in 1979, with results on barium and ytterbium isotopes. When tunable lasers and ion traps became available in the early 1980s, the era of high-precision measurements of radii and masses began. These atomic-physics inventions have revolutionised the study of isotopes far from stability and the initial experimental set-ups are still in use today thanks to continuous upgrades and the introduction of new measurement methods. Most of these developments have been exported to other radioactive beam facilities around the world.

Mass measurements with ISOLTRAP

ISOLTRAP is one of the longest established experiments at ISOLDE. Installed in 1985 by the group of Hans-Jürgen Kluge from Mainz, it was the first Penning trap on-line at a radioactive beam facility, spawning a new era of mass spectrometry. The mass is determined from the cyclotron frequency of the trapped ion, and bringing the technique on line required significant and continuous development, notably with buffer-gas cooling techniques for ion manipulation. Today, ISOLTRAP is composed of four ion traps, each of which has a specific function for preparing the ion of interest to be weighed.

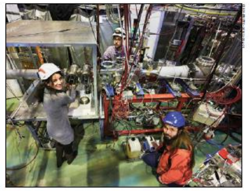
Since the first results on caesium, published in 1987, ISOLTRAP has measured the masses of more than 500 species spanning the entire nuclear chart. The most recent results, published this year by Vladimir Manea (Paris-Saclay), Jonas Karthein (Heidelberg) and colleagues, concern the strength of the N = 82 shell closure below the magic (Z = 50) ^{132}Sn from the masses of (Z = 48) $^{132-130}$Cd. The team found that the binding energy only two protons below the closed shell was much less than what was predicted by global microscopic models, stimulating new ab-initio calculations based on a nucleon–nucleon interaction derived from QCD through chiral effective-field theory. These calculations were previously available for lighter systems but are now, for the first time, feasible in the region just south-east of ^{132}Sn, which is of particular interest for the rapid neutron-capture process creating elements in merging neutron stars.

The other iconic doubly magic nucleus ^{78}Ni (Z = 28, N = 50) is not yet available at ISOLDE due to the refractory nature of nickel, which slows its release from the thick target so that it decays on the way out. However, the production of copper – just one proton above – is so good that CERN's Andree Welker and his colleagues at ISOLTRAP were recently able to probe the N = 50 shell by measuring the mass of its nuclear neighbour ^{79}Cu, finding it to be consistent with that of the doubly magic ^{78}Ni nucleus. Masses from large-scale shell-model calculations were in excellent agreement with the observed copper masses, indicating the preservation of the N = 50 shell strength but with some deformation energy creeping in to help. Complementary observables from laser spectroscopy helped to tell the full story, with results on moments and radii from the COLLAPS and the more recent Collinear Resonance Ionization Spectroscopy (CRIS) experiments adding an interesting twist.

Laser spectroscopy with COLLAPS and CRIS

Quantum electrodynamics provides its predictions of atomic energy levels mostly by assuming the nucleus is point-like and infinitely heavy. However, the nucleus indeed has a finite mass as well as non-zero charge and current distributions, which impact the fine structure. Thus, complementary to the high-energy scattering experiments used to probe nuclear sizes, the energy levels of orbiting electrons offer a marvellous probe of the electric and magnetic properties of the nucleus. This fact is exploited by the elegant technique of laser spectroscopy, a fruitful marriage of atomic and nuclear physics realised by the COLLAPS collaboration since the late 1970s. COLLAPS uses tunable continuous-wave lasers for high-precision studies of exotic nuclear radii and moments, and similar setups are now running at other facilities, such as Jyvaskyla in Finland, TRIUMF in Canada and NSCL-MSU in the US.

A recent highlight from COLLAPS, obtained this year by Simon Kaufmann of TU Darmstadt and co-workers, is the measurement of the charge radius of the exotic, semi-magic isotope ^{68}Ni. Such medium-mass exotic nuclei are now in reach of the modern ab-initio chiral effective-field theories, which reveal a strong correlation between the nuclear charge radius and its dipole polarisability. With both measured for ^{68}Ni, the data provide a stringent benchmark for theory, and allow researchers to constrain the point-neutron radius and the neutron skin of ^{68}Ni. The latter, in turn, is related to the nuclear equation-of-state, which plays a key role in supernova explosions and compact-object mergers, such as the recent neutron-star merger GW170817.



COLLAPS view *Liss Vasquez Rodriguez (Heidelberg), Tassos Kanellakopoulos (KU Leuven) and Mark Bissell (Manchester) at ISOLDE's Collinear Laser Spectroscopy experiment, COLLAPS, in 2019.*

Building on pioneering work by COLLAPS, the collinear laser beamline, CRIS, was constructed at ISOLDE 10 years ago by a collaboration between the groups of Manchester and KU Leuven. In CRIS, a bunched atom beam is overlapped with two or three pulsed laser beams that are resonantly laser-ionised via a particular hyperfine transition. These ions are then deflected from the remaining background atoms and counted in quasi background-free conditions. CRIS has dramatically improved the sensitivity of the collinear laser spectroscopy method so that beams containing just a few tens of ions per second can now be studied with the same resolution as the optical technique of COLLAPS.

Ruben de Groote of KU Leuven and co-workers recently used CRIS to study the moments and charge radii of the copper isotopes up to ^{78}Cu, providing critical information on the wave function and shape of these exotic neighbours, and insight on the doubly magic nature of ^{78}Ni. Both the ISOLTRAP and CRIS results provide a consistent picture of fragile equilibrium in ^{78}Ni, where the failing strength of the proton and neutron shell closures is shored up with binding energy brought by slight deformation.

These precision measurements in new regions of the nuclear chart bring complementary observables that must be coherently described by global theoretical approaches. They have stimulated and guided the development of new ab-initio results, which now allow the properties of extreme nuclear matter to be predicted. While ISOLDE cannot produce absolutely all nuclides on the chart (for example, the super-heavy elements), precision tests in other, key regions provide confidence in the global-model predictions in regions unreachable by experiment.

Most of the developments have been exported to other radioactive beam facilities around the world

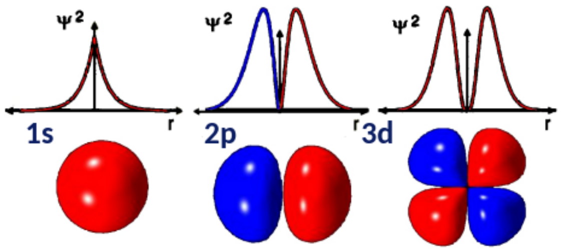
Searches for new physics

By combining the ISOLDE expertise in radioisotope production with the mass spectrometry feats of ISOLTRAP and the laser spectroscopy prowess from the CRIS and

Why Molecules?

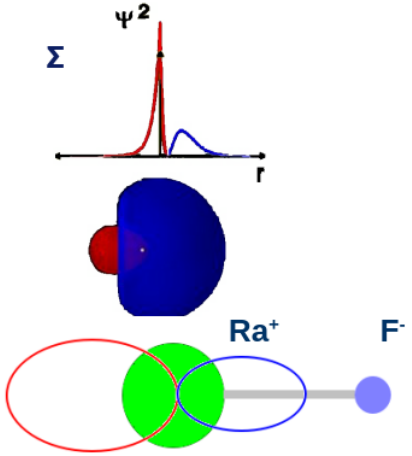
→ New windows into the study of the atomic nucleus, and the fundamental particles and interactions of nature!

Atoms



Figures modify from Orbitron ©2002 M. Winter (U. Sheffield)

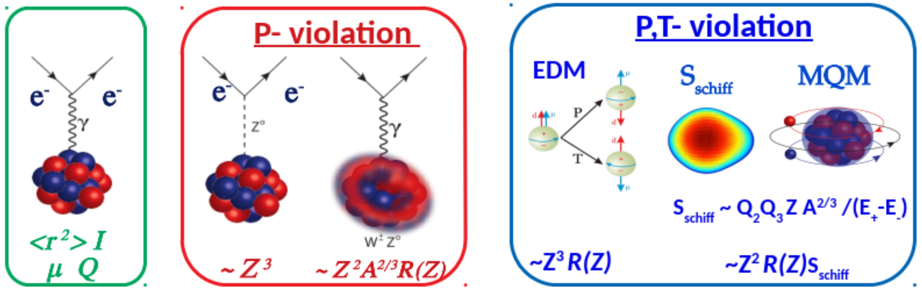
Molecules



- Parity violation > 10^{10}
- Parity and Time reversal violation > 10^{3}

[ACME, Nature 562, 355 (2018)]

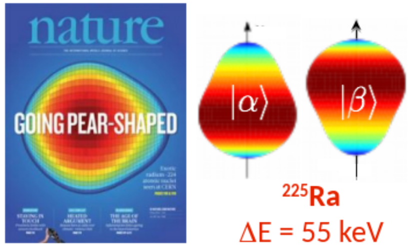
Why Molecules?



Molecules → x	10^N	>10^5	> 10^3	(x 10^5)

Exotic nuclei → Nuclear amplification (>10^3)

→ Large Z, A
→ Max. $Q_2 Q_3$
→ Min. $(E_+ - E_-)$

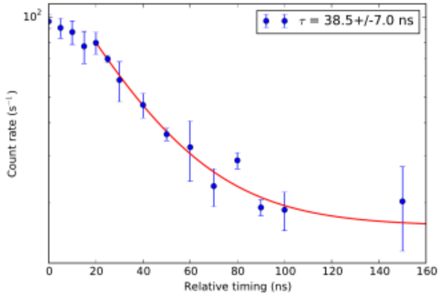


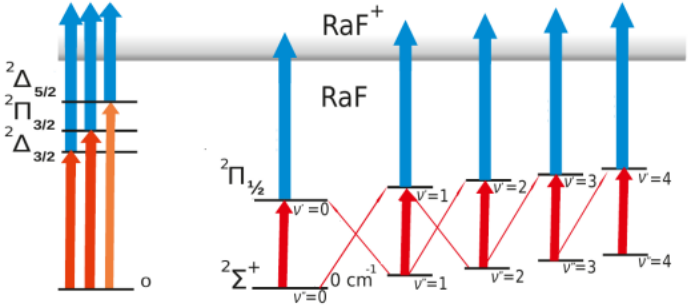
[Gaffney et al. Nature 497, 199 (2013)]

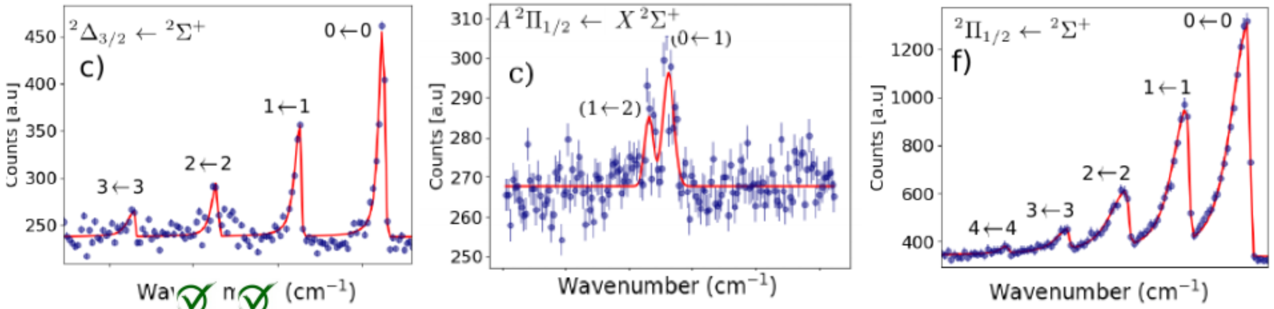
Exotic molecules → **Best of all** worlds
... **BUT, are experimentally unknown!**

Recent results

I. Low-lying structure ✓
II. Feasibility of laser cooling?
  1. Dominant f_{00}? → $f_{00}/f_{ij} > 0.97$ ✓
  2. Short-lived excited state ($T_{1/2}$)? → $T_{1/2} < 50$ ns ✓
  3. Electronic states of lower energy (E)? → 2000 cm^{-1} above ✓







6 $H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + H_{hfs} + H_{PV} + H_{PTV}$

[Garcia Ruiz et al. Nature 581, 396 (2020)]

"Hot" molecules can be super cool!

nature

Article | Open Access | Published: 27 May 2020

Spectroscopy of short-lived radioactive molecules

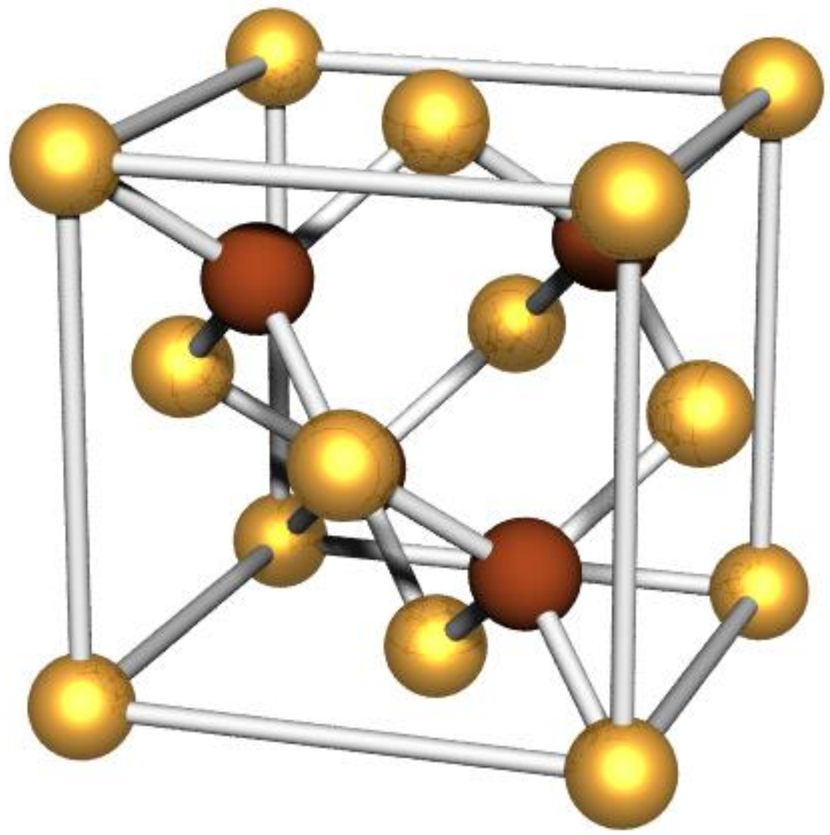
R. F. Garcia Ruiz, R. Berger, [...] X. F. Yang

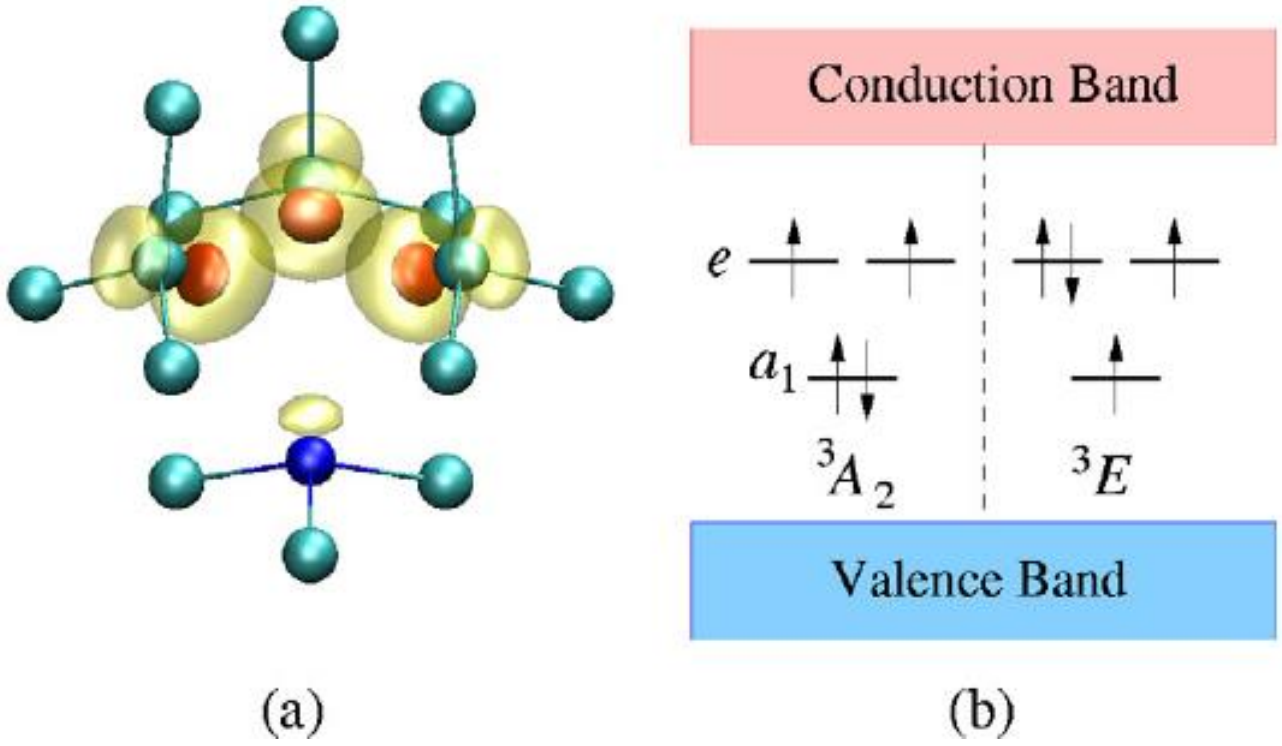
Nature **581**, 396–400(2020) | Cite this article

8120 Accesses | **145** Altmetric | Metrics

6 $H_{mol} = H_e + H_{vib} + H_{rot} + H_{sr} + H_{hfs} + H_{PV} + H_{PTV}$

Solid state physics in a nutshell



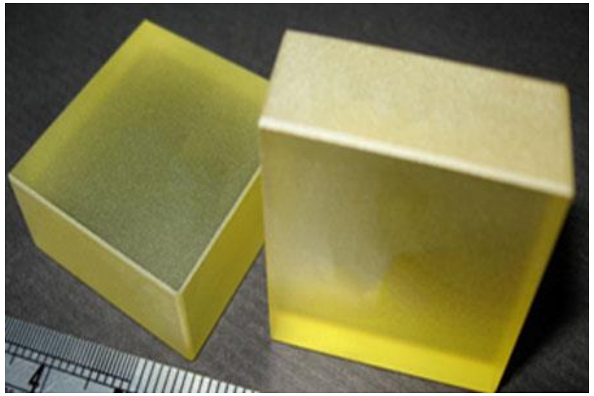


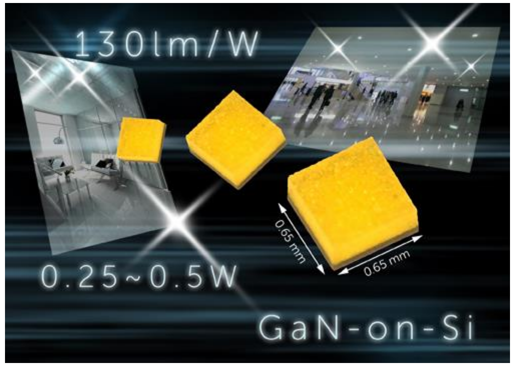
Structural information: location of atoms in lattice

Electronic information: what states are the electrons?

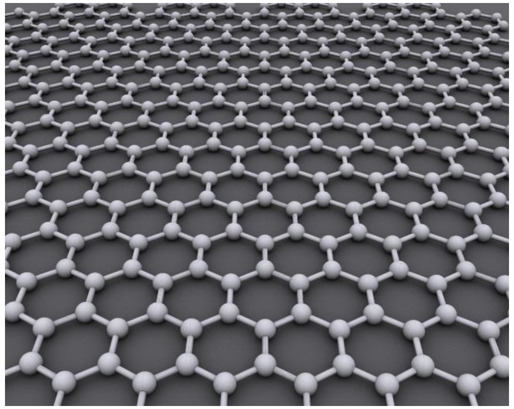
Materials being studied

Semiconductors

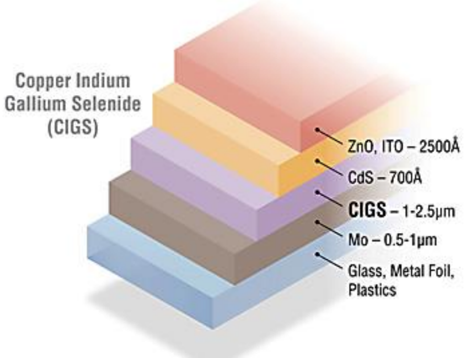




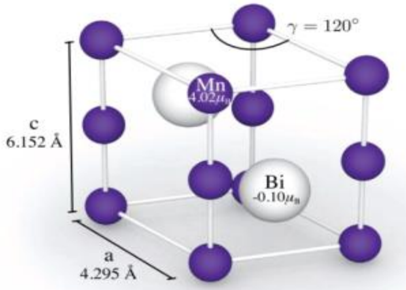
2D materials



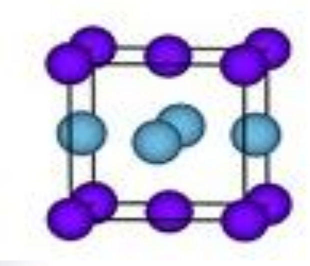
Solar cells



Future magnetic materials

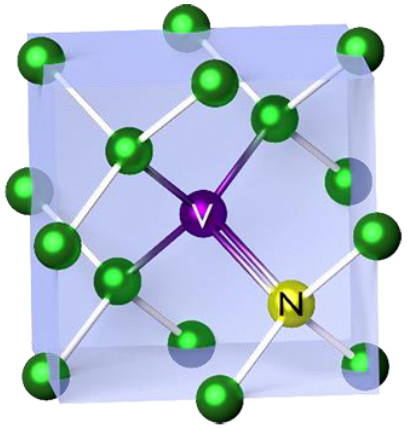


hex.- MnBi

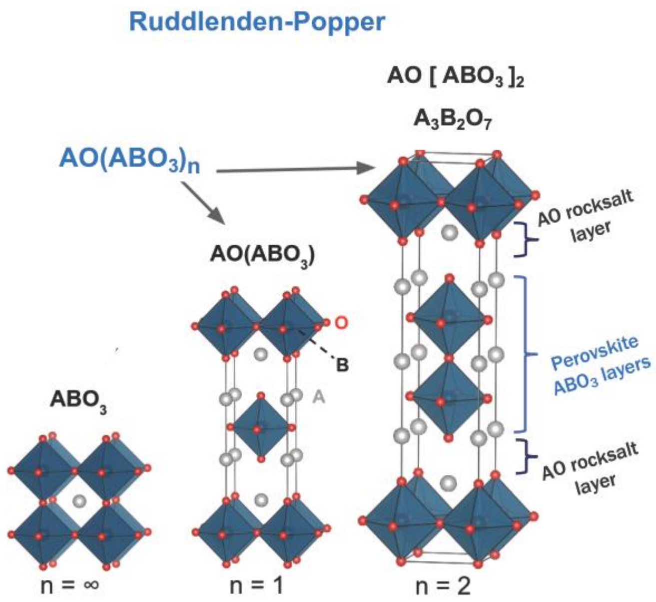


$L1_0$- MnAl

Quantum bits



Multiferroics



Use of radioactive isotopes in materials science:

- **Nuclear radiation acts as “marker” for a specific element:**
  - Radiotracer diffusion
- **Half-life of nuclear decay correlates with signal intensity from “classical” spectroscopy:**
  - Photoluminescence (PL)
  - Deep Level Transient Spectroscopy (DLTS)
  - Hall-effect
- **Nuclear radiation transmits information with atomic resolution:**
  - Mössbauer Spectroscopy (MS)
  - Perturbed Angular Correlation (PAC)
  - Emission Channeling lattice location (EC)
  - Beta Nuclear Magnetic Resonance (β-NMR)

ISOLDE Schedule 2022: weeks 12 - 48

GPS schedule 2022

Month	WK	MO	Entries	RILIS / beams
March	12	21	#627 Ta	RILIS : Dy
	13	28	IS688 (nights); #734 UCVD7; γ-MRI IS691	RILIS : Dy
April	14	4	#756 UCq n; IS685	RILIS : Cd
	15	11	IS685; #634 LIST; Good Fri	RILIS : Cd
	16	18	LOI 219 (LOI 217)	RILIS: Tl/Tb
	17	25		
May	18	2	#534 Sn VDS; IS647 IS652 IS679 IS703	111Cd
	19	9	#734 UCVD7 (TBC); IS659 IS668	8He/6He
	20	16	Tech Stop; #747 LIST	
	21	23	Ascension CERN Holiday (for May 1); IS664 LOI216	RILIS: Ac
	22	30	TBC	RILIS: Ac
June	23	6	Pentecost; IS668 + Colls	RILIS: Ga
	24	13		
	25	20	IS671 + tests	
	26	27	#758 UCq n; TAS IS684	RILIS: Zn
July	27	4		RILIS: Zn
	28	11	#761 UC	
	29	18	IS677 11Be @9-10MeV/u (Str Foil)	RILIS: Be
	30	25	IS702 27Na @9-10MeV/u	RILIS: Be; 27Na
August	31	1	#776 UC n	27Na
	32	8	TISD and IS717	1.7GeV
	33	15	TISD and IS717; #619 Pb	
	34	22	IS703 IS602	199Hg
	35	29	#776 UC n	Stable to MB
September	36	5	Jaune Genevois; IS680 30Mg @ 8MeV/u	RILIS: Mg
	37	12	TS 30h; #779 LaC	stable to MB/XT03
	38	19	XT03; IS698: 110, 108 Sn @ 4.9MeV/u	RILIS: Sn
	39	26	IS698: 110, 108 Sn @ 4.9MeV/u; IS686 110Sn@8MeV/u	RILIS: Sn
October	40	3	TBC UC; IS668 + colls	RILIS: Sn
	41	10	#779 LaC; IS717	1.7GeV
	42	17	#782 UCVD7; IS711 92, 94Kr @ > 7MeV/u	Kr beams
	43	24	IS711 92, 94Kr @ 7.5MeV/u; γ-MRI IS691	Xe beams
	44	31	#534 Sn; IS647 IS652 IS679 IS703	111Cd
November	45	7	#784 UC W; IS697: 131Sb, 133Sb @ 4 MeV/u	RILIS: Sb
	46	14	IS587: 68Ni @ 5MeV/u	RILIS: Ni
	47	21	#619 or #772 Pb; IS563: 182, 184Hg @ 4MeV/u	Hg beams
	48	28		

HRS schedule 2022

Month	WK	MO	Entries	RILIS / beams
March	12	21		
	13	28	#654 UC W; MD + VITO tests	
April	14	4	#753 UC	
	15	11	Good Fri; IS700	RILIS : Al
	16	18	#754 UCn	RILIS : Al
	17	25	IS667	RILIS : Te
May	18	2	#751 UCVDS; TISD (LISA) and/or MD	RILIS : Te
	19	9	#754 UC	
	20	16	Tech Stop; IS666	49K
	21	23	Ascension CERN Holiday (for May 1)	
	22	30	#755 UC n; IS660	RILIS: Ag
June	23	6		RILIS: Ag
	24	13	#752 LIST; IS456 & LOI225	RILIS: Po
	25	20	LA1	RILIS: Po
	26	27	#757 UC n	
July	27	4	IS704	RILIS: Sb
	28	11	#654 UC W; IS666	49K
	29	18	IS687	
	30	25		
August	31	1	TBC	
	32	8	TISD/MD	
	33	15	#757 UC n; IS622	RILIS: Cu
	34	22	UC	
	35	29	TBC IDS development? Else preference for early start of IS680	
September	36	5	#774 LaC; Jaune Genevois	
	37	12	TS 30h; IS718	RILIS: Sn
	38	19		RILIS: Sn
	39	26		
October	40	3	#751 UC VDS	
	41	10	TISD	
	42	17		
	43	24	#781 UC VADIS; TISD	
	44	31	IS702: 130Sn @ 4.4MeV/u	SnS beam
November	45	7	#754 UC	
	46	14	IS666	37K
	47	21	#751 UC VDS	
	48	28	IS706 (Winter)	AcF beams

Start of protons for physics: 28 March
End of protons for physics: 28 November

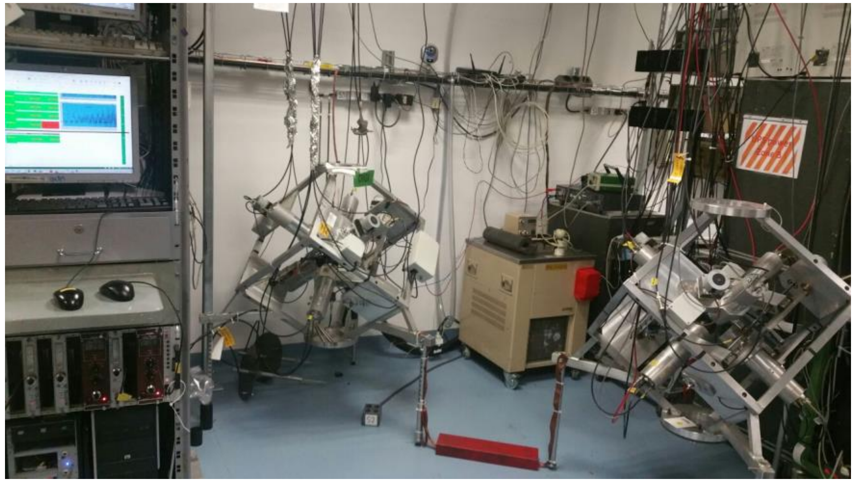
Target change	CERN holiday	Setting up/proton scan/yield	Physics HPS	Physics GRS	RILIS run

KJ: 23.11.22

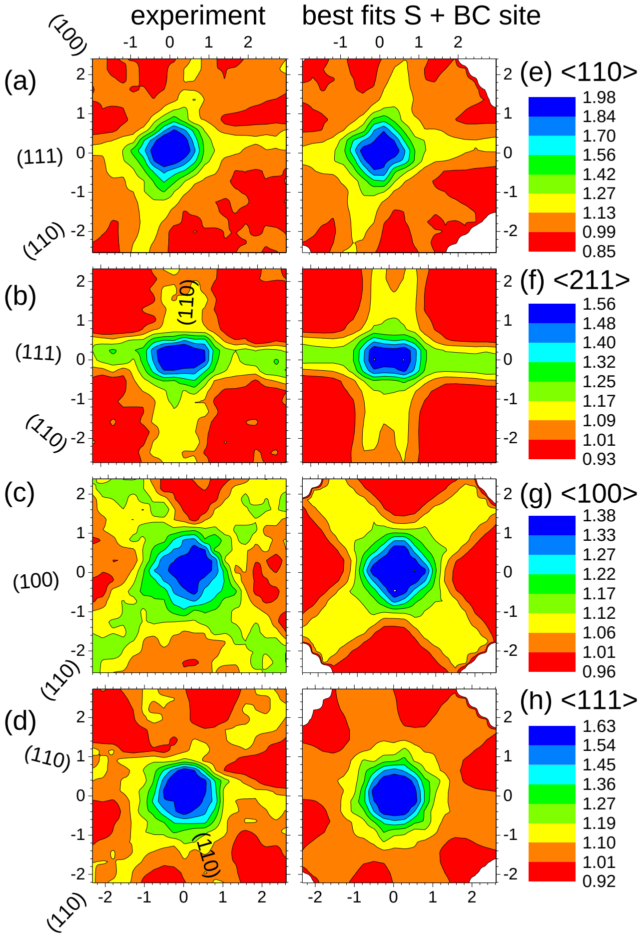
Offline labs based at ISOLDE

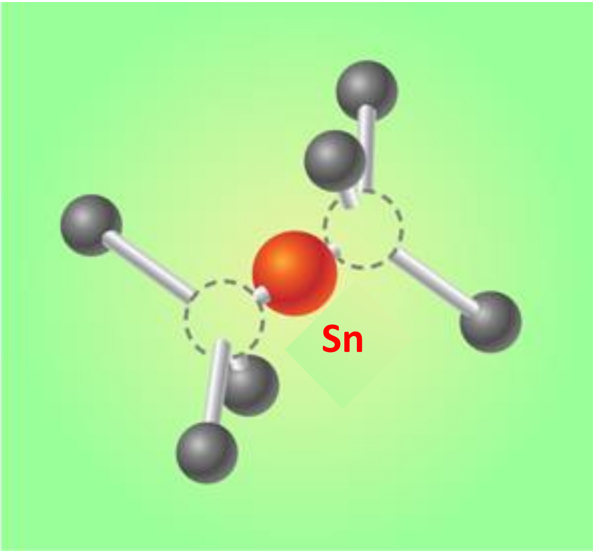






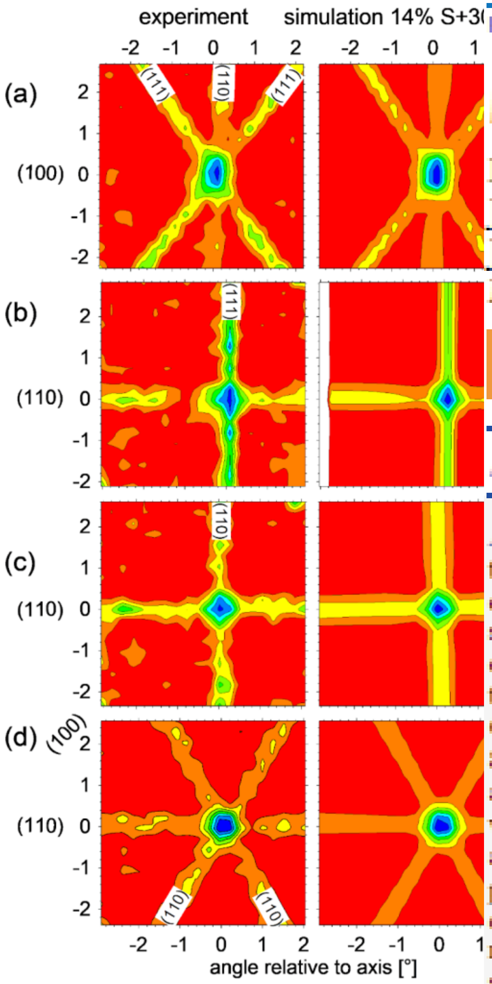

^{121}Sn-vacancy: identification and quantification





- 30% of the implanted Sn in split vacancy configuration!
- Sn exactly at the bond-center (precision of 0.04 Å)
- Other IV elements (ongoing): ^{31}Si, ^{73}Ge, ^{121}Sn, ^{209}Pb

Phys. Rev. Lett. **125**, 045301 2020



T_i=800°C

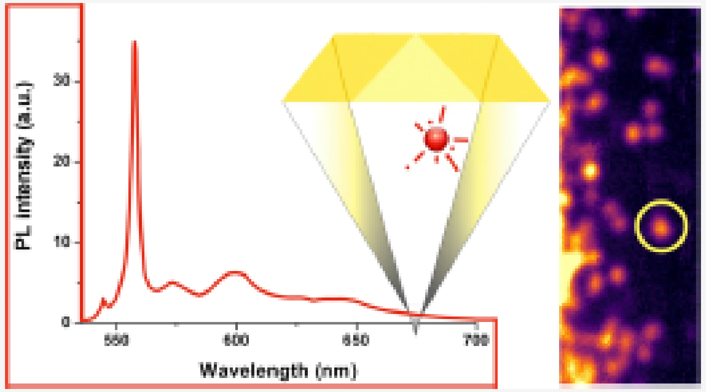
ACS Photonics
pubs.acs.org/journal/apchd5
Article

Magnesium-Vacancy Optical Centers in Diamond

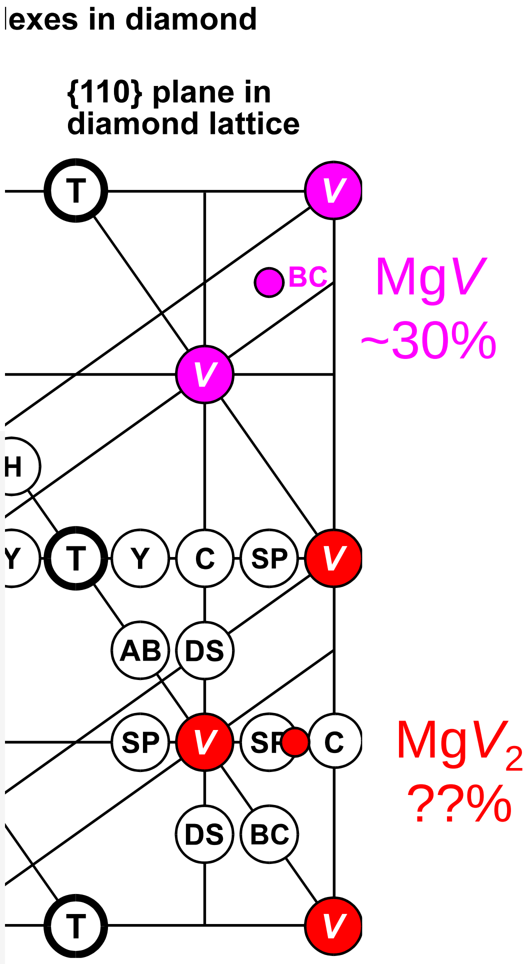
Emilio Corte,[∇] Greta Andrini,[∇] Elena Nieto Hernández, Vanna Pugliese, Ângelo Costa, Goele Magchiels, Janni Moens, Shandirai Malven Tunhuma, Renan Villarreal, Lino M. C. Pereira, André Vantomme, João Guilherme Correia, Ettore Bernardi, Paolo Traina, Ivo Pietro Degiovanni, Ekaterina Moreva, Marco Genovese, Sviatoslav Ditalia Tchernij, Paolo Olivero, Ulrich Wahl,* and Jacopo Forneris*

Cite This: https://doi.org/10.1021/acsphotonics.2c01130
Read Online

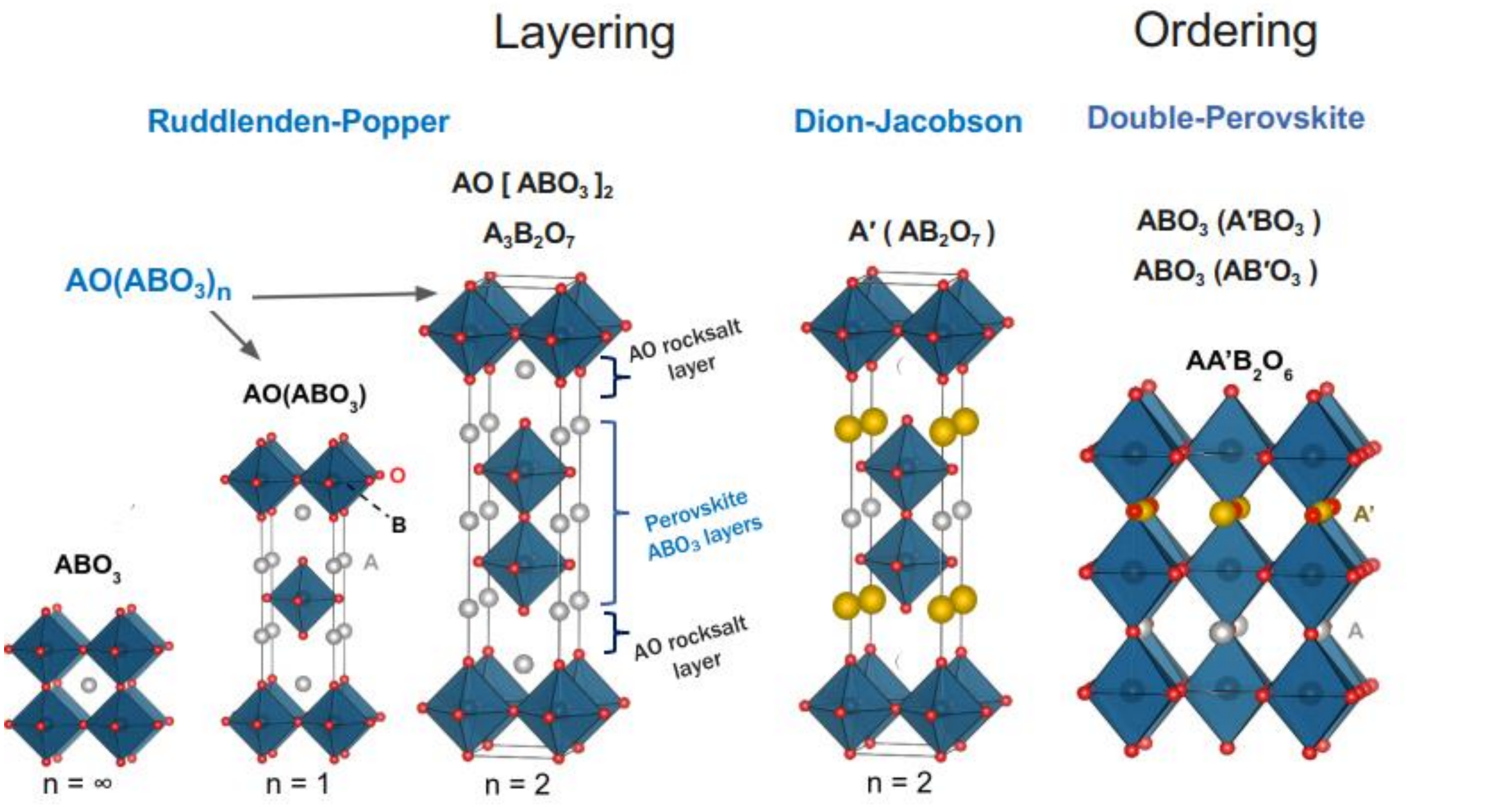
ABSTRACT: We provide the first systematic characterization of the structural and photoluminescence properties of optically active centers fabricated upon implantation of 30−100 keV Mg^+ ions in synthetic diamond. The structural configurations of Mg-related defects were studied by the electron emission channeling technique for short-lived, radioactive ^{27}Mg implantations at the CERN-ISOLDE facility, performed both at room temperature and 800 °C, which allowed the identification of a major fraction of Mg atoms (∼30 to 42%) in sites which are compatible with the split-vacancy structure of the MgV complex. A smaller fraction of Mg atoms (∼13 to 17%) was found on substitutional sites. The photoluminescence emission was investigated both at the ensemble and individual defect level in the 5−300 K temperature range, offering a detailed picture of the MgV-related emission properties and revealing the occurrence of previously unreported spectral features. The optical excitability of the MgV center was also studied as a function of the optical excitation wavelength to identify the optimal conditions for photostable and intense emission. The results are discussed in the context of the preliminary experimental data and the theoretical models available in the literature, with appealing perspectives for the utilization of the tunable properties of the MgV center for quantum information processing applications.



KEYWORDS: *diamond, ion implantation, magnesium, color centers, emission channeling, lattice location*



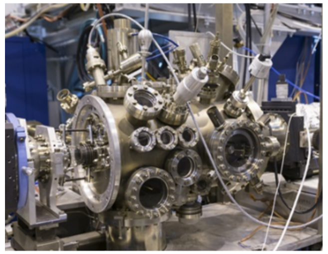
Perovskite related structues



Future possibilities: available in 2022-23

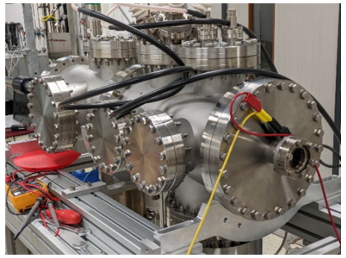
ASPIC

Surface/interface
Modification & characterization



ASCII

Ultra-low energy implanation
Control of probe isotopes



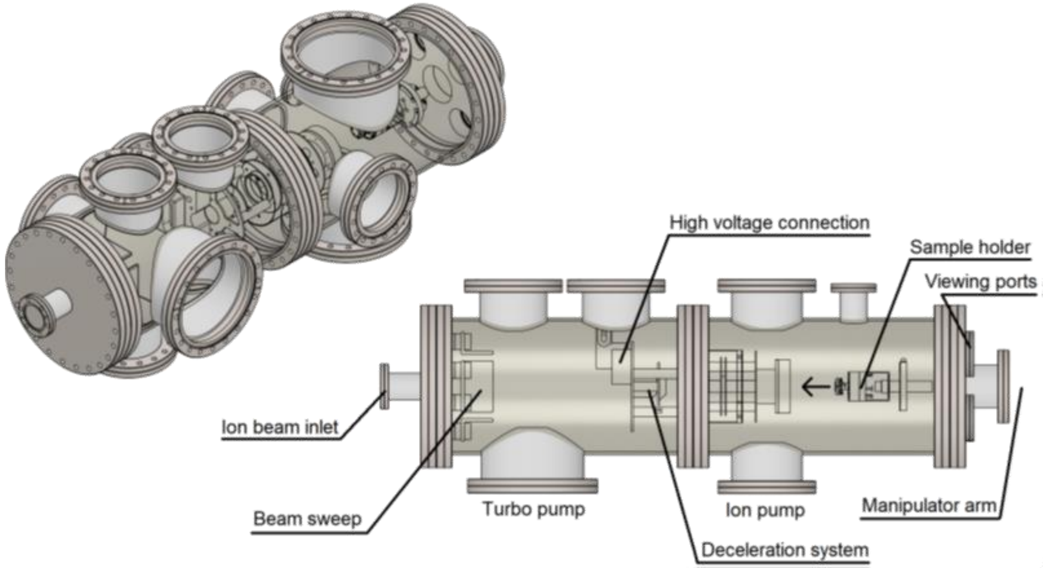
PAC

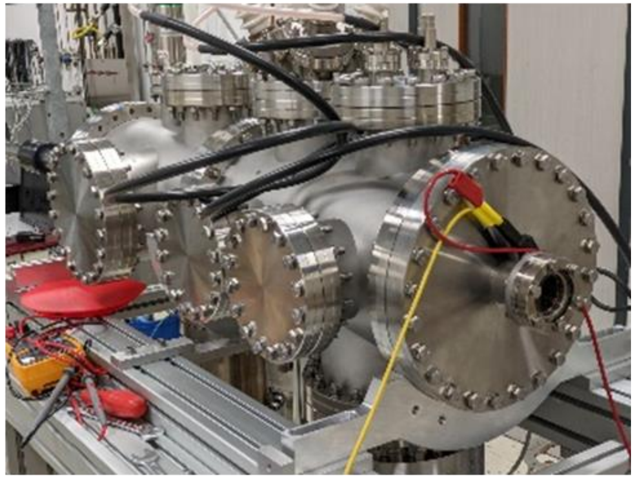
(atomically) local information

research into

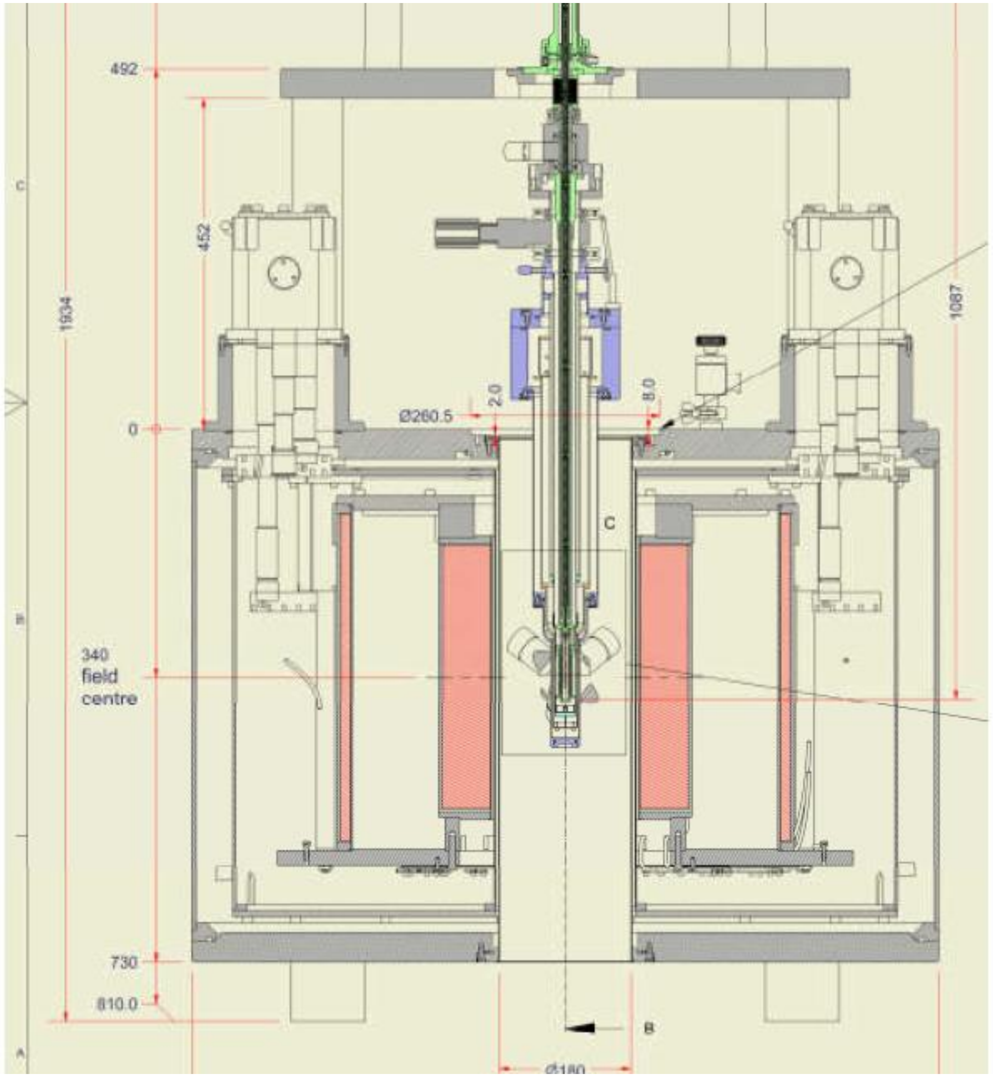
2D materials

- **AS**PI**C**'s **I**on **I**mplantation chamber
- Decelerates ions from 60 keV to ≤ 20 eV

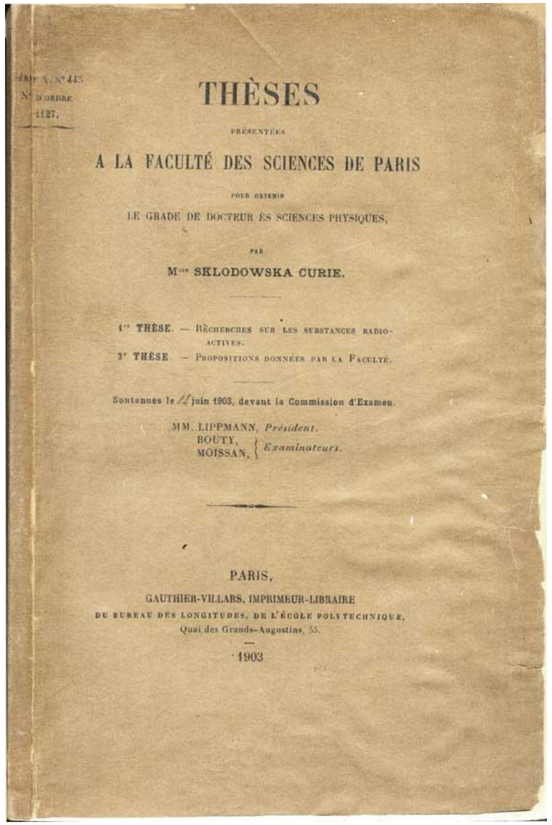




High field magnetic spectrometer to study magnetic materials using PAC



The early days



THÈSES

PRÉSENTÉES

A LA FACULTÉ DES SCIENCES DE PARIS

POUR OBTENIR

LE GRADE DE DOCTEUR ÈS SCIENCES PHYSIQUES,

PAR

Mme SKLODOWSKA CURIE.

1re THÈSE. — Recherches sur les substances radio-actives.

2e THÈSE. — Propositions données par la Faculté.

Soutenues le juin 1903, devant la Commission d'Examen.

MM. LIPPMANN, *Président*.
BOUTY, MOISSAN, } *Examinateurs*.

PARIS,

GAUTHIER-VILLARS, IMPRIMEUR-LIBRAIRE

DU BUREAU DES LONGITUDES, DE L'ÉCOLE POLYTECHNIQUE,

Quai des Grands-Augustins, 55.

1903

Marie Sklodowska-Curie
1867-1934

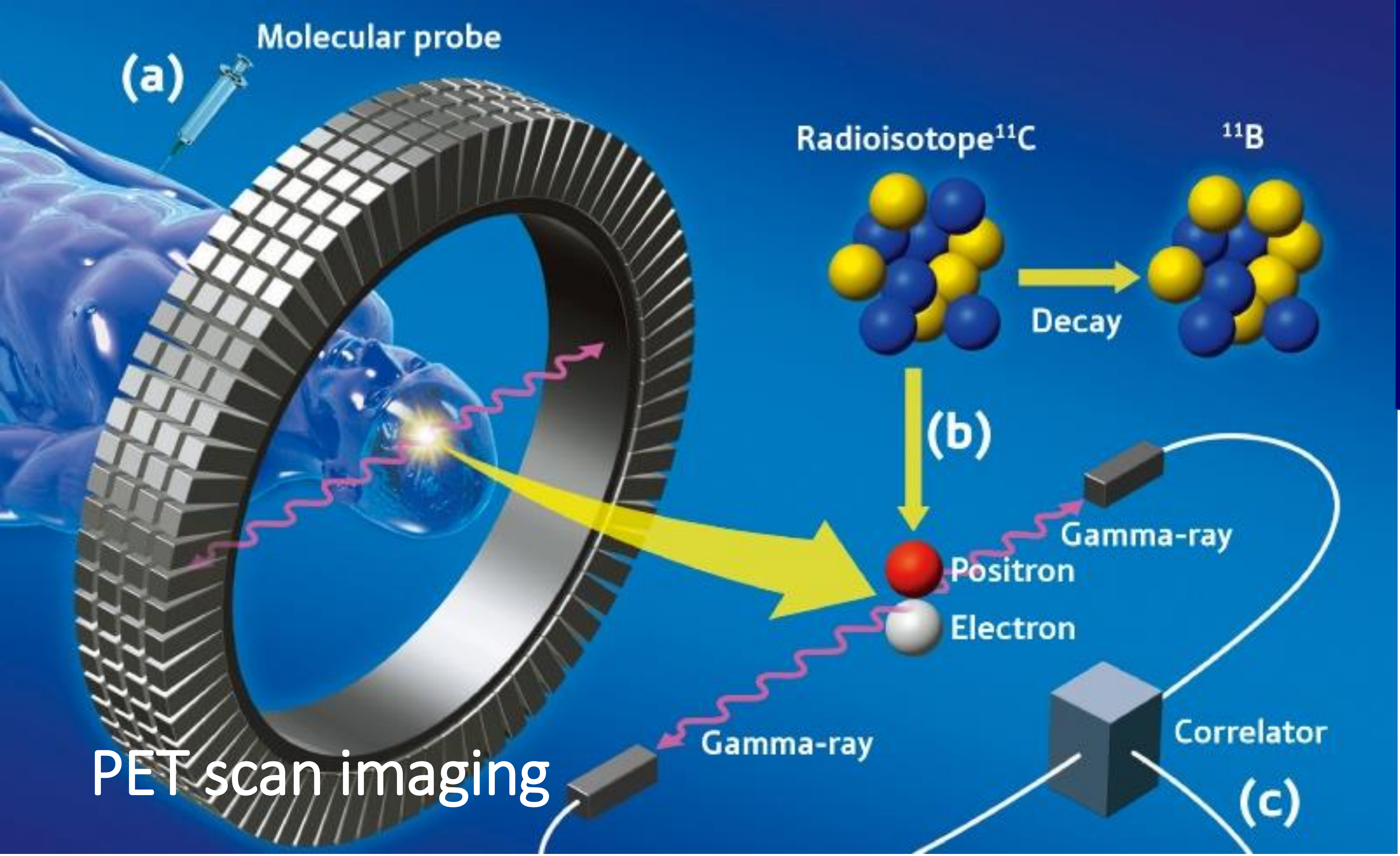
Published:
May 12th 1921
© The New York Times

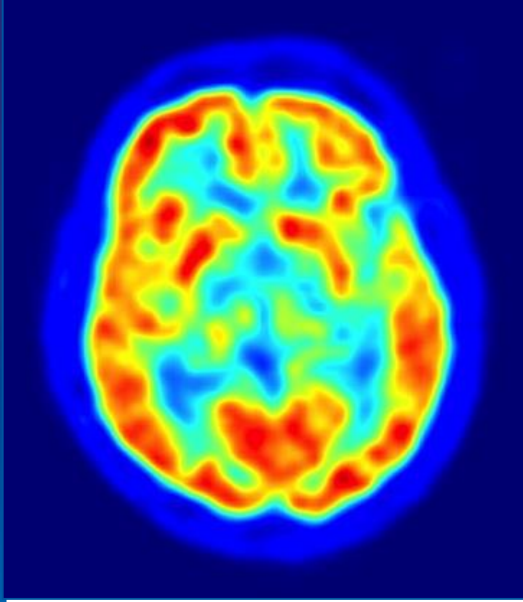
The New York Times.

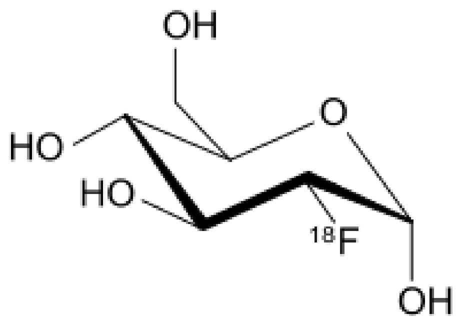
MME. CURIE PLANS TO END ALL CANCERS

Says Radium Is Sure Cure, Even in Deep-Rooted Cases, if Properly Treated.

Courtesy prof O. Ratib







Fluorodésoxyglucose (^{18}F)

PET-CT scan imaging

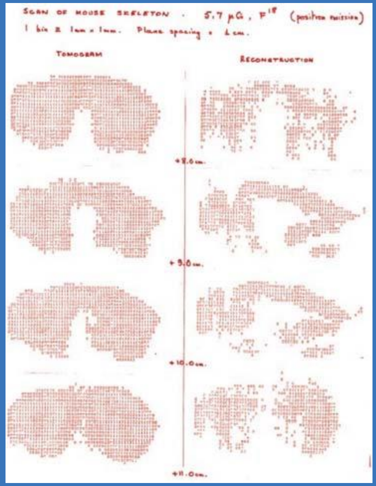
1977

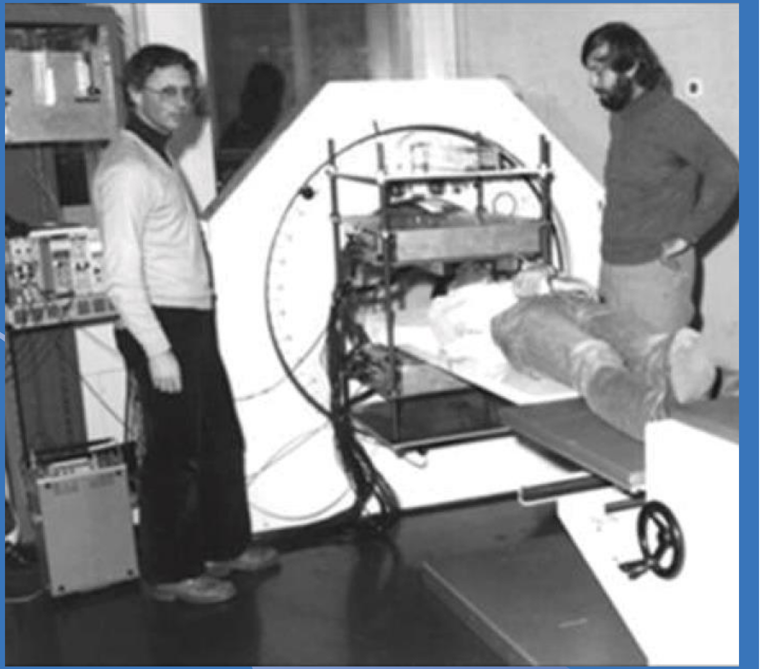
Alan Jeavons and David Townsend

Alan Jeavons and David Townsend

built and used in Geneva Hospital

a PET system based on
high-density avalanche gas chambers
HIDACs





CMASC - UA - 30.3.16

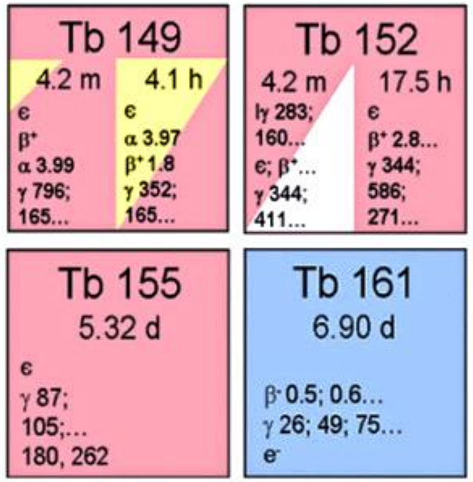
TERA 3

Courtesy Ugo Amaldi

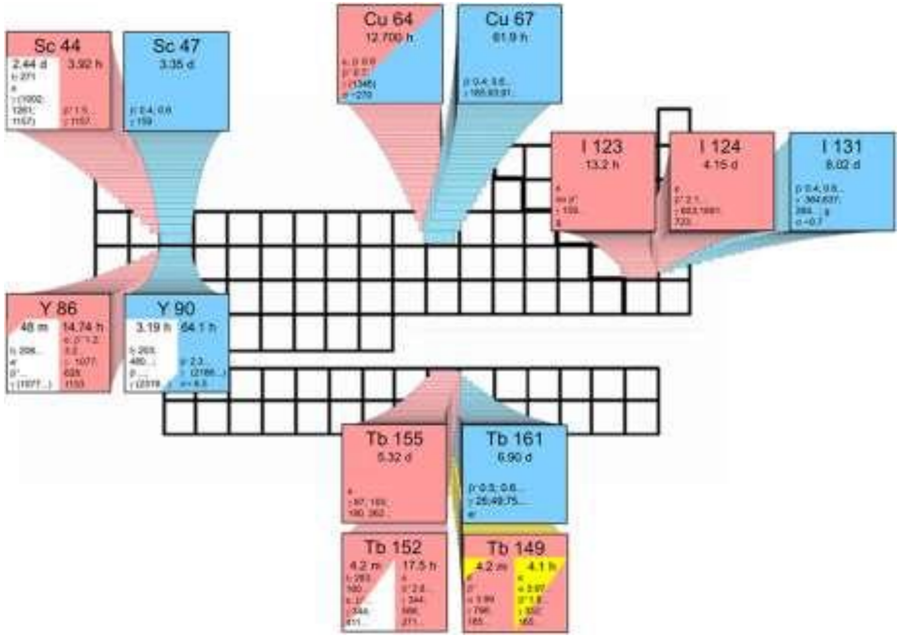
https://home.cern/news/news/knowledge-sharing/forty-years-first-pet-image-cern

Nuclear Physics : ISOLDE and MEDICIS

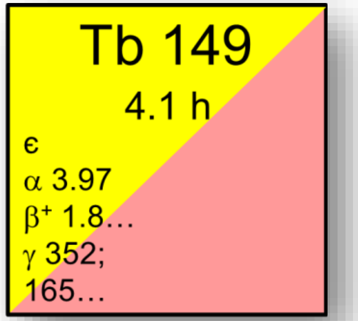
14 years ago – now :
Innovative radioisotopes

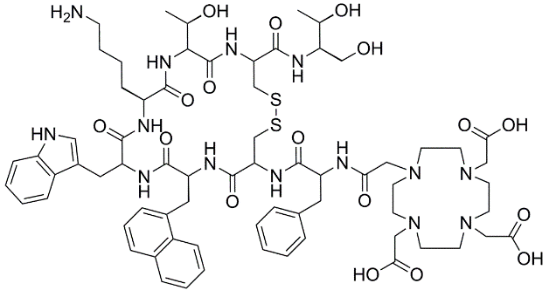


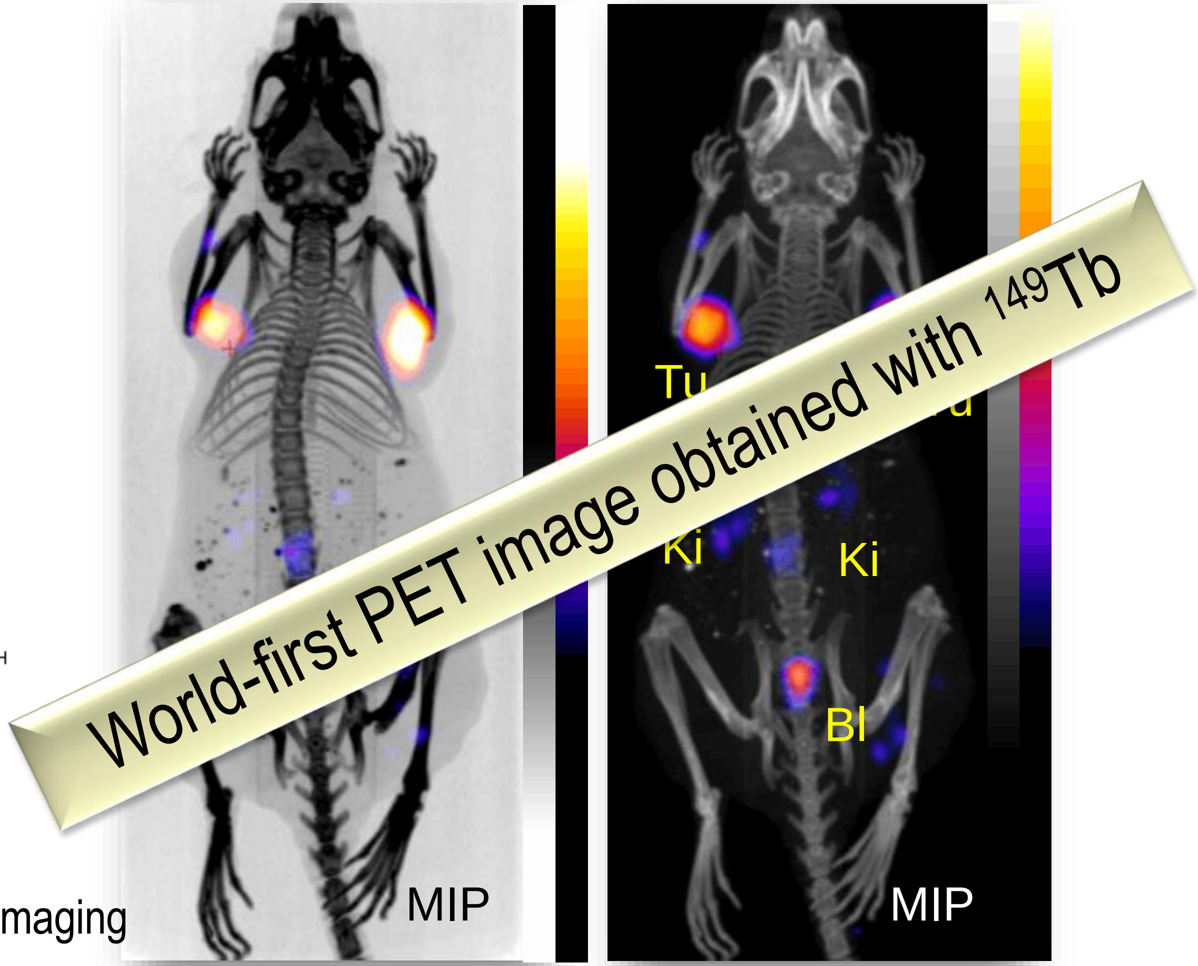
Matched pairs for theranostics



^{149}Tb





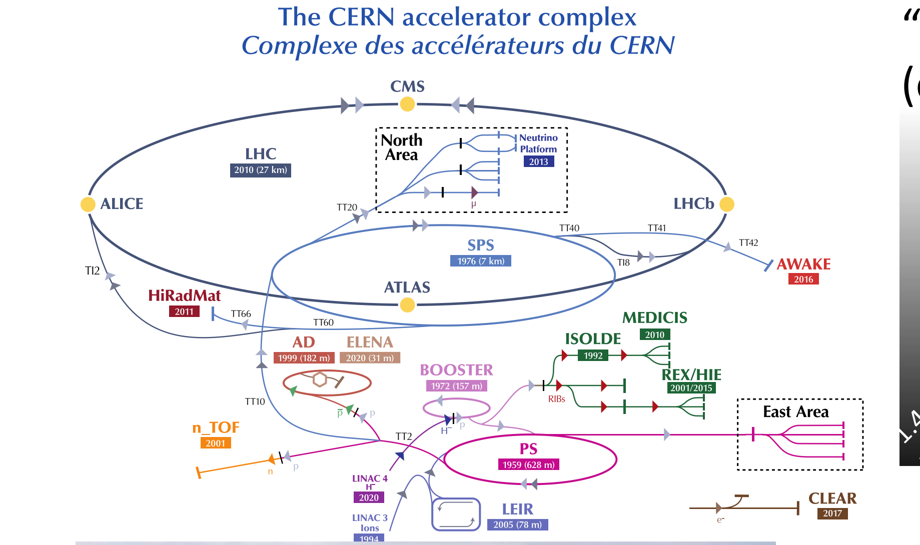


Useful for α-Therapy and PET Imaging

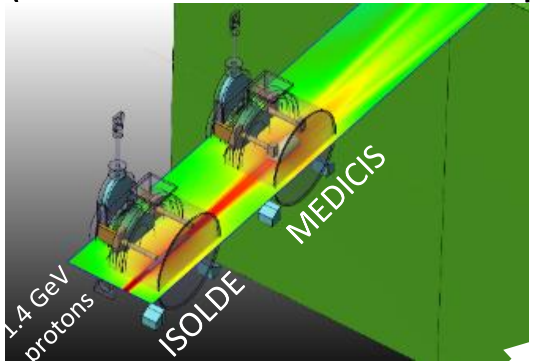
PET/CT scan of a AR42J tumor-bearing mouse performed 2 h after injection of ^{149}Tb-DOTANOC

Muller et al., *EJNMMI Radiopharmacy and Chemistry*, (2016) 1:5.

Mass separation as applied in MEDICIS in a snapshot

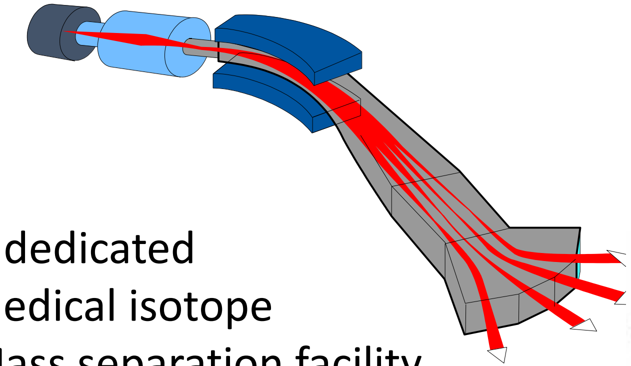


"Free" proton beam
(otherwise lost in the dump)

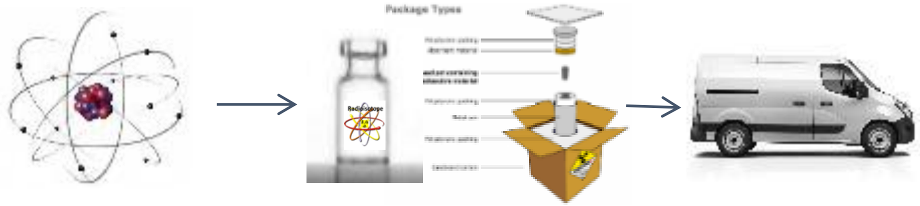


Some **MEDICIS isotopes** :

High activity Sm-153, Ba/Cs-128, Tm/Er-165

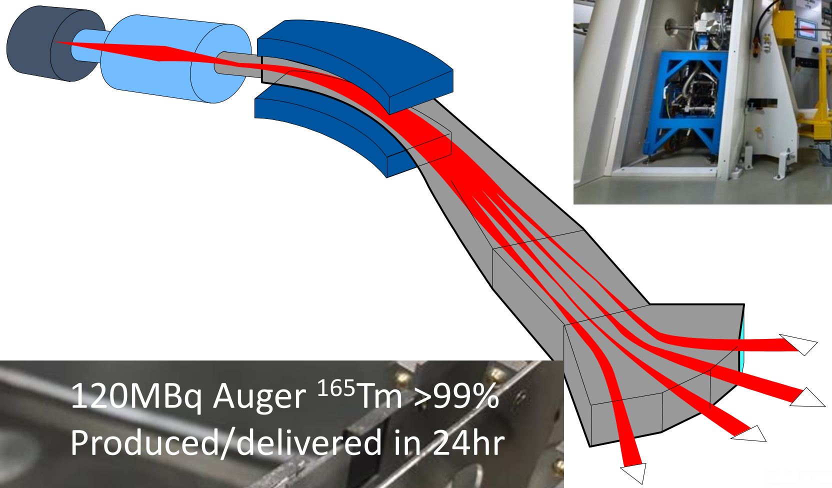


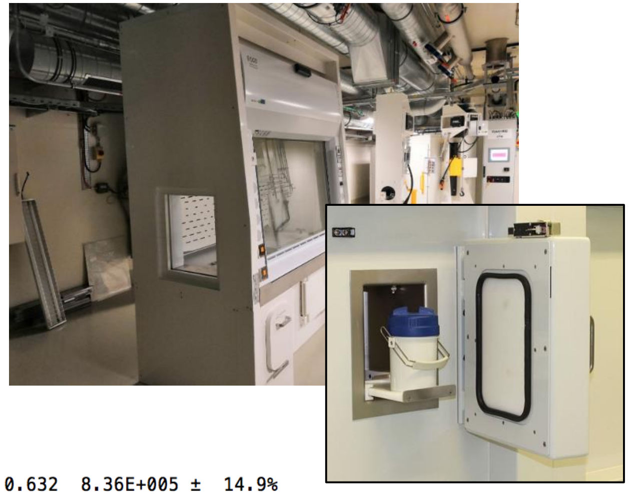
A dedicated
medical isotope
Mass separation facility
in Europe.



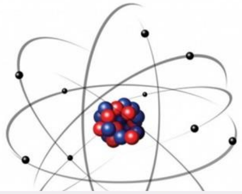
From CERN- MEDICIS to the lab/Hospital

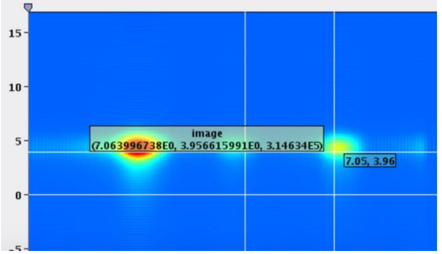
From CERN- MEDICIS to the lab/Hospital



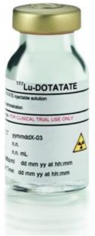


Gd-149	@	9.28E+000 D	0.632	8.36E+005	±	14.9%
Tb-149	@	4.12E+000 H	0.964	1.71E+006	±	9.4%
Er-165		1.04E+001 H	0.894			
Tm-165	@	1.25E+000 D	0.979	1.21E+008	±	6.3%

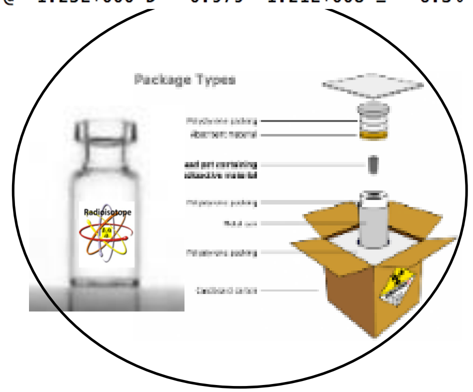




→



→



→

Isotope separation for experiment MED011
from external 168/169Er source

From CERN- MEDICIS to the lab/Hospital
(Countries: BE, CH, FR, PK, PT, LV, UK)

How to supply "novel" radionuclides with mass separation

- **PRISMAP** proposes to federate a consortium of high energ… cyclotrons, research reactors, and isotope mass separation … in

Accelerator

Isotope mass separation

Research reactor

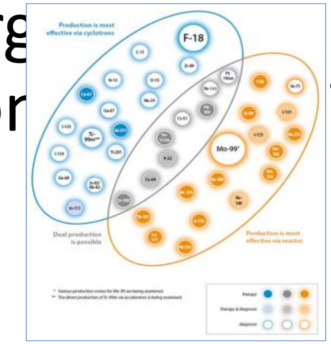
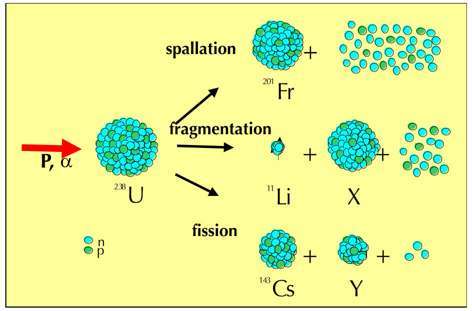


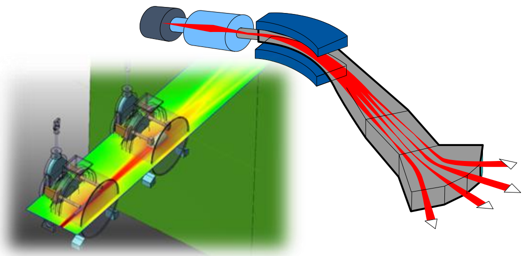
Figure 31 : Main medical radioisotopes production process

European Commission ENER/17/NUCL/SI2.755660 (2018)

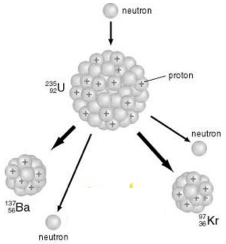


$I_{[pps]} \sim F_{[pps]}\ S_{[barn]}\ N_{[g/cm2]}$ **production rate**

10^{10}pps 100µA (6.10^{14}) 1mbarn 1g/cm^2 for A_{target}=30g/mol



$I_{[pps]} \sim F_{[pps]}\ S_{[barn]}\ N_{[g/cm2]}\ e_{[\%]}$



$$\frac{dN'}{dt} = nv\sigma_{act} N_T$$

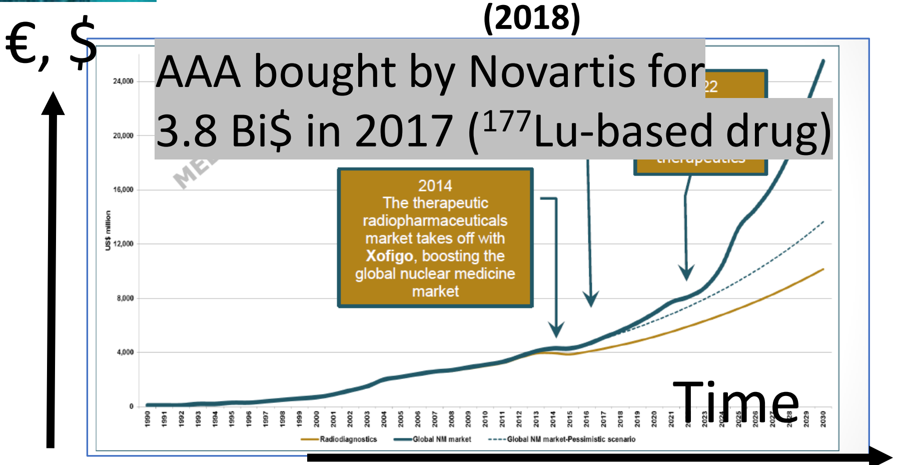


Figure 8: Possible market evolution for radiotherapeutics – source MedRaysIntell (2016)

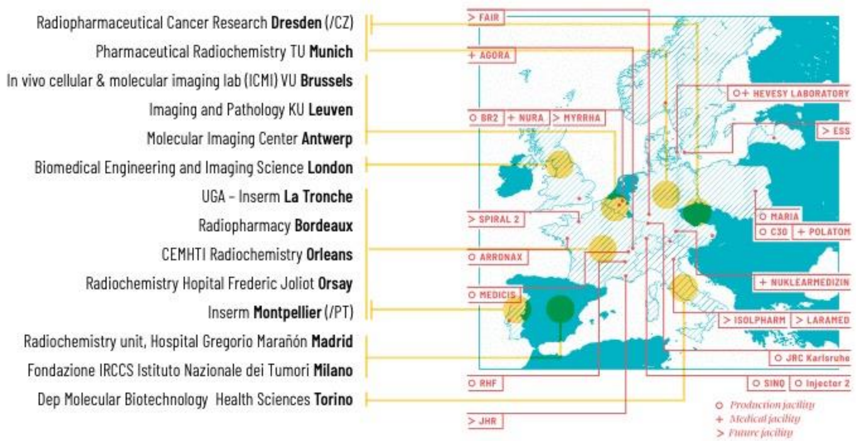
Economics, Innovators

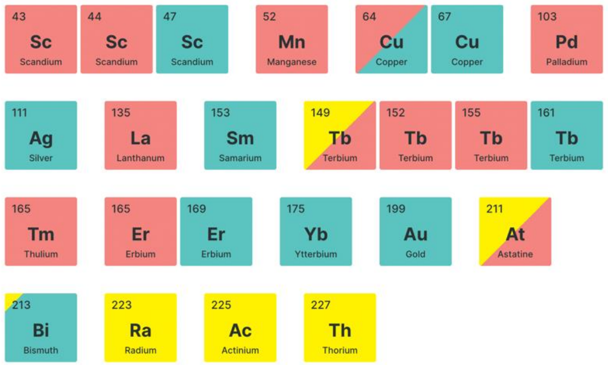
PRISMAP – The European medical radionuclides programme (2021-2025)

https://medical-radionuclides.eu

- Achievements in 2022:
  - 15 projects for biomedical research with novel radionuclides were selected for services across Europe

    www.prismap.eu/access/user-projects (BE, CZ, DE, ES, FR, IT, PT, UK)





…ch needs in the field of novel biomedical radionuclides to the EU Commissioner for research and education Mariya Gabriel