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Outline

What do we have?
What can we do?
What did we do?
What do we want to do?

Dorothea Schumann, Rugard Dressler

Radioactive isotope and target production for nuclear astrophysics

Nuclear Astrophysics at the Dresden Felsenkeller, 26.-28.06.2017

Overview

The ERAWAST project

Sources for isotopes at PSI
Processing material from outside

List of available isotopes and performed measurements

Examples for isotope and target preparation

^{10}Be from graphite wheels
^{91}Nb from irradiated ^{92}Mo
^{60}Fe from copper

Requirements for isotope and target preparation

Summary

ERAWAST@PSI

(Exotic Radionuclides from Accelerator WAste for Science and Technology)

Objective:

Exploitation of accelerator waste for isolating rare exotic radionuclides

History:

- Radiochemical analytics of activated components for disposal
- Results showed high content of several rare isotopes
- Looking for potential users of these isotopes: I. ERAWAST workshop 2006 (PSI), funded by ESF
- Five-years working program
- II. ERAWAST workshop 2011 at PSI: first results and future program
- CHANDA-workshop in 2015
- ~ 20 Partners
- Member of n_TOF

Collaboration between

Nuclide production facilities

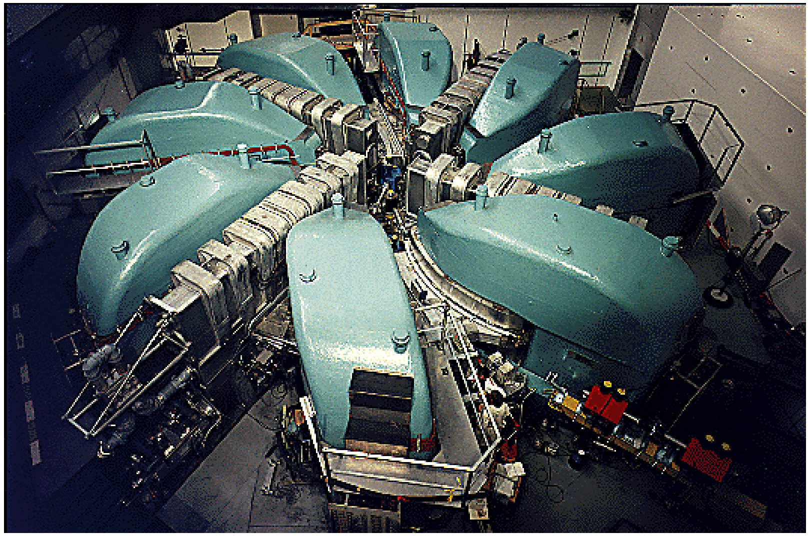
Basic nuclear physics research

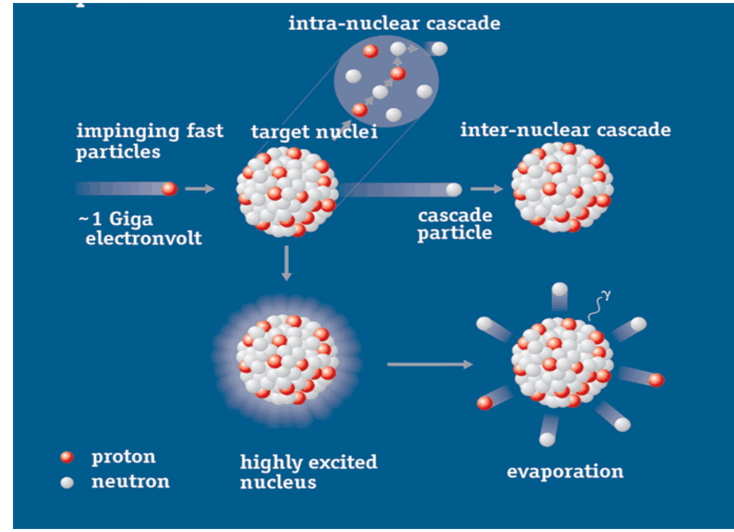
Nuclear astrophysics

AMS measurement groups

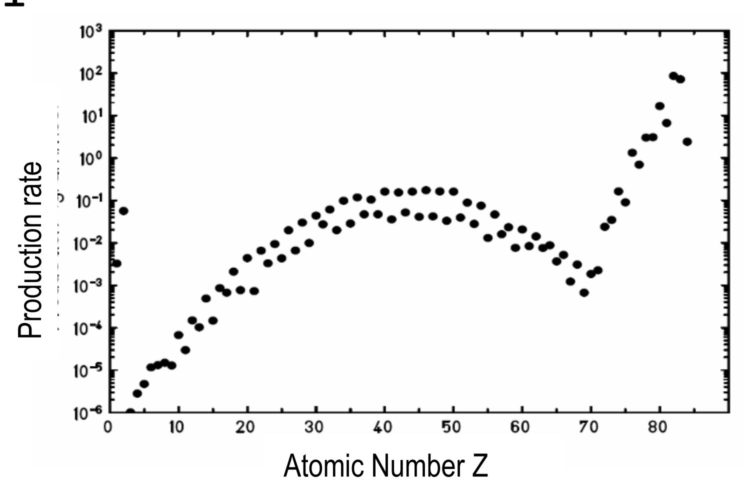
Environmental chemistry

Spallation Reactions and PSI facilities

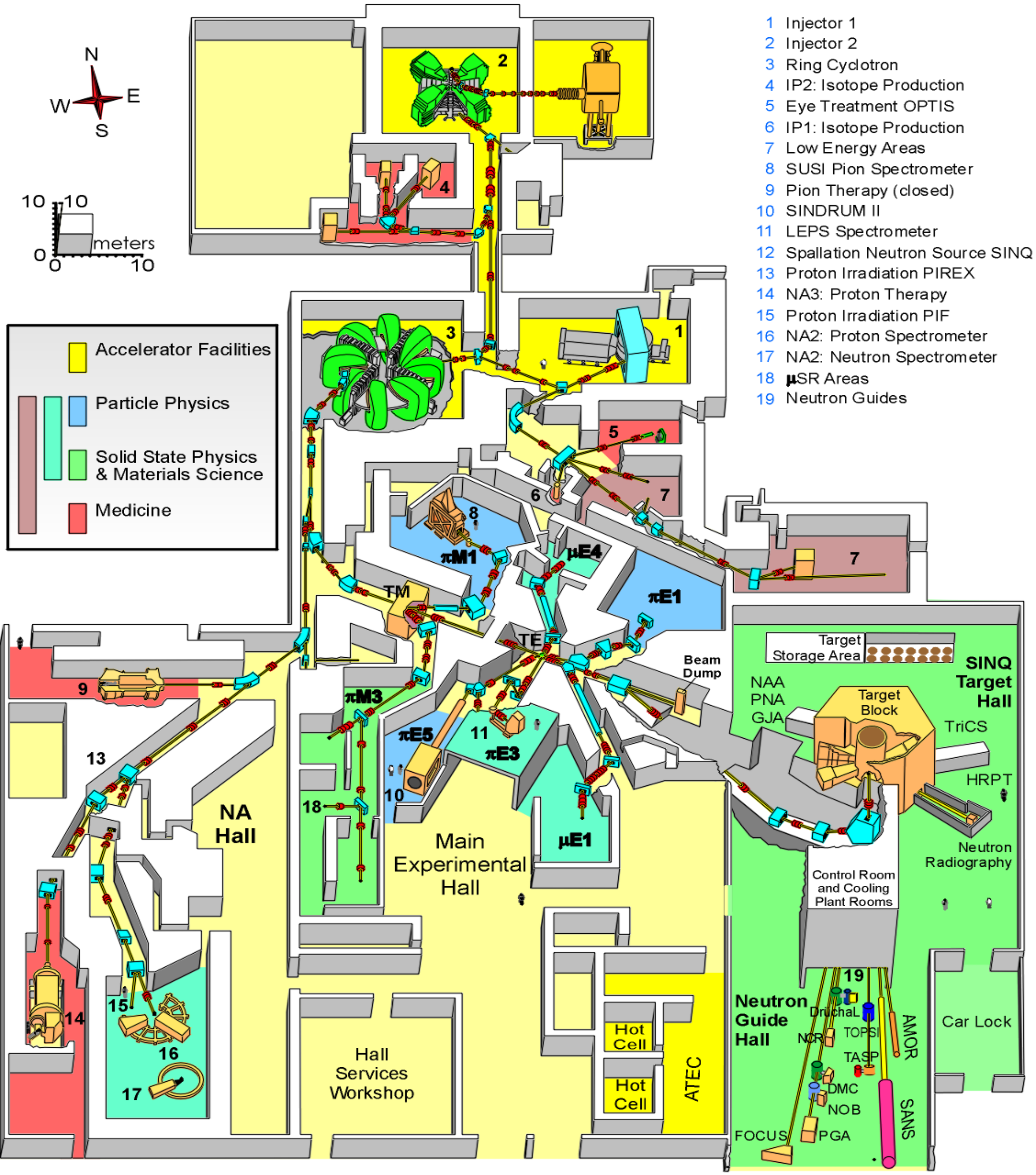




All elements of periodic table with $Z \leq Z_{target} + 1$



- 590 MeV protons
- 2.4 mA beam current
- High activiation of shieldings, targets, structure material



PSI accelerator facilities

Injector cyclotron (72 MeV protons)

590 MeV Ring Cyclotron (up to 2.4 mA proton beam current)

SINQ – spallation neutron source

COMET (cyclotron 250 MeV) for medical use

Ultra Cold Neutrons

SLS Swiss Light Source

„Useful“ components

Copper beam dump

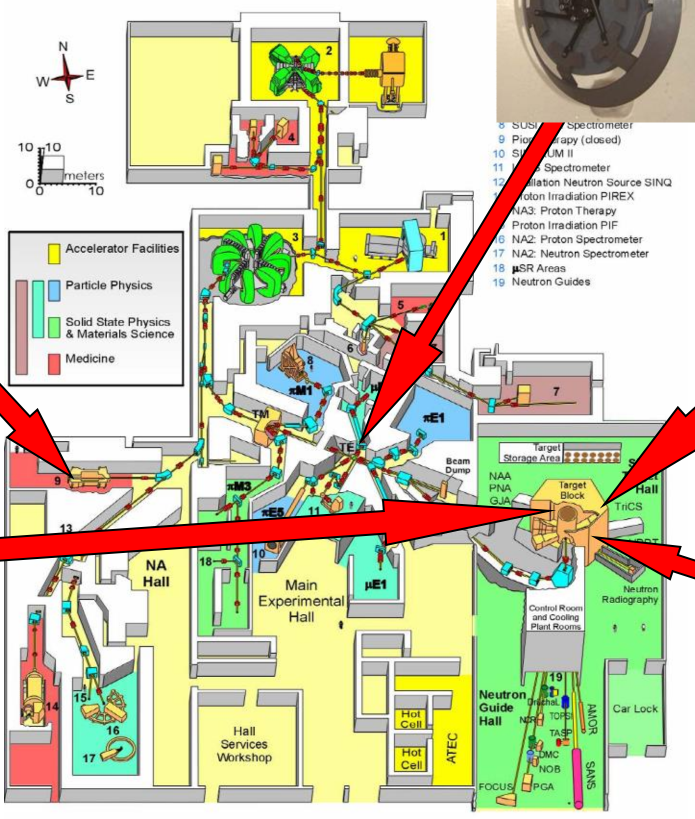
- ^{44}Ti, ^{53}Mn, ^{26}Al, ^{60}Fe
- ^{60}Co – 5 GBq

Myon production station

- Operation 1-3 years
- Beam doses 4 – 11 Ah
- Source for ^{10}Be

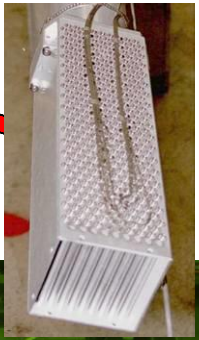
SINQ Target Irradiation Program-STIP

^{44}Ti, ^{53}Mn, ^{26}Al, Lanthanides



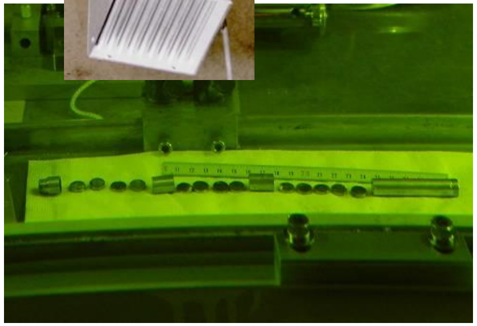
SINQ cooling water

^{7}Be, ^{54}Mn, ^{22}Na, ^{88}Y



SINQ target

- ^{207}Bi, ^{172}Hf,
- ^{173}Lu, ^{194}Hg,
- ^{202}Pb, ^{125}Sb,
- ^{106}Ru, ^{44}Ti



Special irradiation positions with 590 MeV protons

V for ^{32}Si production

Processed material from outside

Target manufacturing and measurements finished

• ^{63}Ni @ n_TOF	10 mg	neutron capture cross section
• ^{171}Tm @ n_TOF, SARAF, Mainz	3 mg	neutron capture cross section
• ^{147}Pm @ n_TOF	72 µg	neutron capture cross section

Isotope separation performed, samples ready for use

• ^{163}Ho@HOLMES	1.5 mg	neutrino mass measurement
• ^{91}Nb@FRANZ	1 µg	neutron capture cross section

Isotope production planned

• ^{79}Se@n_TOF	?	neutron capture cross section

Isotopes produced at PSI

Isotope production and measurements finished

- ^{60}Fe 1 μg half-life and neutron capture cross sections, @several
- ^{44}Ti 30 μg $^{44}Ti(\alpha,p)$ reaction, @ISOLDE/Uni Edinburgh
- ^{7}Be 15 μg $^{7}Be(n,\alpha)$ and $^{7}Be(n,p)$, @n_TOF
- ^{10}Be 4 mg $^{10}Be(n,\gamma)$ thermal, @Uni Mainz

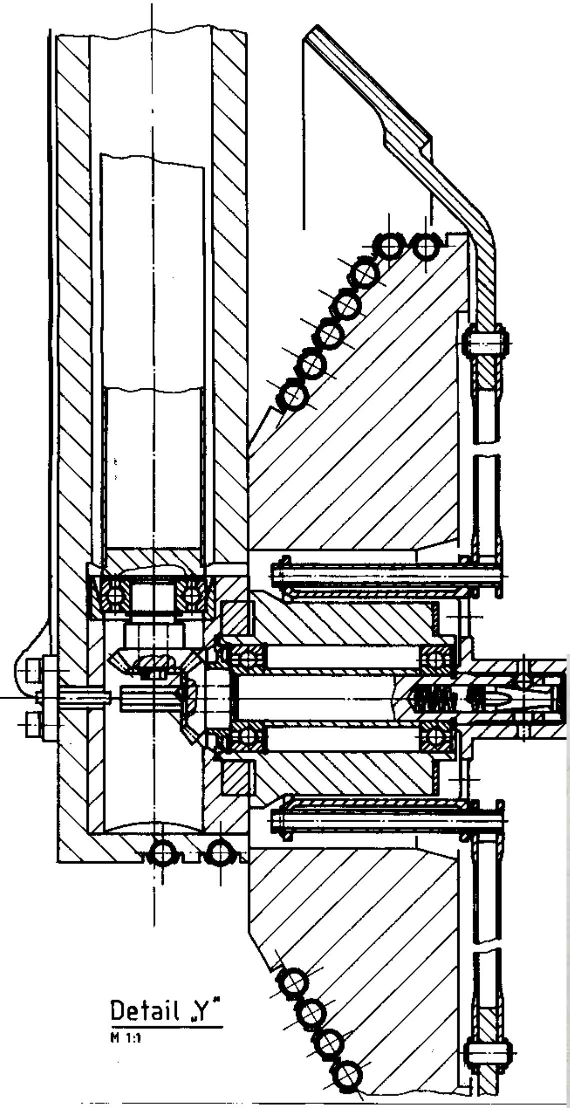
Isotope production performed, isotopes ready for use

- ^{26}Al 0.4 μg half-life measurement
- ^{53}Mn 3 mg half-life and neutron capture cross sections

Isotope production planned

- ^{32}Si 60 μg half-life and cross section measurements
- ^{146}Sm 100 μg half-life measurements
- ^{148}Gd 80 μg half-life measurements
- ^{154}Dy 25 μg half-life measurements
- ^{209}Po ? half-life measurements
- Actinides and fission products from spent nuclear fuel solutions

^{10}Be from target-E graphite targets

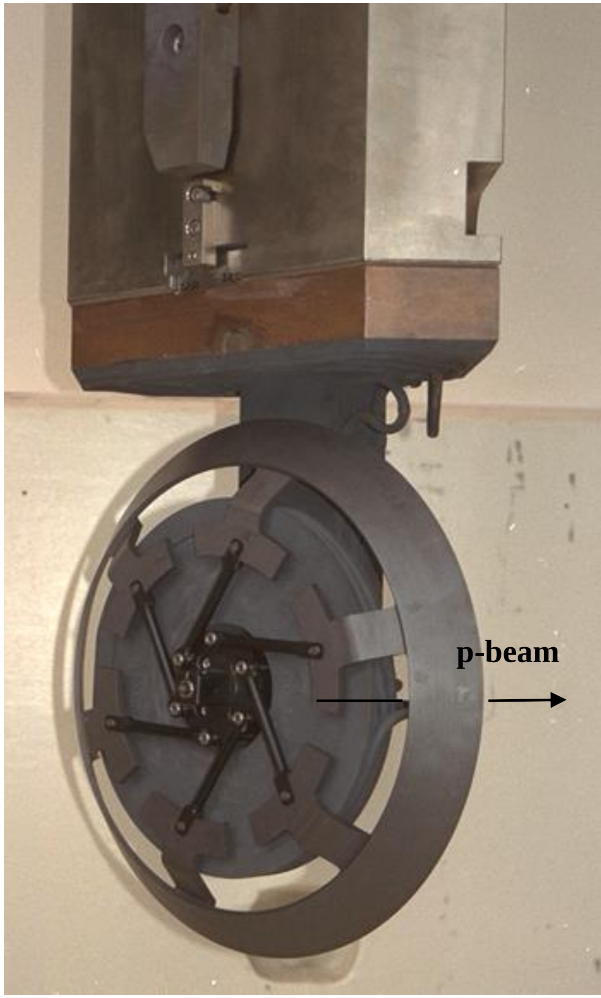


Myon production station

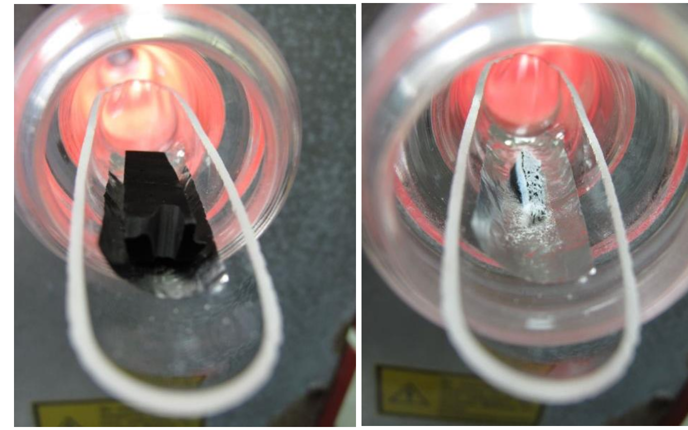
consumes up to 20% of the proton beam

Typical operation time: 1-3 years

Source for ^{7}Be and ^{10}Be

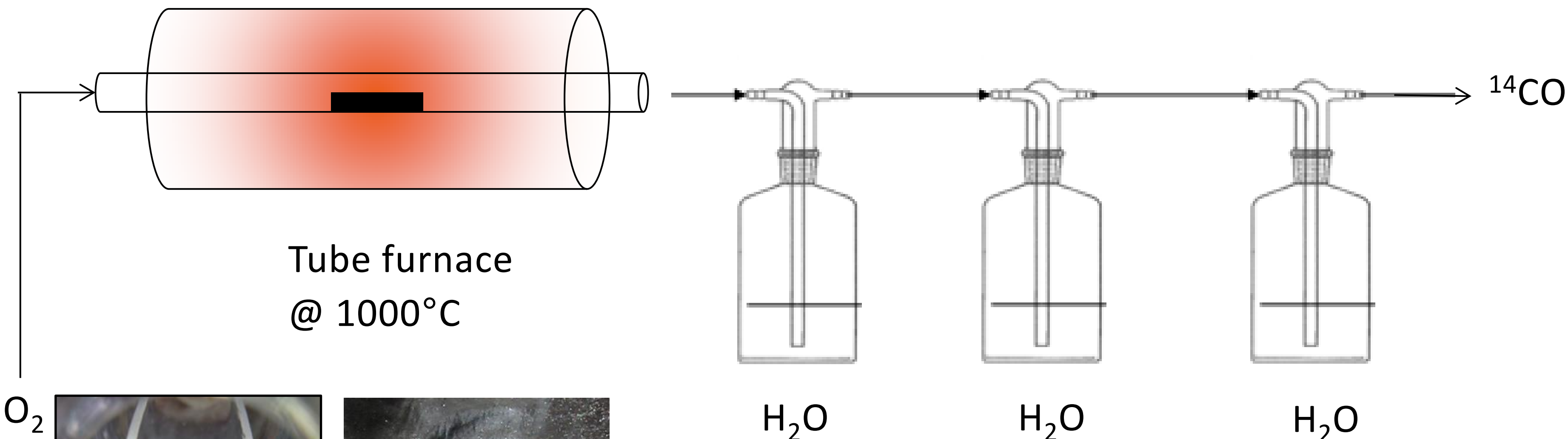


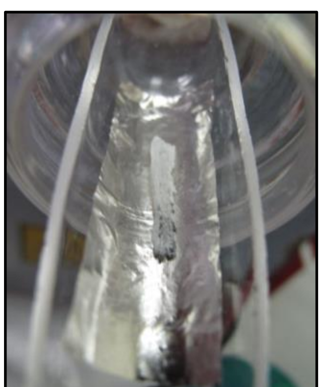
Chemical separation

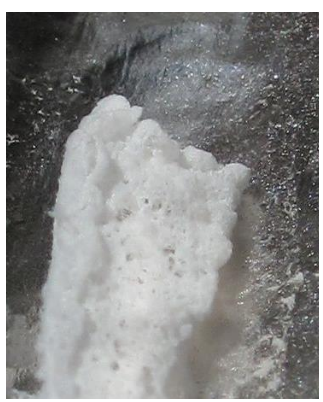


Main radioactive components: ^{3}H, ^{14}C

Combustion of graphite in oxygen stream







$^{3}H_2O$ capture efficiency > 99.99%

35 kBq ^{10}Be on Carbon pellet

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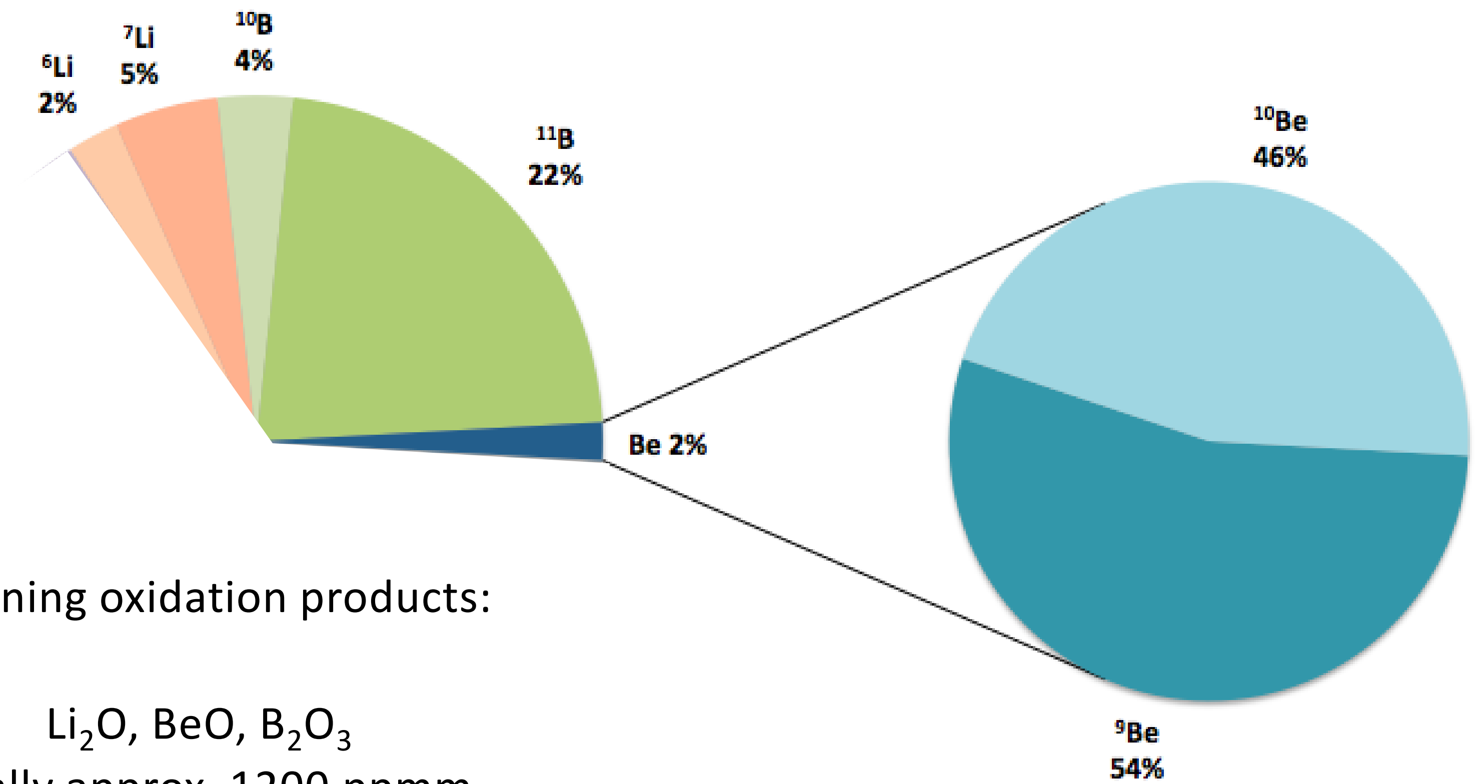
MCNPX calculation for target E92

Spallation products in carbon by mass:



Remaining oxidation products:

Li_2O, BeO, B_2O_3
totally approx. 1200 ppmm
14 µg ^{10}Be per g graphite
currently available: ca. 4 mg ^{10}Be

data by courtesy of Dr. D. Kiselev

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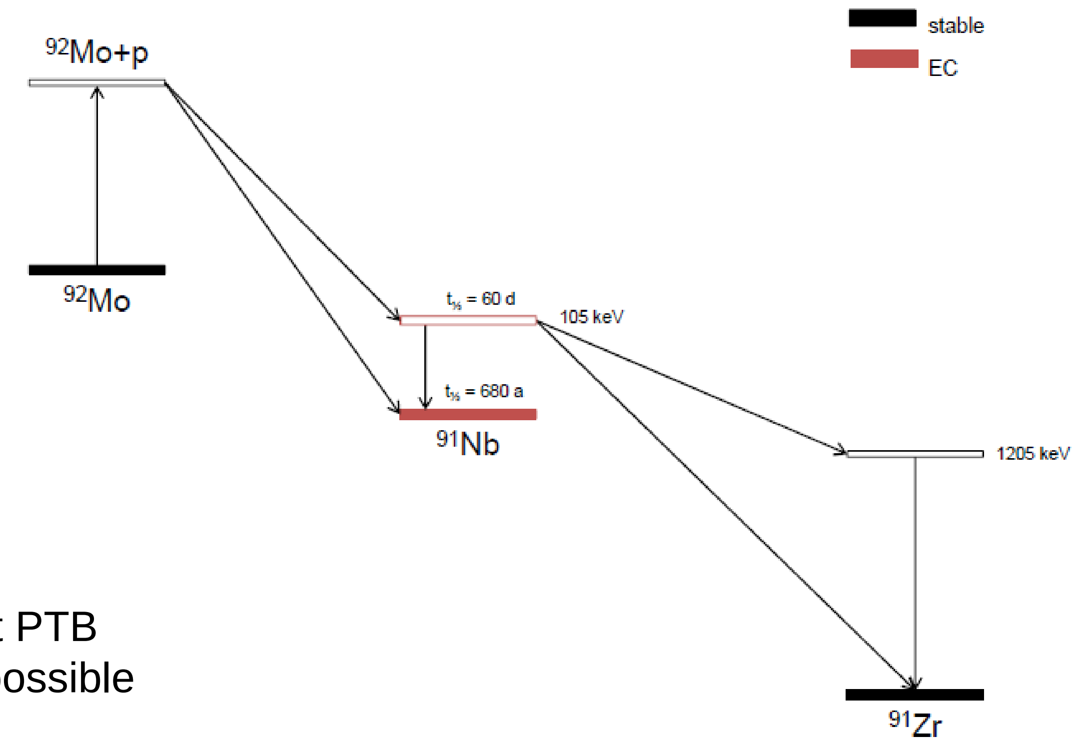
^{91}Nb – from proton-irradiated ^{92}Mo

^{91}Nb(p,γ)^{92}Mo reaction at 2 MeV proton energy

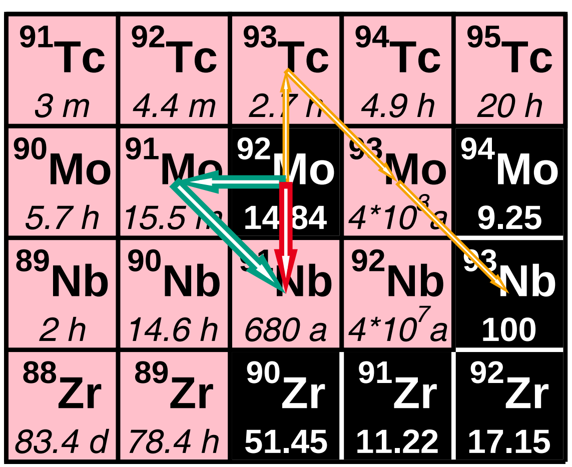
Relevant nuclear reaction for p-process

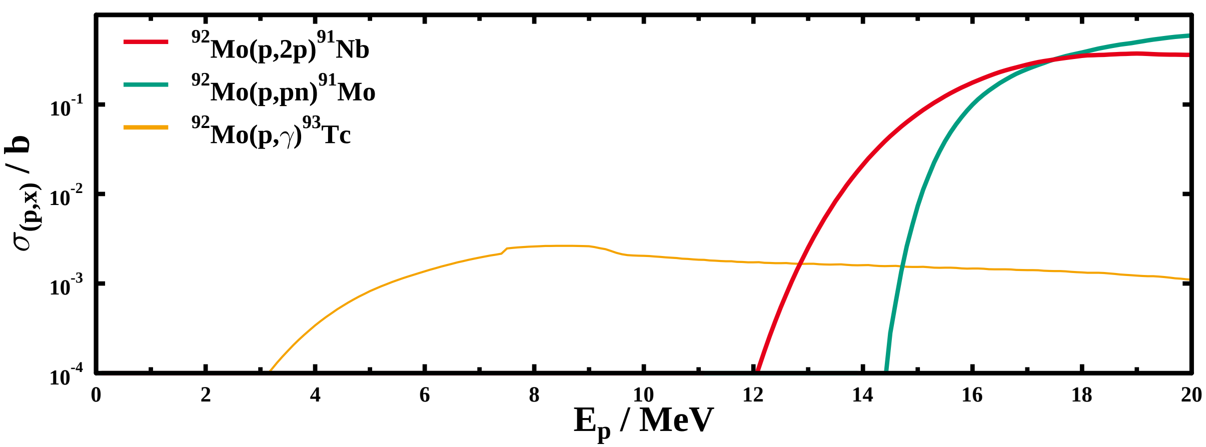
production of the most abundant *p* nucleus ^{92}Mo



Cross sections from TALYS

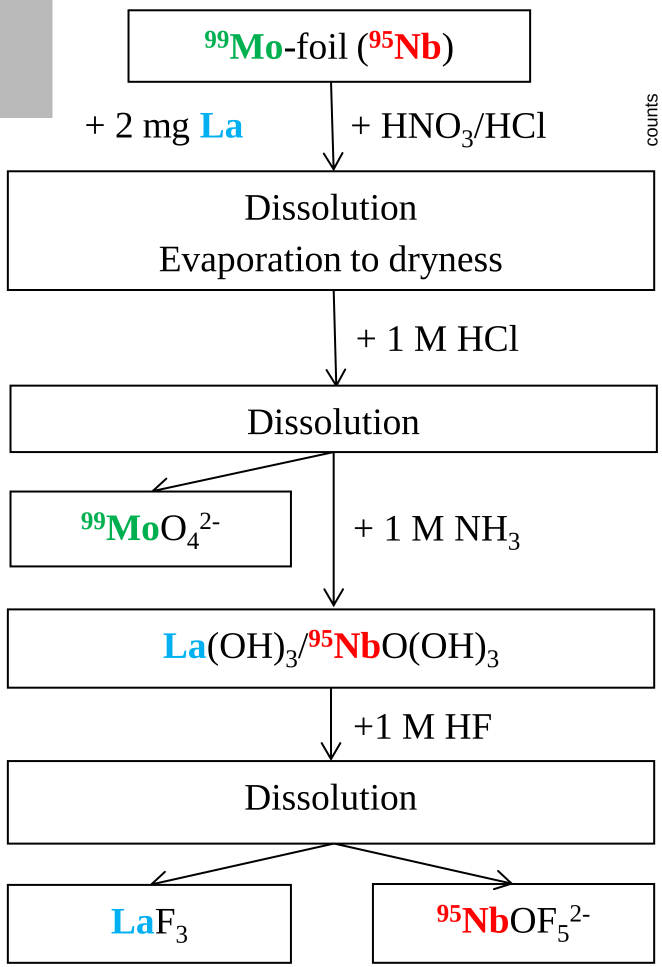
10^{16} ^{91}Nb nuclei with cyclotron at PTB Braunschweig in about 7 days possible

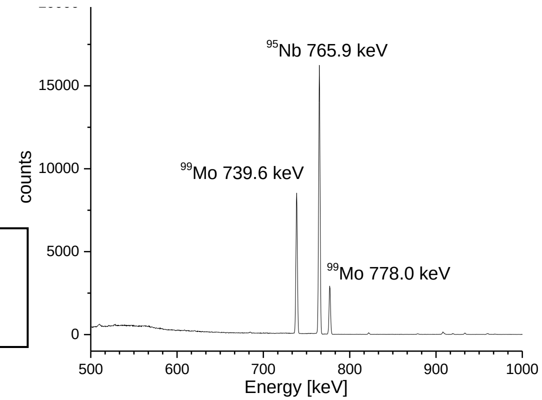


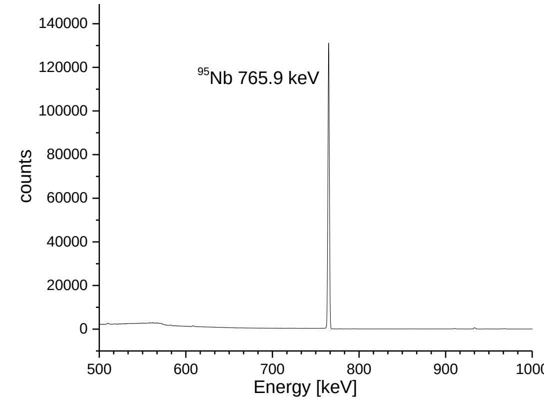


Radiochemical separation

Development of the chemical system using model tracers



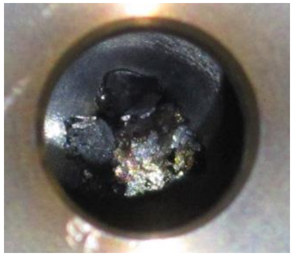




Sample preparation:

Irradiation of 971.3 mg ^{92}Mo with 20 MeV protons

Determination of the decontamination factor from ^{92}Mo by ICP-MS: > 10^5; ~ 1 µg ^{91}Nb



^{60}Fe in 2016

The Astrophysical Journal, 827:48 (17pp), 2016 August 10

RADIOACTIVE IRON RAIN: TRANSPORTING ^{60}Fe IN SUPERNOVA DUST TO THE OCEAN FLOOR

Brian J. Fry[1], Brian D. Fields[1], and John R. Ellis[2]
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[2] Theoretical Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, UK; Theory Department, CERN, CH-1211 Geneva 23, Switzerland
Received 2016 April 3; revised 2016 May 11; accepted 2016 May 18; published 2016 August 5

Nature 2016:
Transport calculations

LETTER

doi:10.1038/nature17424

The locations of recent supernovae near the Sun from modelling ^{60}Fe transport

D. Breitschwerdt[1], J. Feige[1], M. M. Schulreich[1], M. A. de. Avillez[1,2], C. Dettbarn[3] & B. Fuchs[3]

ASTROPARTICLE PHYSICS

Observation of the ^{60}Fe nucleosynthesis-clock isotope in galactic cosmic rays

W. R. Binns,[1]* M. H. Israel,[1]* E. R. Christian,[2] A. C. Cummings,[3] G. A. de Nolfo,[2] K. A. Lave,[1] R. A. Leske,[3] R. A. Mewaldt,[3] E. C. Stone,[3] T. T. von Rosenvinge,[2] M. E. Wiedenbeck[4]

Science 2016:
Mass spectrometry with CRIS

PRL 116, 151104 (2016) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2016

Interstellar ^{60}Fe on the Surface of the Moon

L. Fimiani,[1] D. L. Cook,[2,*] T. Faestermann,[1] J. M. Gómez-Guzmán,[1] K. Hain,[1] G. Herzog,[2] K. Knie,[1,†] G. Korschinek,[1,‡] P. Ludwig,[1] J. Park,[2] R. C. Reedy,[3] and G. Rugel[1,§]
[1] *Physik Department, Technische Universität München, D-85748 Garching, Germany*
[2] *Department of Chemistry and Chemical Biology, Rutgers University, Piscataway, New Jersey 08854, USA*
[3] *Planetary Science Institute, Los Alamos, New Mexico 87544-3826, USA*
(Received 18 November 2015; published 13 April 2016)

samples from the Apollo missions measured by AMS

Nature 2016:
Investigation of ocean floor samples with AMS

LETTER

doi:10.1038/nature17196

Recent near-Earth supernovae probed by global deposition of interstellar radioactive ^{60}Fe

A. Wallner[1], J. Feige[2]†, N. Kinoshita[3], M. Paul[4], L. K. Fifield[1], R. Golser[2], M. Honda[5], U. Linnemann[6], H. Matsuzaki[7], S. Merchel[8], G. Rugel[8], S. G. Tims[1], P. Steier[2], T. Yamagata[9] & S. R. Winkler[2]

The discovery of ^{60}Fe from a nearby supernova explosion
~ 2.5 million years ago

Separation and preparation

Dissolution of Cu chips (3 g) in 7 M
HNO_3

Evaporation to dryness

Dissolution in 7 M HCl + 5 mg Co^{2+} as
carrier

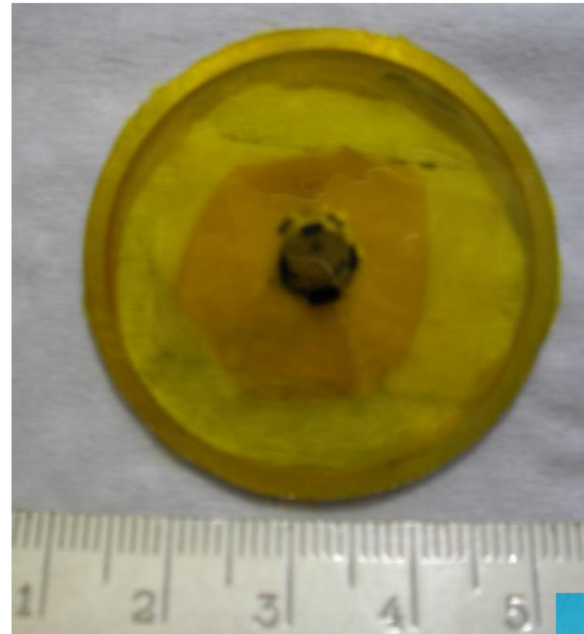
Extraction with methylisobutylketone

Aqueous phase:
Ni, Co, Cu,
organic phase: Fe

Back extraction with 0.1 M HCl,
repetition of procedure

Result: $7.8 \cdot 10^{15}$ or 777 ng ^{60}Fe atoms,
decontamination factor (Co) > 10^8
(0.3 Bq)

Evaporation of the final solution onto a
graphite backing



^{60}Fe - summary

- **Sample preparation for 4 half-life determinations**
- **Target preparation for 2 neutron capture cross section experiments (thermal energy and 25 keV)**
- **Preparation of standard material for AMS measurement**

All sample-requiring experiments on ^{60}Fe world-wide within the last 20 years work with material produced at PSI

- New measurement of the ^{60}Fe half-life, **G. Rugel** et.al. PRL 2009
- Determination of the neutron capture cross section at stellar energies, **E. Ueberseder** et.al. PRL 2009
- Quantification of ^{60}Fe atoms by MC-ICP-MS for the redetermination of the half-life, **N. Kivel** et.al. ABC 2013
- The thermal neutron capture cross section of the radioactive isotope ^{60}Fe, **T. Heftrich** et.al., PRC 2015
- Settling the half-life of ^{60}Fe – fundamental for a versatile astrophysical chronometer, **A. Wallner** et.al., PRL 2015
- Activity measurement of ^{60}Fe through the decay of ^{60m}Co and confirmation of its half-life, **K. Ostiek** et.al. PRC 2017
- Nuclear properties of ^{60}Fe, **R. Dressler** et.al., currently ongoing

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PSI

KARLSRUHER NUKLIDKARTE

8. Auflage 2012

CHART OF THE NUCLIDES, 8th Edition 2012 / CARTE DES NUCLEIDES, 8ème Edition 2012
CARTA DE NUCLEIDOS, 8a Edición 2012 / ТАБЛИЦА НУКЛИДОВ, 8-е Издание 2012
核素图，2012年第8版

J. Magill[1], G. Pfennig[2], R. Dreher[1], Z. Sóti[2]

[1] Nucleonica GmbH, c/o European Commission, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany, eMail: joseph.magill@nucleonica.com, http://www.nucleonica.com

[2] European Commission – Joint Research Centre – Institute for Transuranium Elements P.O. Box 2340, 76125 Karlsruhe, Germany

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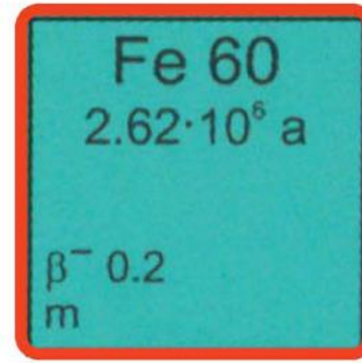

G. Rugel, et al.:
Phys. Rev. Lett. **103** (2009) 072502

nucleonica

JRC
EUROPEAN COMMISSION

itu Institute for Transuranium Elements

KIT Karlsruhe Institute of Technology

Requirements for sample and target preparation

Isotope production and separation

- Total amount of activity?
- Which chemical form?
- With carrier or non-carrier-added?
- Disturbing isotopes?
- Magnitude of decontamination factors?
- Matrix of the final sample?
- Single or multiple separation?
- Shielding equipment (hotcell) necessary?

Target preparation

- Self-supporting or with backing?
- Which backing?
- Thickness of the backing to be known?
- Isotope composition required?
- Distribution to be known?
- Thickness measurement required?
- Single or multi-use?
- Radioprotection issues
- Transport issues

Collaboration on the basis of a material transfer agreement (MTA)

Summary and conclusions

- **Exotic radionuclides are produced in components of the 590 MeV proton accelerator at PSI**
- **After chemical separation, these isotopes are available for scientific applications**
  - Nuclear astrophysics
  - Geoscience
  - Basic nuclear physics
  - AMS standards
- **PSI owns a store house of several very rare isotopes, some of them being unique world-wide in quality and quantity ($^{7/10}$Be, ^{60}Fe, ^{53}Mn, ^{44}Ti and others)**
- **Examples for front-end experiments using targets made by PSI**
  - ^{60}Fe half-life and neutron capture cross section measurements
- **Examples for ongoing experiments** (^{10}Be, ^{91}Nb)
- **We need a network on target preparation**
- We need a dedicated mass separation device for exotic radionuclides!

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  - Uni Frankfurt
  - and many others
- CHANDA (7th EC framework)
- Swiss National Science Foundation
- You for your attention!