Workshop on Spectroscopic Factors
ECT*, Trento 2nd-12th March 2004

Na and Mg n-deficient beam production for Nuclear Astrophysics and Collinear Laser Spectroscopy experiments at ISOLDE-CERN: theoretical outline and primary target study.

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MAIN POINTS

1) WHY Mg and Na RIBs?
2) OUTLINE AND GOAL OF THE EXPERIMENTS
3) ISOLDE @ CERN
4) RIB PRODUCTION AND PRIMARY TARGET STUDY
5) CONCLUSIONS

1) WHY Mg and Na RIBs?

Na and Mg n-deficient beams are mainly needed for two experiments at ISOLDE-CERN.

NUCLEAR ASTROPHYSICS @ REX-ISOLDE
Lund - CERN Coll. – J.Cederkall

^{22}Na nucleosynthesis in nova phenomena ?

1 p-transfer reaction

COLLAPS
(COLLinear LAser sPectroScopy)
Leuven – Mainz – CERN Coll.
G.Neyens-M.Kowalska

Mg exotic isotopes nuclear structure study
(0^+ , 1^- , 2^+ moments)

Proposal available on the web

2) Exp goal & outline

NUCLEAR ASTROPHYSICS @ REX-ISOLDE
Lund - CERN Coll. – J.Cederkall

EXP. MOTIVATIONS:

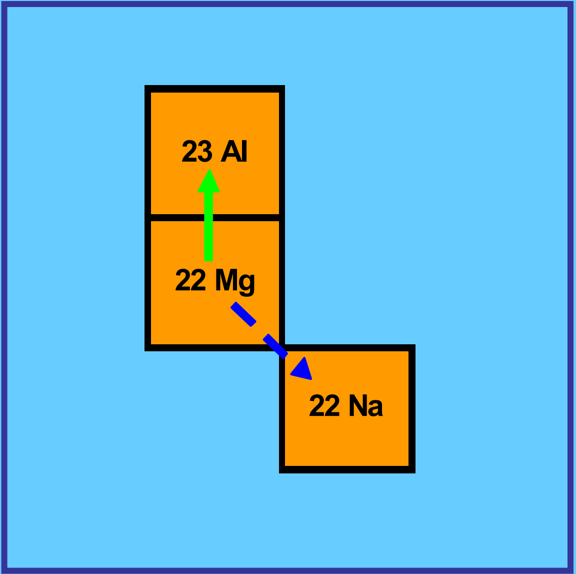
- Constraint and improvement of nova models.
- Problem concerning the predicted and observed abundance of ^{22}Na.

EXP. PURPOSES:

- Development of a beam to study the reactions that occur in novae just after the break out from the hot CNO cycle.
- Study of the **proton capture** $^{22}Mg(p,\gamma)^{23}Al$ reaction

INVERSE KIMEMATICS

INDIRECT METHOD



1st STEP

Elastic scattering exp

Optical parameters
needed for 2nd step

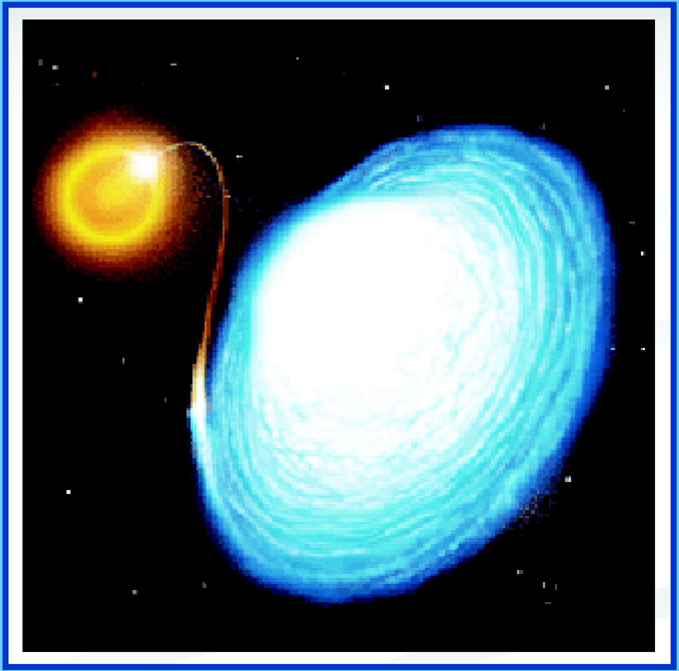
Plastic (PE) target
Set of Si detectors

2nd STEP

p-pickup on ^{22}Mg
via p-transfer

More complicated set-up
Deuterated PE target
New detectors
New spectrometer

2) Exp goal & outline



ONe white dwarf stars binary system → Accretion onto w.d.

↓

Thermonuclear runaway

↓

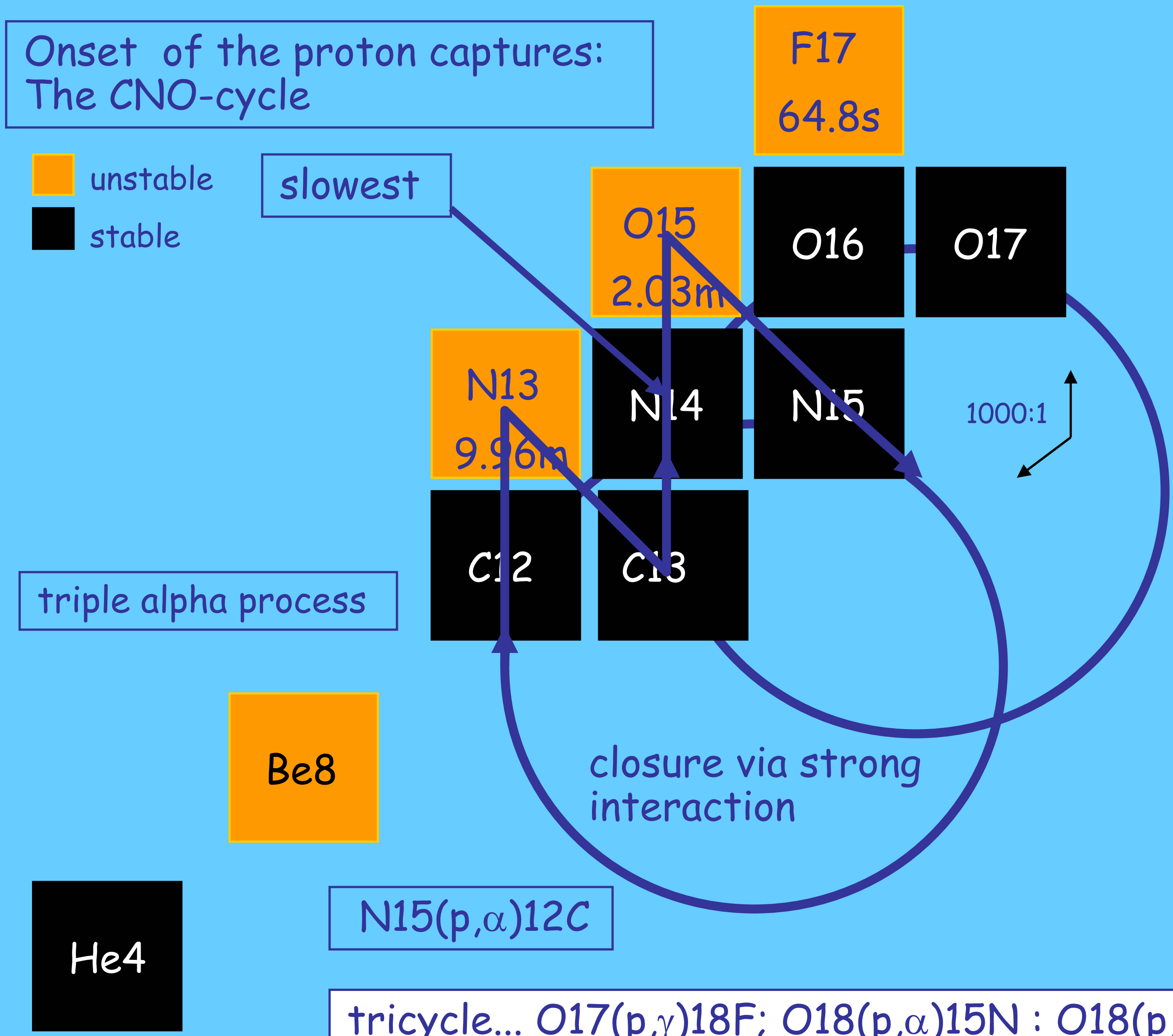
Nova explosion → Radiative p-capture On unstable nuclei

↓

Synthesis of light and intermediate-mass elements

p-p chain → CNO → NeNa

The rp-process in short:



Onset of the proton captures:
The CNO-cycle

slowest

triple alpha process

closure via strong interaction

N15(p,α)12C

CN cycle:

C12(p,γ)N13

N13(e+,ν)C13

C13(p,γ)N14

N14(p,γ)O15

O15(e+,ν)N16

CNO bicycle:

N15(p,γ)O16

O16(p,γ)F17

F17(e+,ν)O17

closure

O17(p,α)N14

tricycle... O17(p,γ)18F; O18(p,α)15N : O18(p,γ)F19, F19(p,α)O16

The rp-process in short:

Hot CNO cycle and the break-out into the rp-path

T=1E8-1E9 K

interior of sun T6 = 16

↓

Energy becomes high enough for reactions on unstable nuclei to occur.

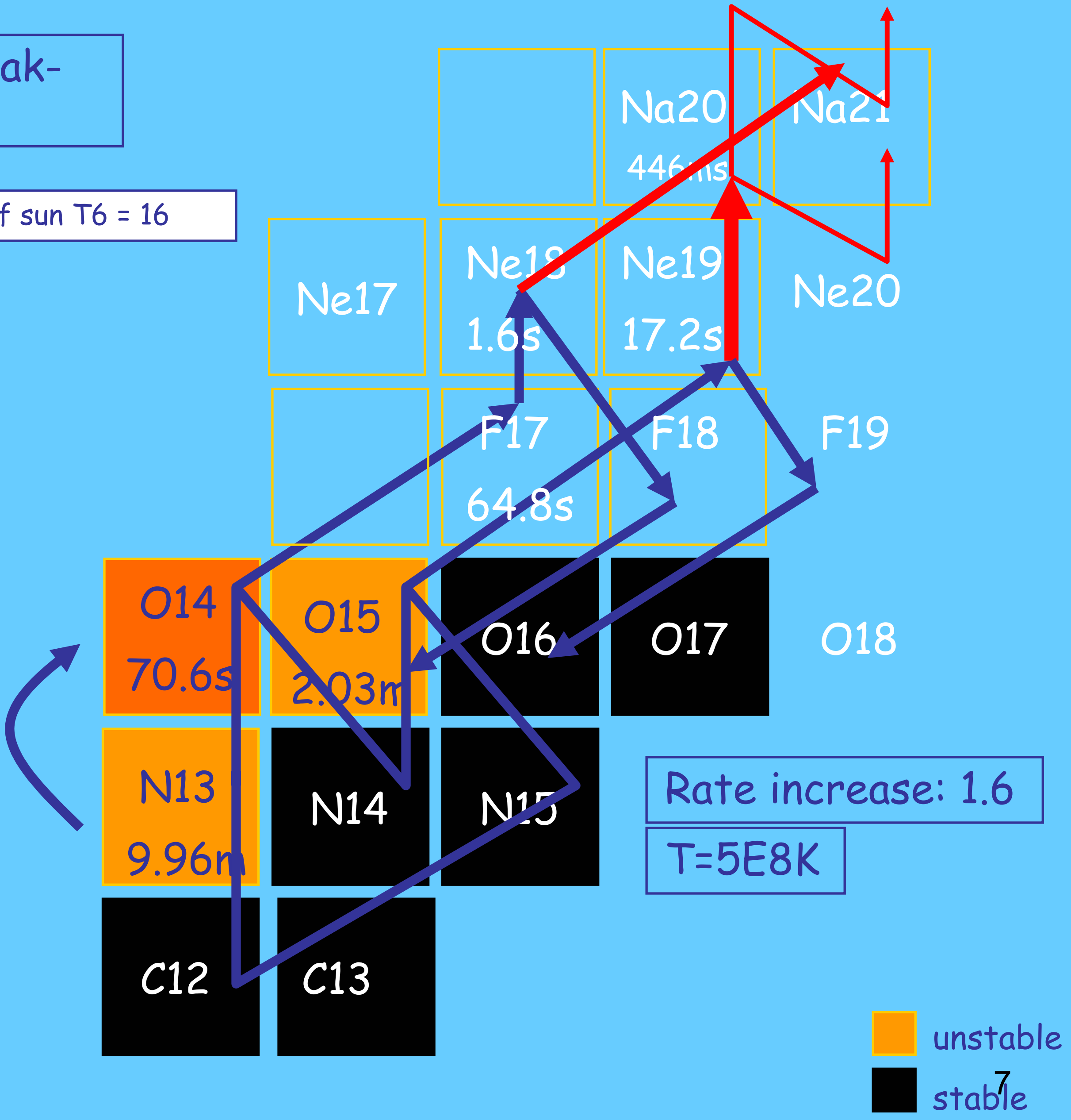
The limiting factor is now the $\beta+$ decay of O14 and O15 (instead of the N14 p-capture)

Other cycles can form again at higher mass number

Reactions on (at same distance from the line of stability):

NeNa cycle: 23Na(p,a)20Ne

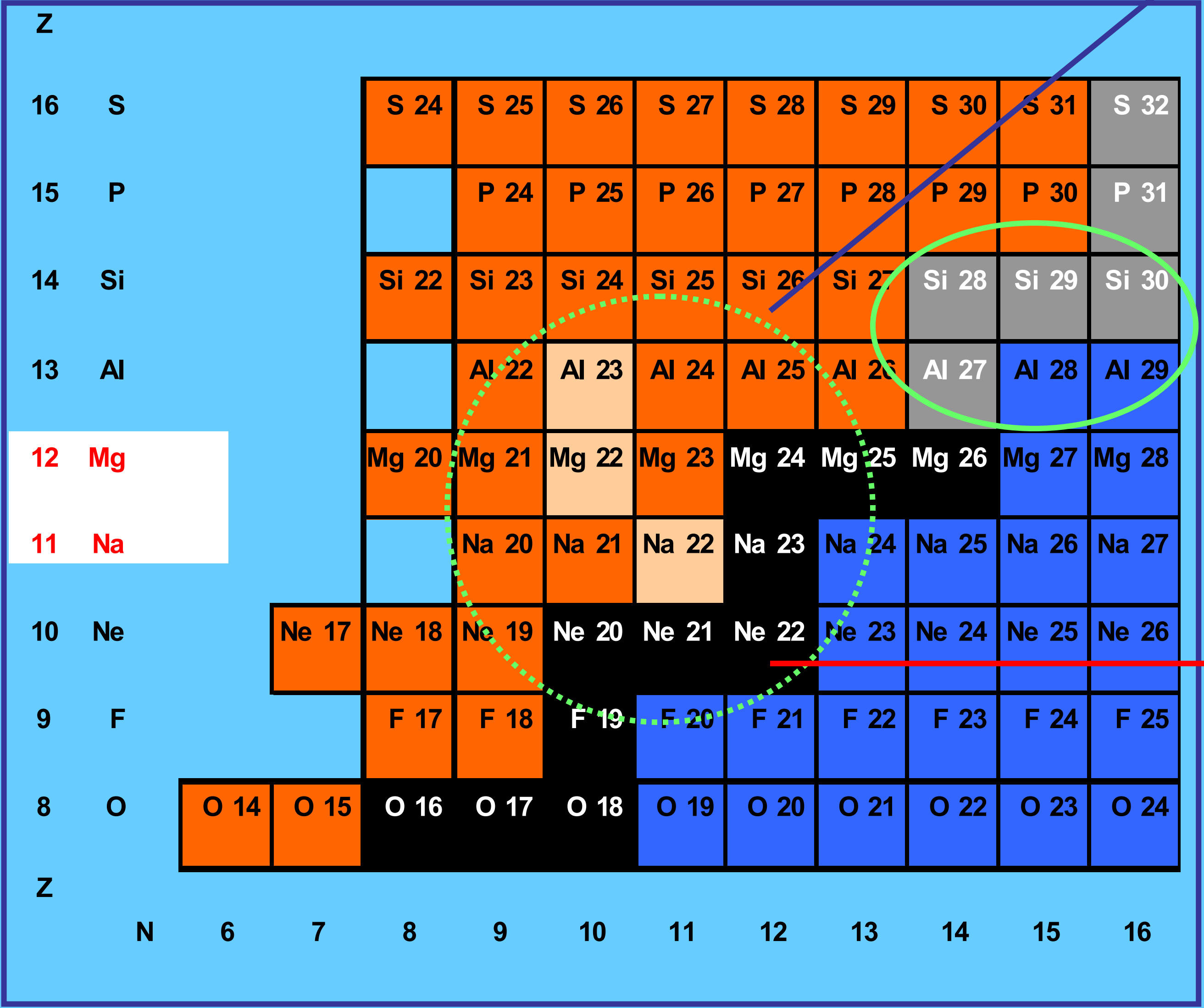
MgAl cycle: 27Al(p,a)24Mg



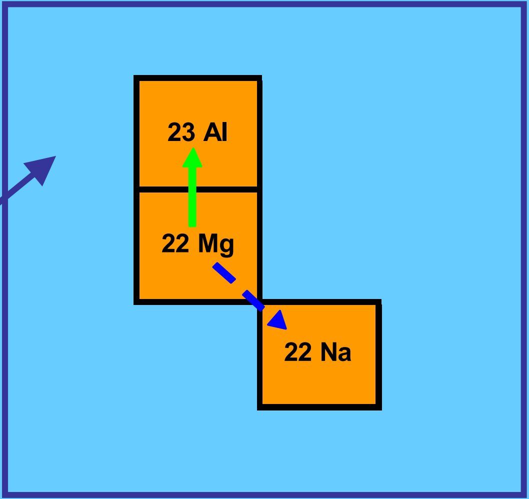
Rate increase: 1.6

T=5E8K

2) Exp goal & outline



Z	N	6	7	8	9	10	11	12	13	14	15	16
16	S			S 24	S 25	S 26	S 27	S 28	S 29	S 30	S 31	S 32
15	P				P 24	P 25	P 26	P 27	P 28	P 29	P 30	P 31
14	Si			Si 22	Si 23	Si 24	Si 25	Si 26	Si 27	Si 28	Si 29	Si 30
13	Al				Al 22	Al 23	Al 24	Al 25	Al 26	Al 27	Al 28	Al 29
12	Mg			Mg 20	Mg 21	Mg 22	Mg 23	Mg 24	Mg 25	Mg 26	Mg 27	Mg 28
11	Na				Na 20	Na 21	Na 22	Na 23	Na 24	Na 25	Na 26	Na 27
10	Ne		Ne 17	Ne 18	Ne 19	Ne 20	Ne 21	Ne 22	Ne 23	Ne 24	Ne 25	Ne 26
9	F			F 17	F 18	F 19	F 20	F 21	F 22	F 23	F 24	F 25
8	O	O 14	O 15	O 16	O 17	O 18	O 19	O 20	O 21	O 22	O 23	O 24
Z												



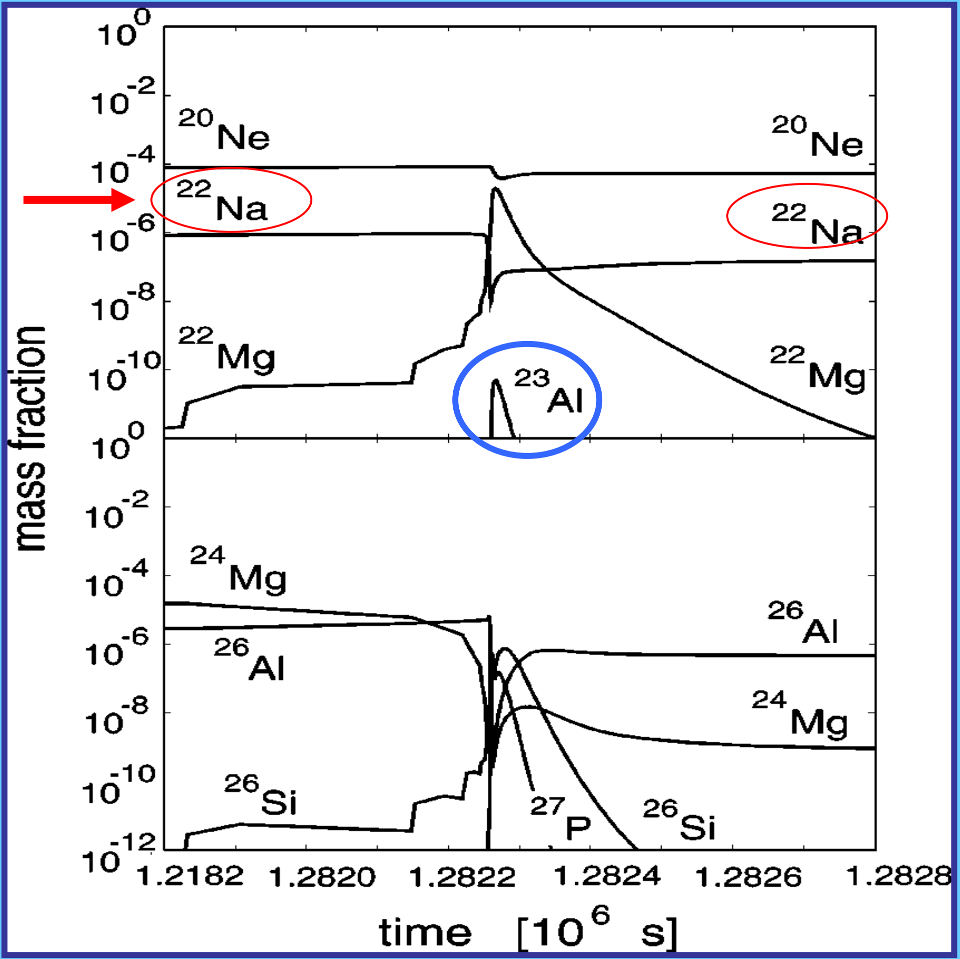
Oct 2003
ESA's INTEGRAL

Galactic γ-emitter
1.275 MeV

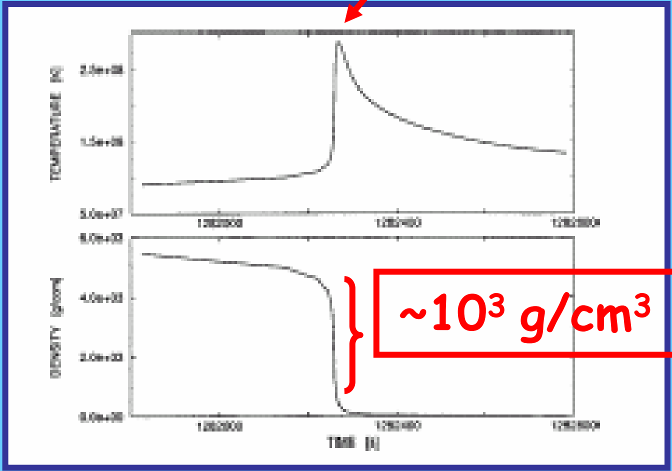
Not detected by
Nasa's COMPTEL

2) Exp goal & outline

For 22Mg p-pickup to 23Al only an indirect estimation has been performed (Caggiano et al, Phys.Rev.C 64,025802 (2001)).



~0.4 GK

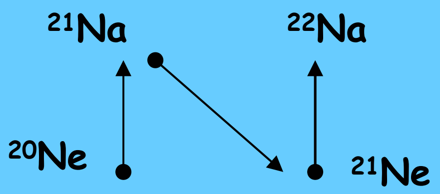


~10^3 g/cm^3

Temperature and density conditions as predicted by Nova models.

22Na decrease at nova outburst does not account for lack of γ-line detection by COMPTEL.

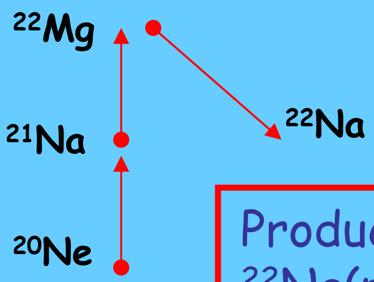
2) Exp goal & outline



^{22}Na production
in ONeMg novae
&
pervious studies

"Cold" NeNa cycle: **^{20}Ne $(p,\gamma)^{21}$Na$(\beta+,\nu)^{21}$Ne$(p,\gamma)^{22}$Na**

"Hot" NeNa cycle: **^{20}Ne $(p,\gamma)^{21}$Na$(p,\gamma)^{22}$Mg$(\beta^{+},\nu)^{22}$Na**



Production depleted by ^{22}Na$(p,\gamma)^{23}$Mg process

^{21}Na (p,γ) ^{22}Mg

TRIUMF: ^{21}Na ISOL beam available

^{21}Na (p,γ) ^{22}Mg
studied via ^{22}Mg p-decay

Davids et al.,
Phys. Rev C 68, 055805 (2003)
Inverse kinematics

^{24}Mg (7Li,8He) ^{23}Al

Caggiano et al.,
Phys.Rev.C 64,025802 (2001).

Beta decay and proton pick up to ^{23}Al to be compared: escape mechanism

^{22}Mg nuclear structure

Energy level diagram

HF-BCS single particle spectrum

$\Delta_N = 2.3$ MeV $\Delta_P = 1.6$ MeV
R_N=2.84 fm R_P=2.84 fm

Calculations performed by fortran codes: Nuclear theory group University of Milan (private communication)

The mean field (HF-BCS+QRPA with SLy4 Skyrme interaction) results are in good agreement with the experimental ground-state and excited states data: the pairing effects are well reproduced at the proton drip-line. In this mirror open-shell system, proton-neutron correlations are very enhanced (overlap between **1d5/2** orbitals). The excited states **0+, 2+, 4+** around **5 MeV** (proton separation energy) are important:

→ proton pairing inhibites β^+ **decay to ^{22}Na ?**

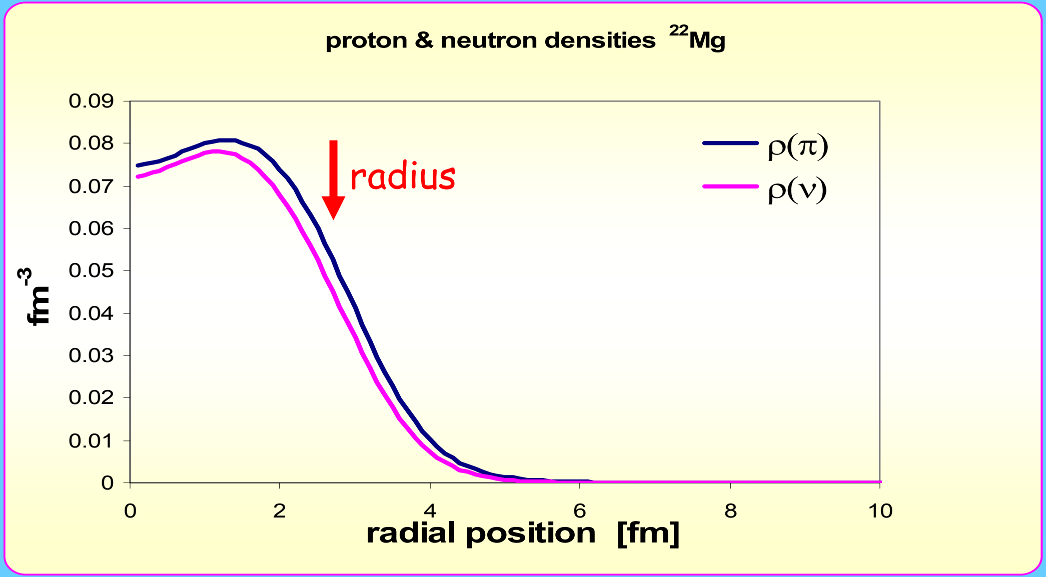
2) Exp goal & outline

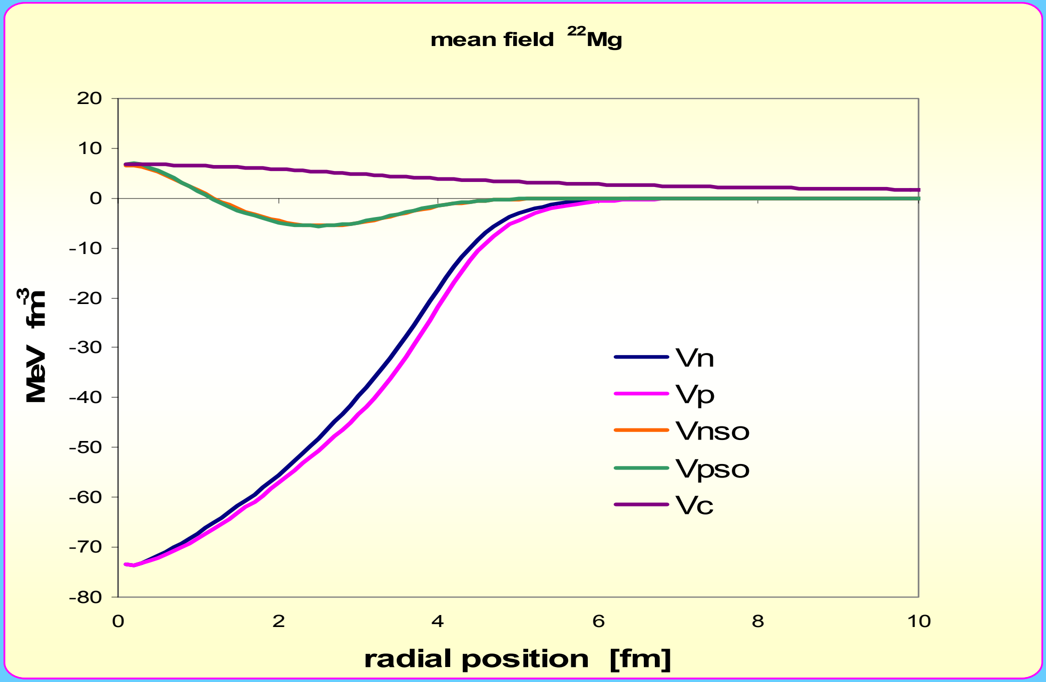
Proton and neutron densities are very similar:
proton excess enhances the density around the surface (2-3 fm)
No proton-halo

HF mean field and spin-orbit interaction give very similar proton and neutron form factors.
The Coulomb barrier is not very enhanced (compared to spin-orbit)

Peripheral reaction?

This result is obtained by a **mean field** approach,
with the **effective force** SLy4,
(not a realistic one) and both short range (repulsive) and long range (phonons, attractive) correlations are **not taken into account**





Theoretical prediction of transfer cross-section

DWBA amplitude

$$M = \sum_{M_{spin}} \left\langle \chi_f^- I_{ex}(r_{ex}) \middle| V \middle| I_{in}(r_{in}) \chi_i^+ \right\rangle$$

Optical model parameters set on elastic scattering

Spectroscopic method

$$I^{\alpha}_{ex(in)}(r_{ex(in)}) = S_{\alpha}^{1/2} \phi_{\alpha}(r_{ex(in)}) \xrightarrow{r_{ex(in)}>R} S_{\alpha}^{1/2} b_{\alpha} \frac{W_{\alpha}(R_{ex(in)})}{r_{ex(in)}}$$

ANC cross section

$$I^{\alpha}_{ex(in)}(r_{ex(in)}) \xrightarrow{r_{ex(in)}>R} C_{\alpha} \frac{W_{\alpha}(R_{ex(in)})}{r_{ex(in)}}$$

W = Whittakaer function
(asympt.behav.of 2 charged particle bound state w.f.)

If an ANC approach gives a good prediction → peripheral reaction

The ANC method can be used tentatively for proton transfer also
(see Azhari et al., Phys. Rev. C 63, 055803 (2001))

Uncertainties on spectroscopic factors and nuclear part of optical potential
(WoodSaxon) can be eliminated.

Nuclear structure along Mg chain: the Collaps experiment
Leuven - Mainz - CERN Collaboration

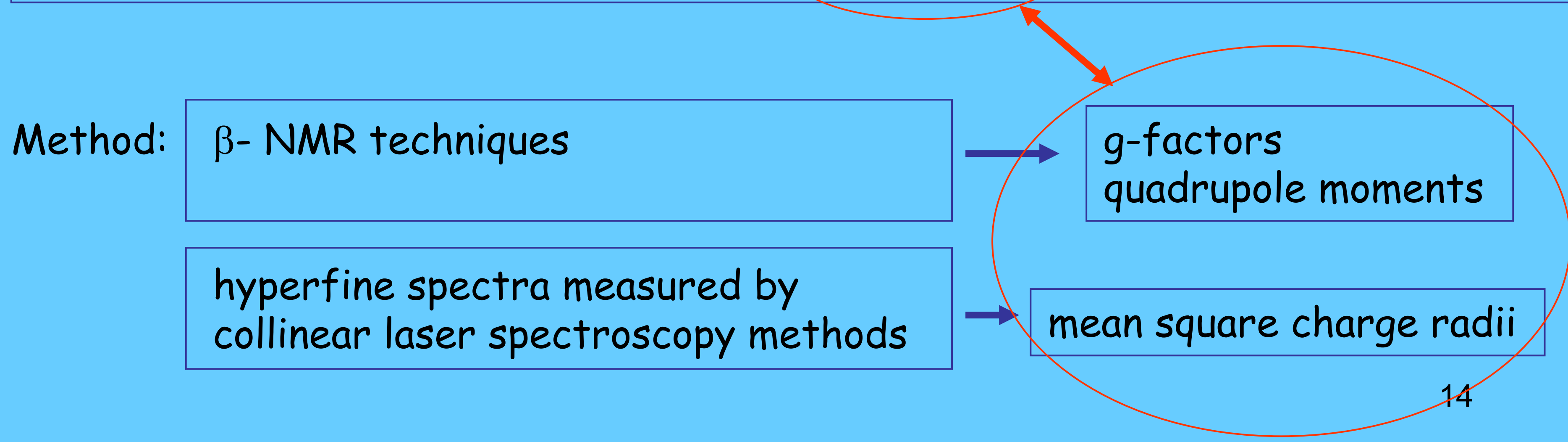
Which aspects can be investigated?

Proton-neutron interaction for systems between the shell closures **8** and **20:**

known shell scheme is preserved in exotic nuclei (n-deficient / n-rich) ?

how **pairing correlations** and **spin-orbit** interaction are modified?

the **neutron excess (defection)** changes the **ground state** and
the **collectivity** of the **excited states**:
Nuclear radius trend and **halos**, **deformation**...

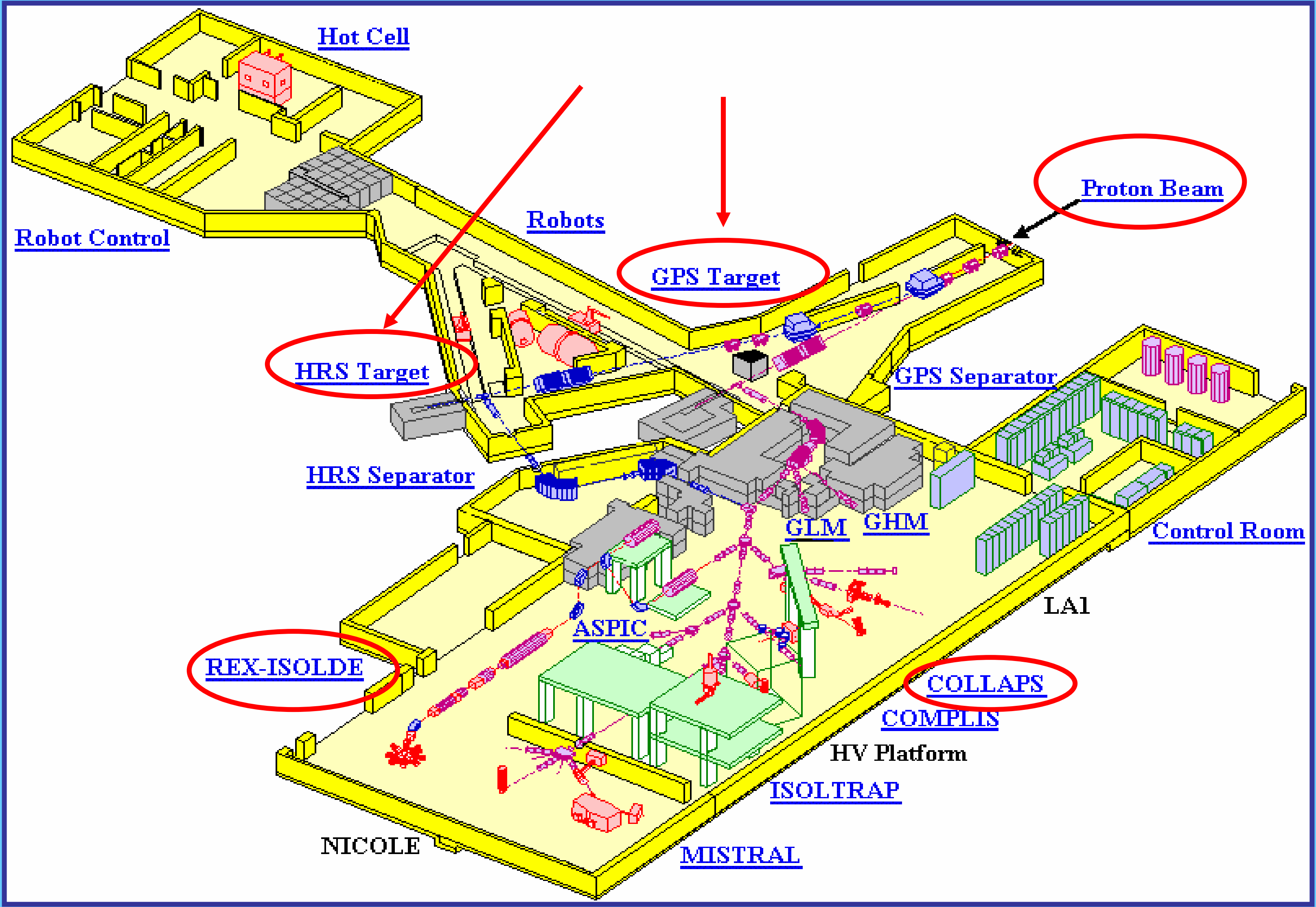


Method:

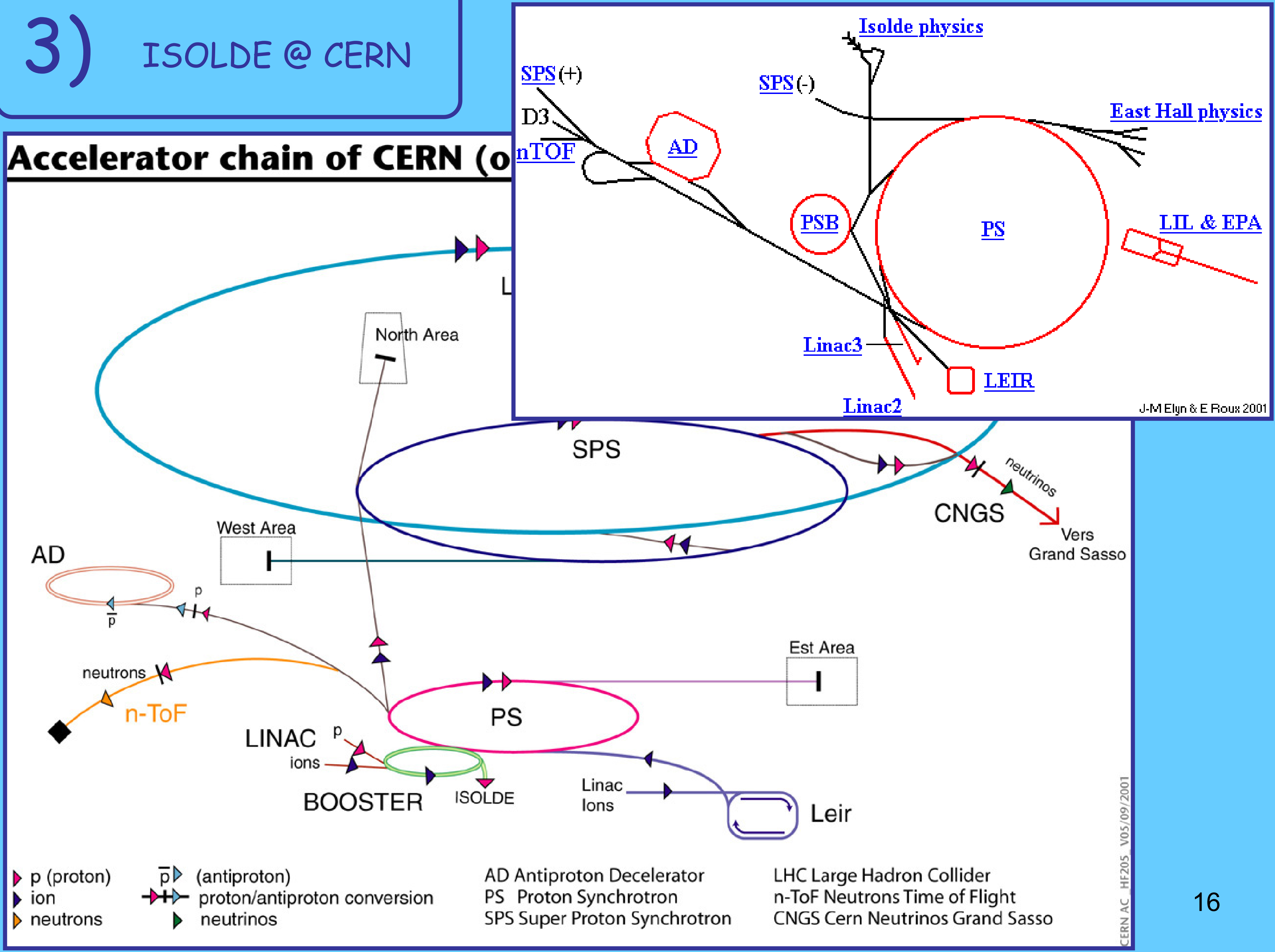
β- NMR techniques → g-factors
quadrupole moments

hyperfine spectra measured by collinear laser spectroscopy methods → mean square charge radii

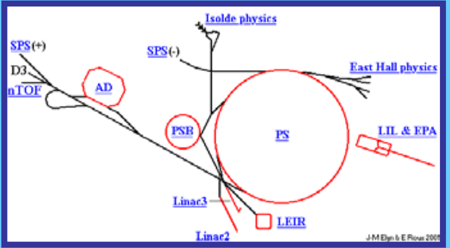
3) ISOLDE@CERN



3) ISOLDE @ CERN



4) RIBs & Primary Target

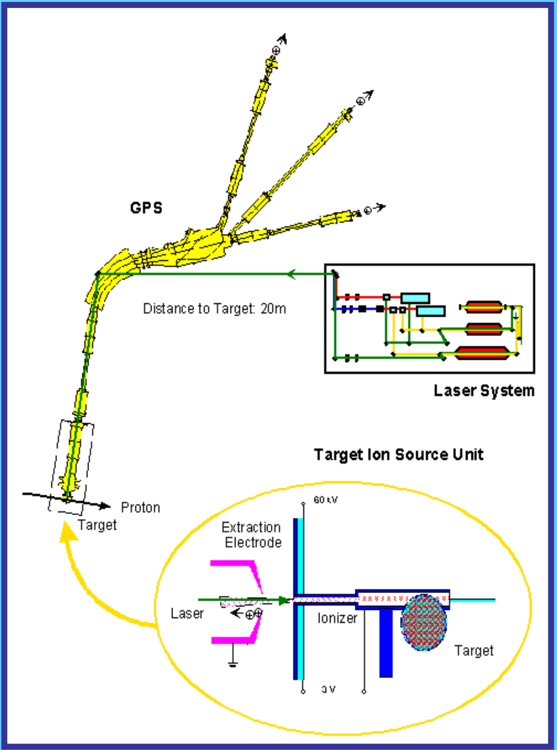


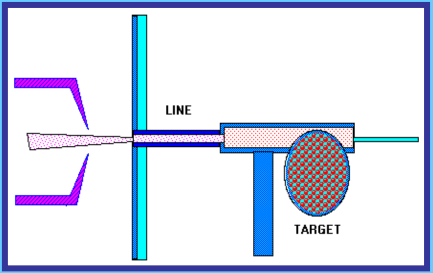
BEAM PRODUCTION CHAIN:

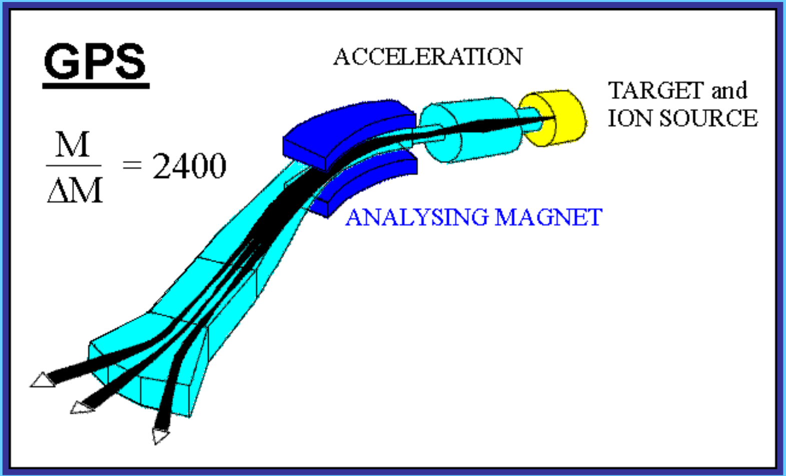
PSB 1,4 Gev Proton beam → Primary Target → Transfer Line → Ion Source → RIB → Mass separation

HRS

GPS







4) RIBs & Target

PSB 1,4 Gev Proton beam → Primary Target → Transfer Line → Ion Source → RIB → Mass separation

Nuclear reactions in the target:
ISOL method: “thick“ target in
which nuclei are stopped
and then diffuse out.

- SPALLATION
- FISSION
- FRAGMENTATION

Diffusion study:
radioactive nuclei have to diffuse out of the target matrix to be ionized

OFF-LINE **Release from different materials**

IMPLANTED SAMPLES IRRADIATED SAMPLES

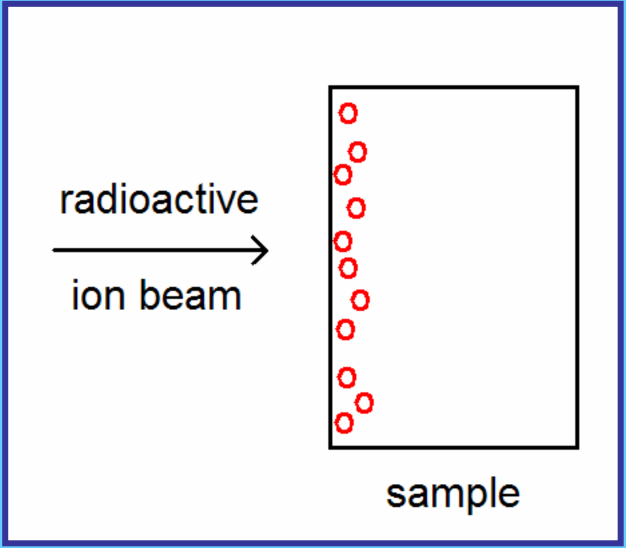
Selection of potential ISOL TARGETS

ON-LINE Selected samples are now used as real targets to extract RIBs

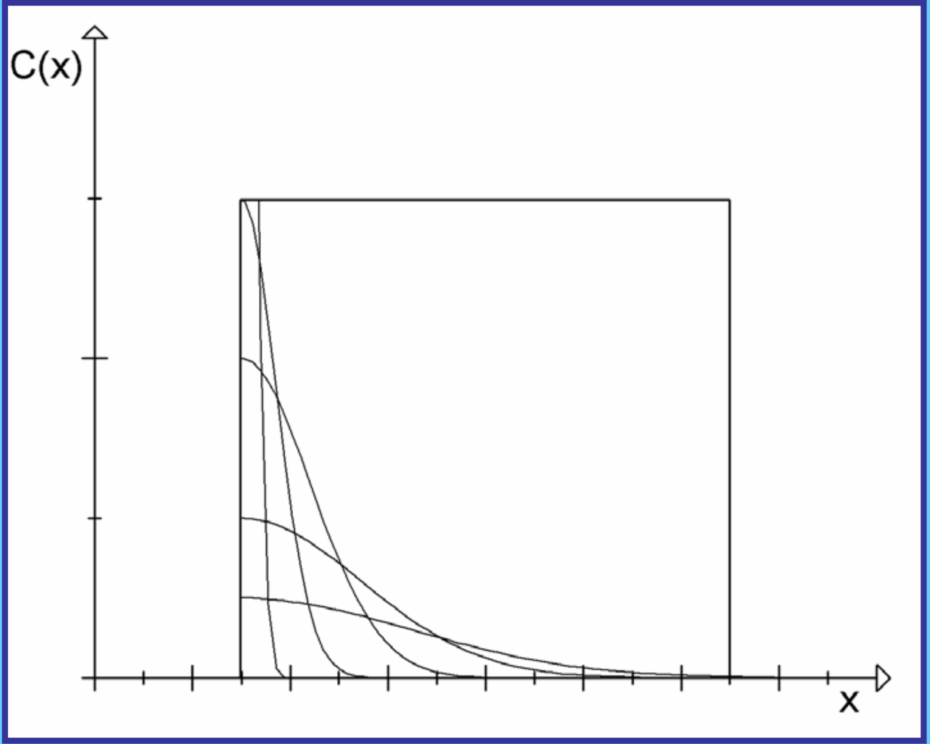
4) RIBs & Target

IMPLANTATION

An available RIB is used to bombard the sample



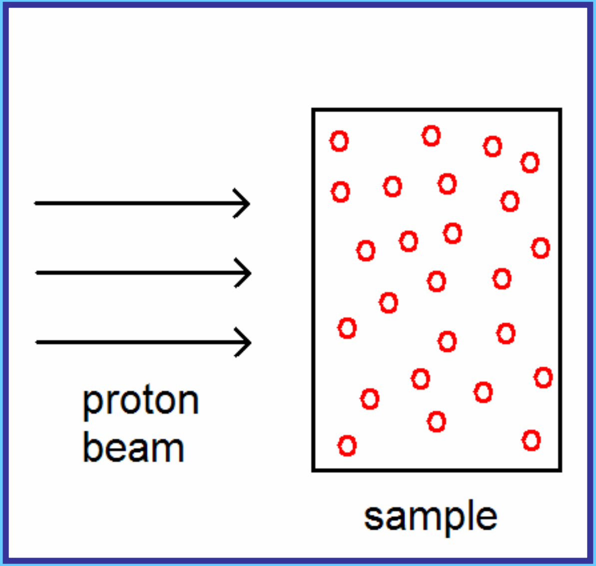
Implanting the sample is effective to probe surface effects (desorption)



4) RIBs & Target

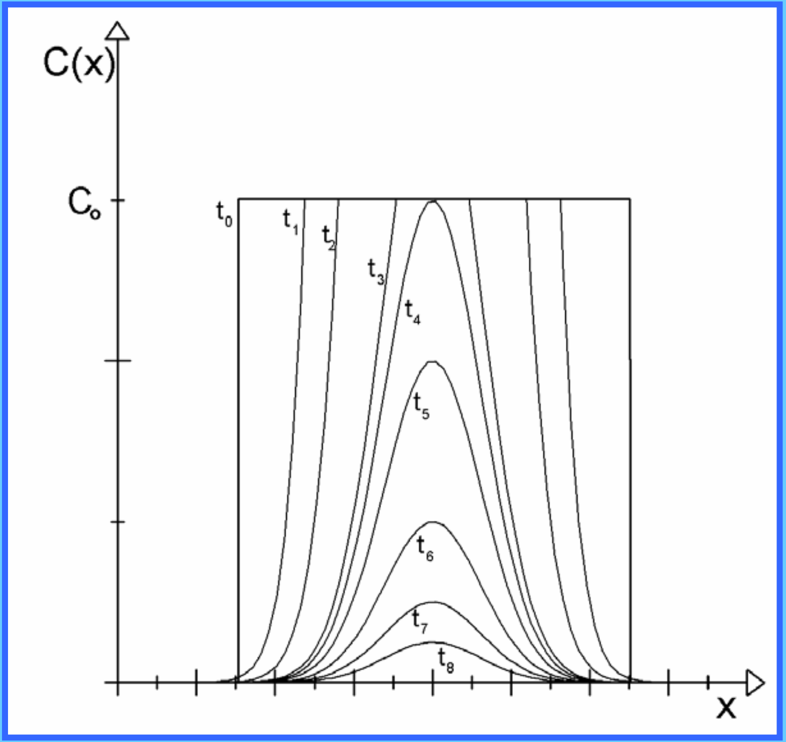
IRRADIATION

The sample is activated by the 1.4 GeV proton beam coming from CERN PSB.



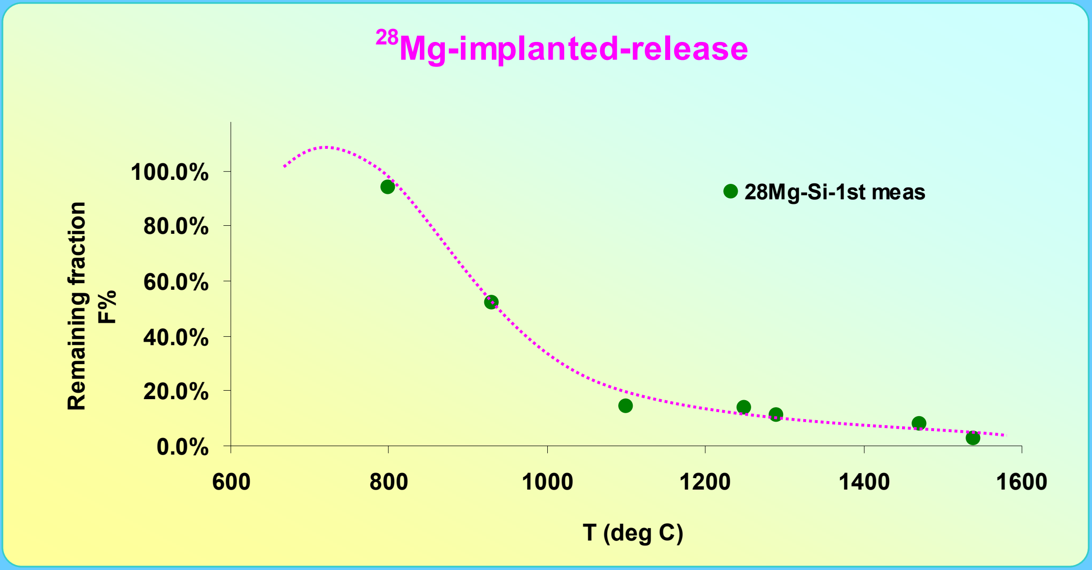
Irradiating the sample is effective to probe bulk diffusion effects.

Initial homogeneous distribution Of activated material



4) RIBs & Target

Release curve of ^{28}Mg implanted into a Si pill



$$\boxed{\frac{\partial C}{\partial t} = D\,\frac{\partial^2 C}{\partial x^2}}$$

GOAL:

-Solving the diffusion equation for different sample materials and the appropriate geometry-boundary conditions-initial conditions.
-Studying the dependence D(T) via Arrhenius relation.

4) RIBs & Target

Time resolved 28Mg concentration in Si sample

Initial ion distribution set with a Montecarlo simulation (TRIM)

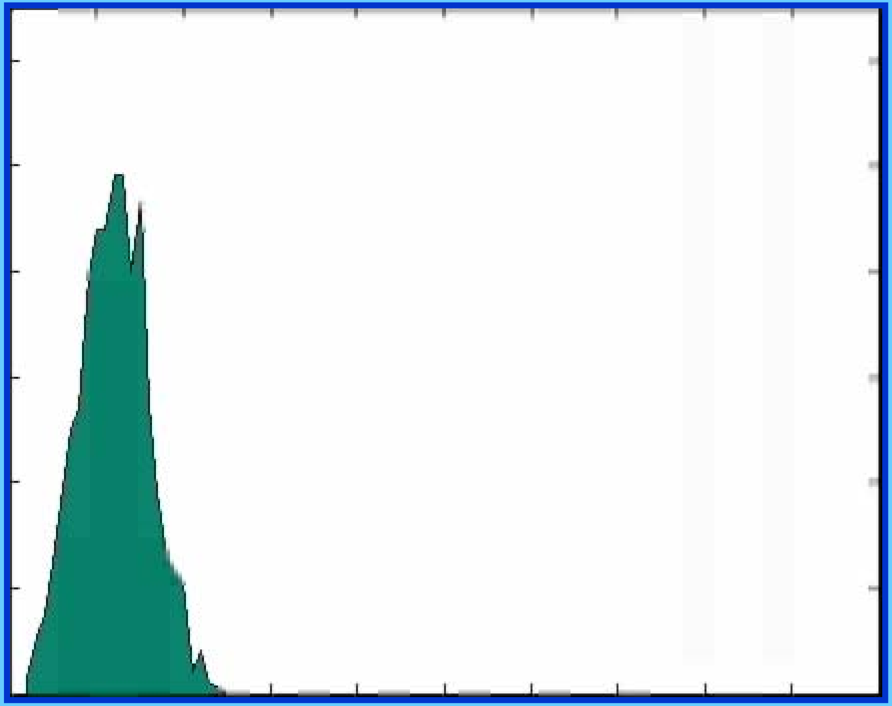
Dynamics simulated (Fortran code) by the ´´Quadratic filling´´ method

At short times, the evolution follows a quasi-gaussian smooth shape (independent on the I.C.)

Differences respect to an isotropic diffusive process:

asymmetry of the peak, which moves slowly into the sample

desorption effects (hardly to evaluate) at the implanted surface.



4) RIBs & Target

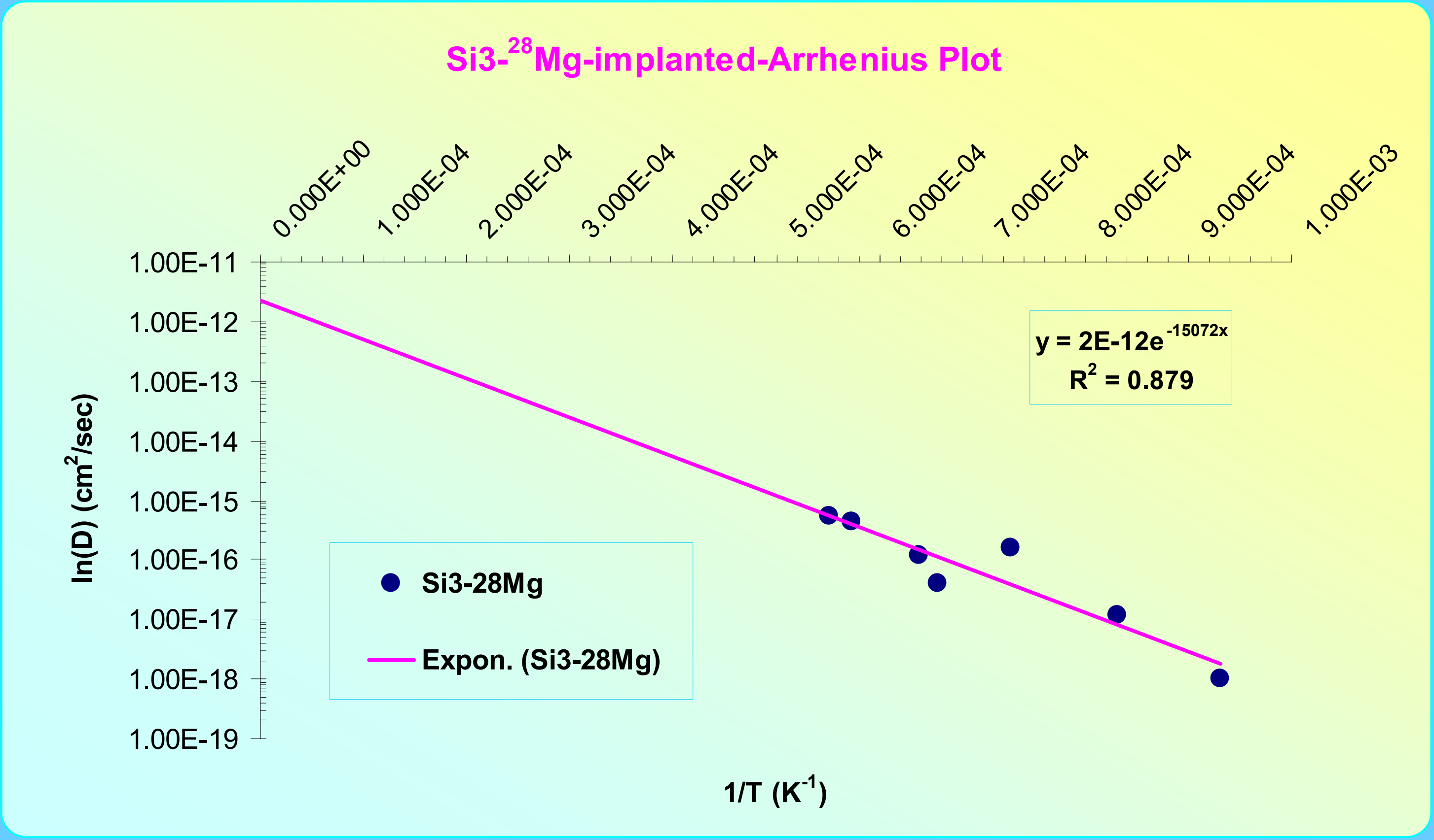
$$D(T) = D_0 \exp\left(-Q/RT\right)$$

Q Activation energy for diffusion (jump mechanism)

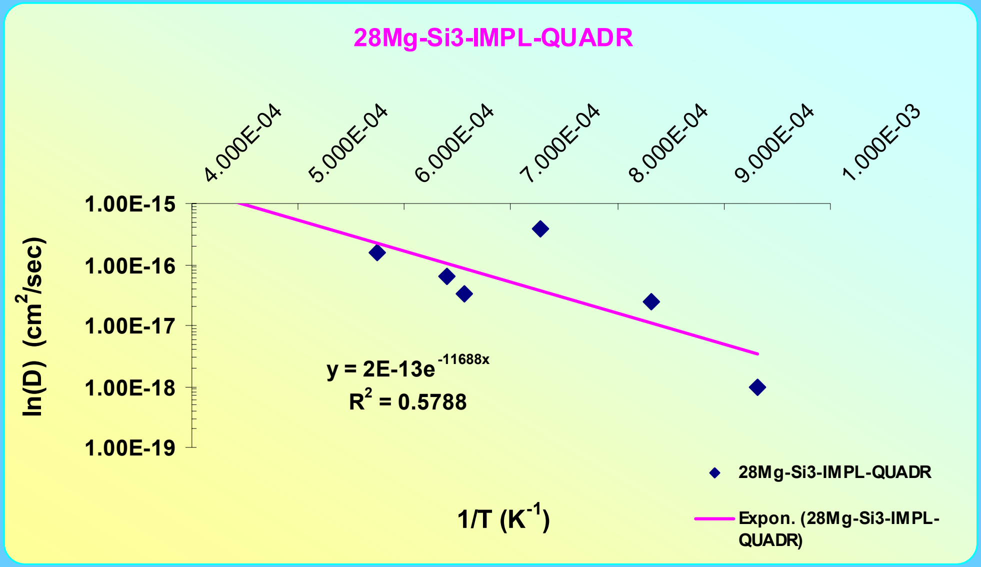
$$D_0 = \lim_{t \to \infty} D(T)$$

-Si3 - 28Mg

T (K)	1/T (K^{-1})	D (cm^2/sec)	F%	t (sec)
1073.15	9.318E-04	1.00E-18	0.942	900



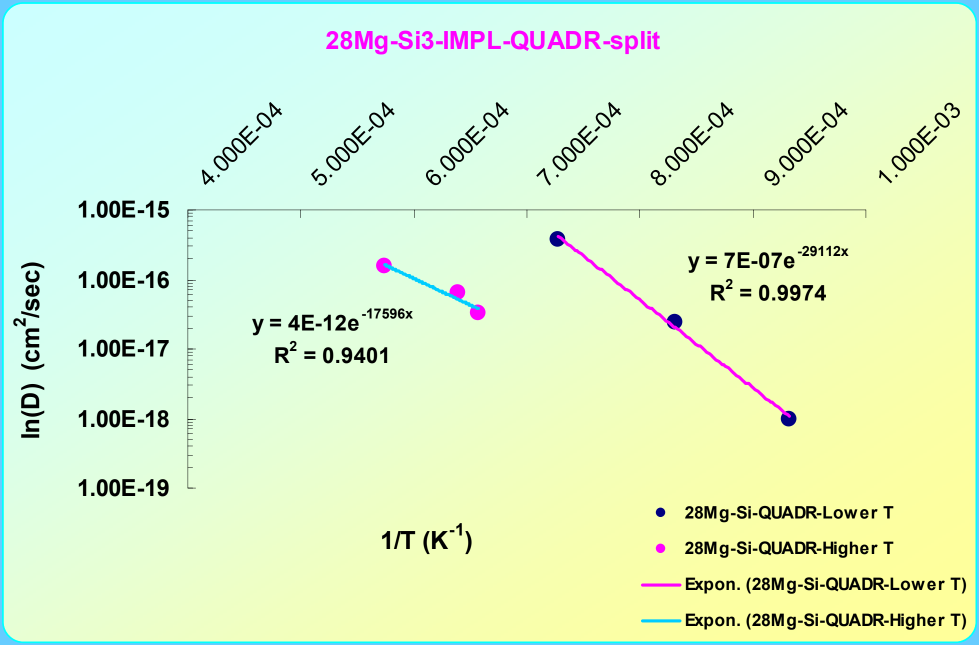
4) RIBs & Target



Quadratic filling method:

The distribution evolves inside the sample, following the discrete relation:

$$\Delta x \sim (\Delta t)^{1/2}$$



2 different **regimes** emerge from data at **low (short time)** and **high (long time) temperature**:

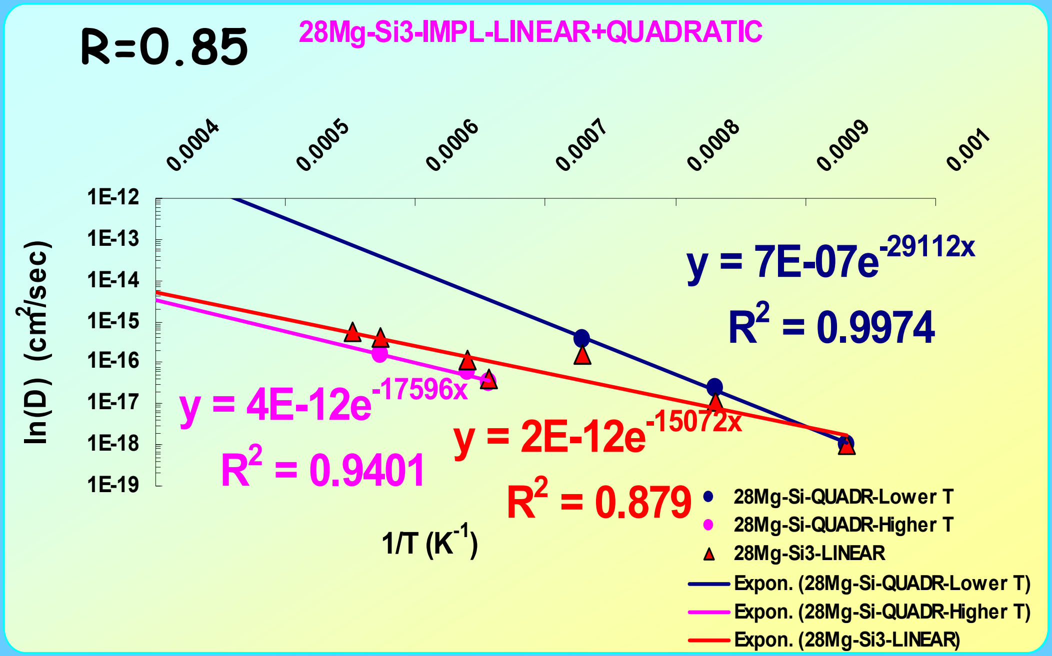
The **activation energy** changes (induced vacancies, sputtering…)? **or** the **desorption** effect is important **at short time?**

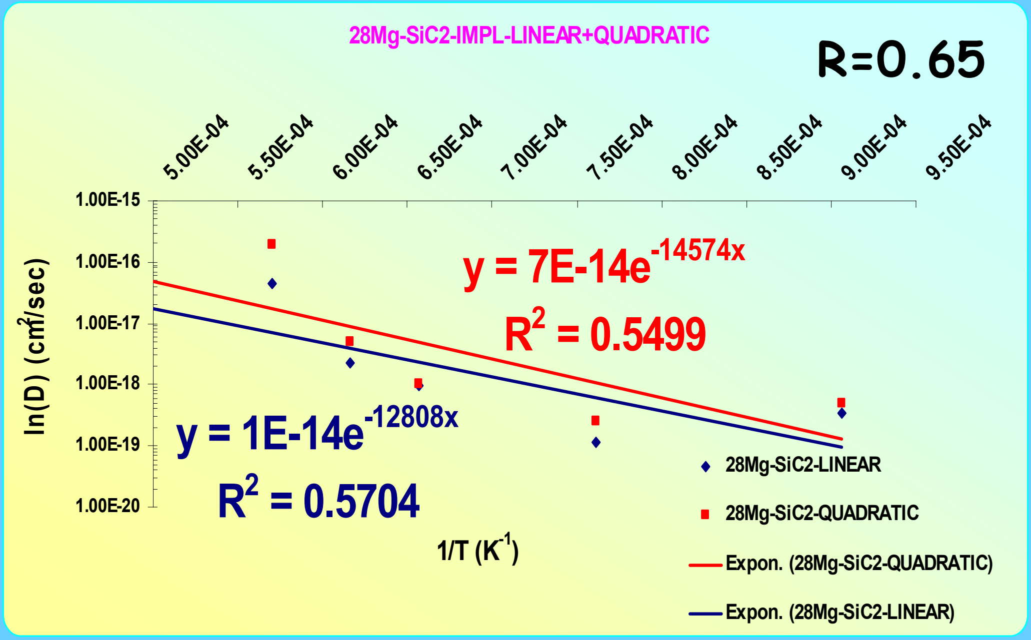
4) RIBs & Target

Different target, same isotope

Si: 2 regimes

Activation energy reduced at high temperature

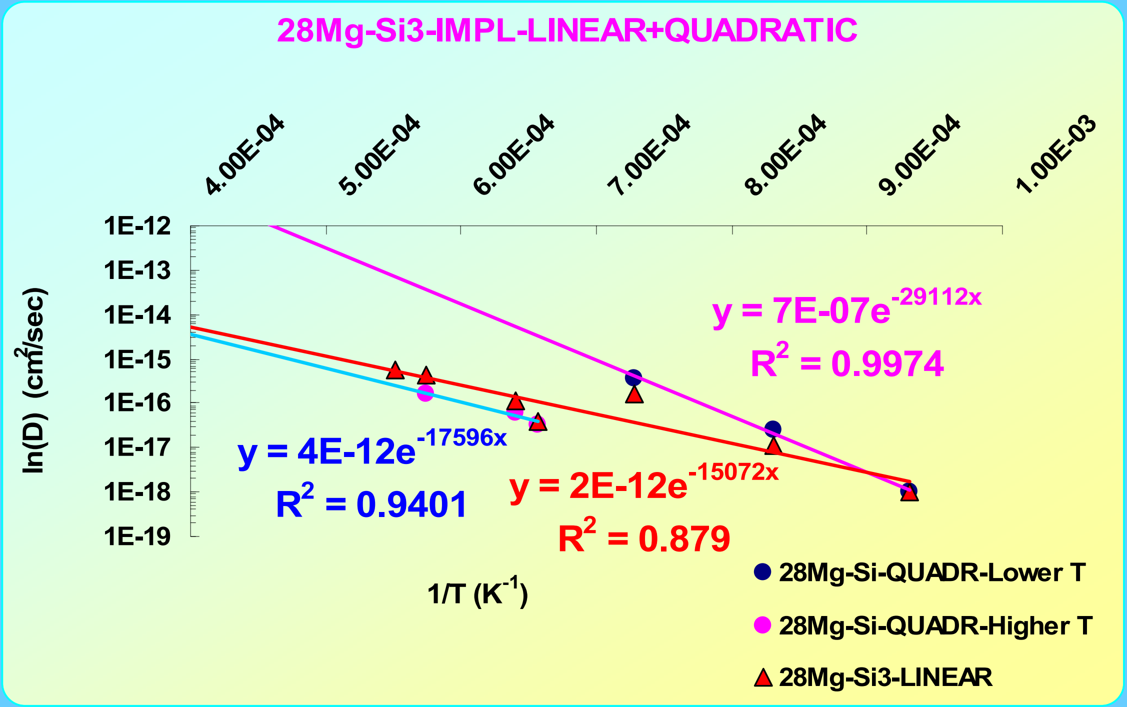




SiC: linear behaviour fails at low temperature (short time): DESORPTION ?

At high temperatures the diffusion in SiC is less dependent on temperature (activation energy smaller)

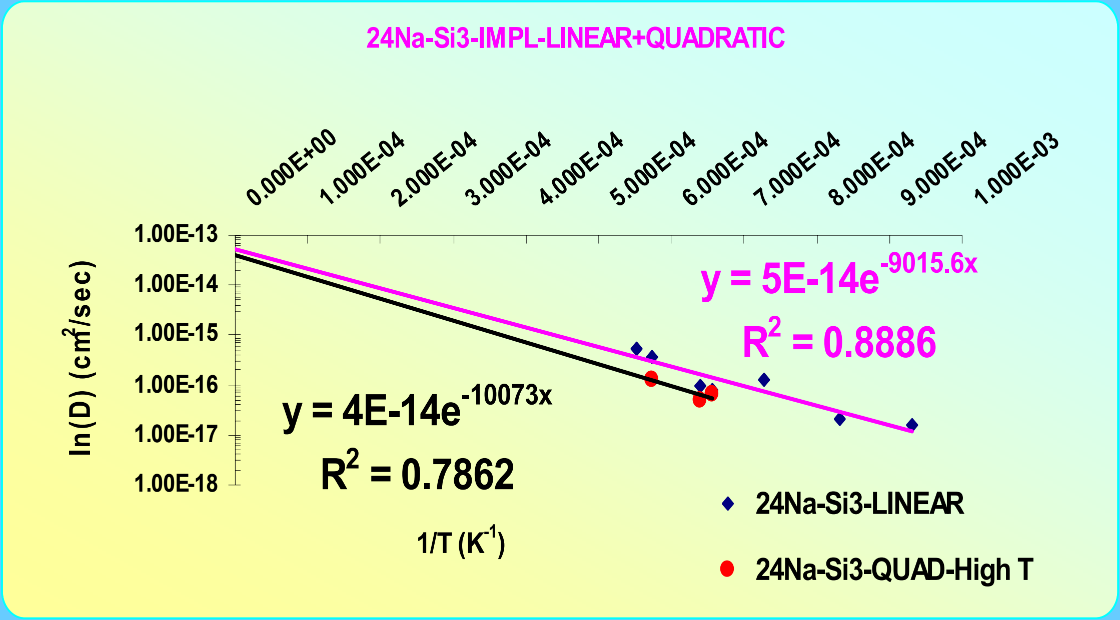
4) RIBs & Target



Different nucleus
same target

2 regimes emerge for Mg *only*

Activation energy is much smaller for Na



In all the implantation examples quadratic filling and absorbing layer methods seem in good agreement

Strong dependence on nuclear species implanted (for similar Z also)

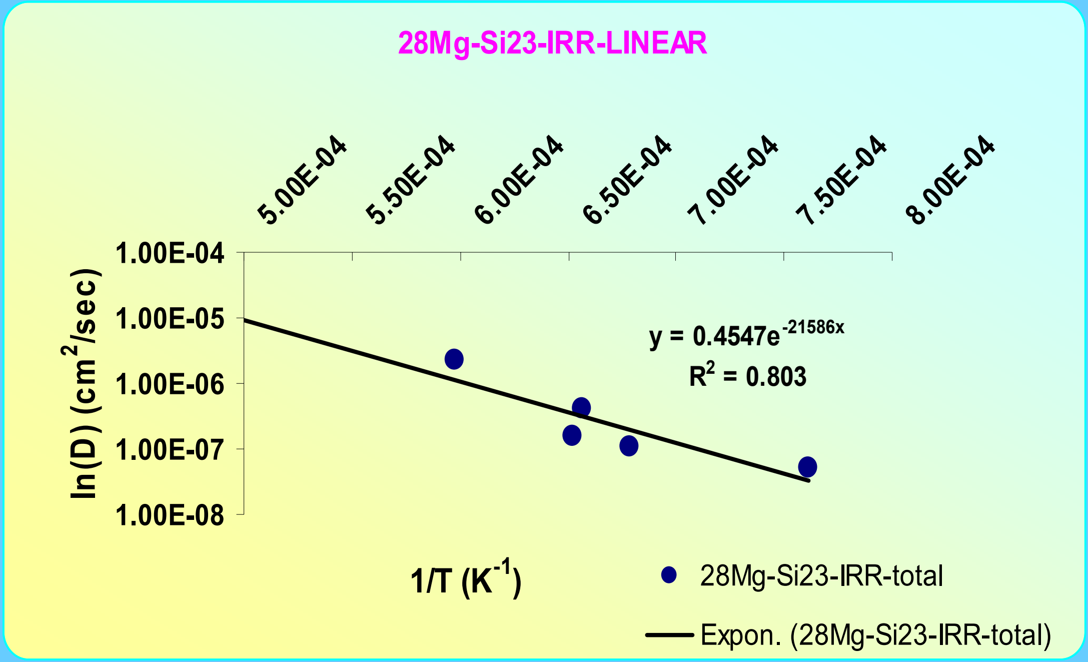
4) RIBs & Target

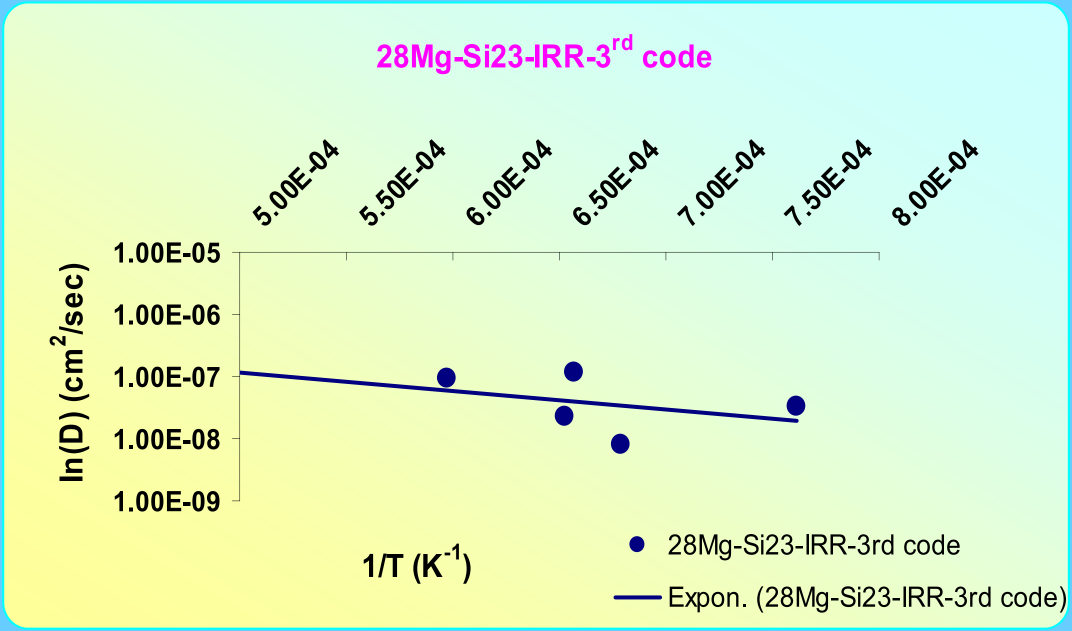
IRRADIATION

Numerical simulation and analytical evaluation (for standard powder) are compared:

The results are not in agreement: analytical evaluation gives a non-linear trend:

microscopic phenomena may affect the dynamics and introduce some memory effects.





5) Conclusions and perspectives

Radioactive beams of **^{22}Mg** and other **n-rich Mg** isotopes
will be obtained at Isolde-Cern for future experiments.

Astrophysical motivation:
1-proton transfer reaction **^{22}Mg(p,γ)^{23}Al** will be realized in order to obtain an estimation of the rate of the proton capture reaction between the same nuclei, at novae outburst temperature:
^{22}Na nucleosynthesis will be investigated.

Nuclear structure information:
The study of the evolution of the ground state along the Mg isotopic chain will be allowed, exploring the effect of the **correlations beyond the standard shell model**: highly **deformed** systems?

Analyses of diffusion processes in different targets allows to select the major candidates to obtain a beam with the **sufficient intensity**:
This study presents some **fundamental physics problems**: their experimental and theoretical investigation can also improve the knowledge of the **microscopic solid-ion interaction**.

EURISOL
European Isotope Separation On-line Radioactive Nuclear Beam facility

Operating ISOL facilities

ISOLDE - CERN (Geneve, Switzerland)
GSI-ISOL (Darmstadt, Germany)
SPIRAL - GANIL (Caen, France)
CRC (Louvain-la-Neuve, Belgium)
LISOL (KU Leuven)
PARRNE (IPN Orsay, France)
OSIRIS (Studsvik, Sweden)
IRIS (PNPI, Gatchina, Russia)
ISAC (TRIUMF, Vancouver, Canada)
BEARS - LBL (Berkeley, CA, USA)
IRIS - LBL (Berkeley, CA, USA)
HRIBF - ORNL (Oak Ridge, TN, USA)
RNB facility at INS - KEK/Tanashi (Tokyo, Japan)
IMP Lanzhou (Lanzhou, China)

Proposed ISOL facilities

EXCYT INFN-LNS (Catania, Italy)
SPES INFN-LNL (Legnaro, Italy)
MAFF (München, Germany)
SPIRAL-II - GANIL (Caen, France)
SIRIUS - CASIM (Daresbury, UK)
SPL - CERN (Geneve, Switzerland)
DRIBS FLNR (Dubna,Russia)
MASHA FLNR(Dubna, Russia)
Rare Isotope Accelerator RIA @ Argonne - RIA @ MSU/NSCL (USA)
High Intensity Proton Accelerator Facility JAERI (Tokai, Japan)
VEC-RIB (Calcutta, India)

Collaboration

Prof. A.Bracco
Prof. F.Camera
Universita' degli Studi di Milano.

Target development & Study
EURISOL-TARGISOL Project.

U.Koster, ISOLDE - CERN.

V.Troncale,
Universita' degli Studi di Milano-INFN – CERN.

H.Frånberg, PSI – CERN.
M.Bersani, Universita' degli Studi di Padova.

REX-ISOLDE:
J. Cederkall, Lund - CERN Collaboration.

COLLAPS:
G.Neyens - R.Neugart - M.Kowalska
Leuven - Mainz - CERN Collaboration.