

#### **Light Radio-isotopes**

## **Nuclear Astrophysics, Neutrino Physics** and

**Fundamental Interactions** 

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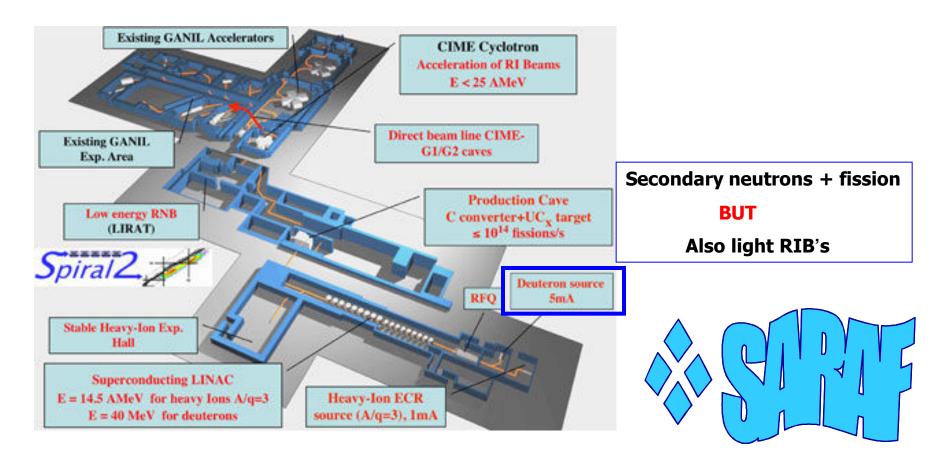
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- 3. GANIL, Caen, FRANCE
- 4. LBL, Berkeley, USA



















### ECR Ion Source, RFQ and 1st cryo-module in situ



The SARAF accelerator at Soreq, Israel.
Summer 2009

Final Commissioning of Phase —I

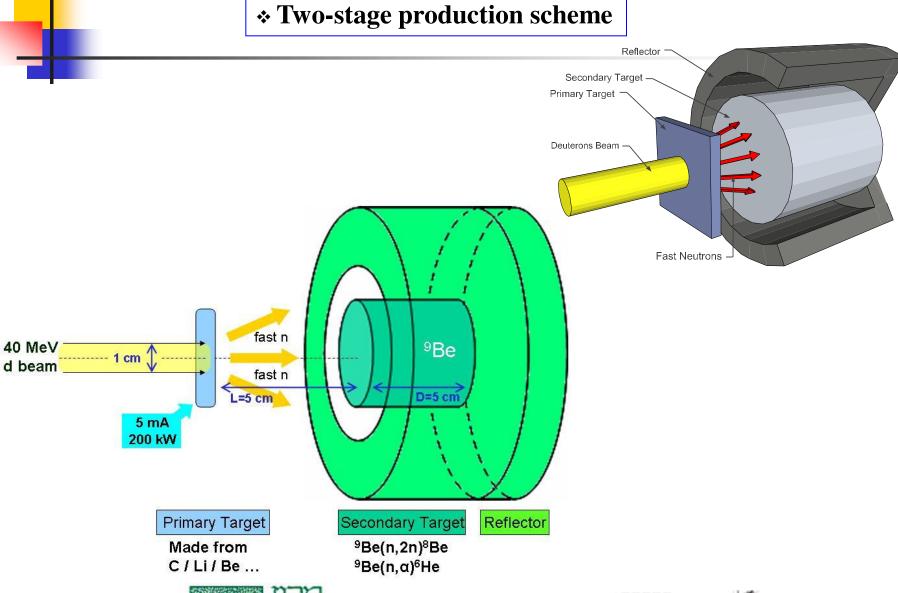
Nov. 2009 -

1 mA p @ 3.5 MeV









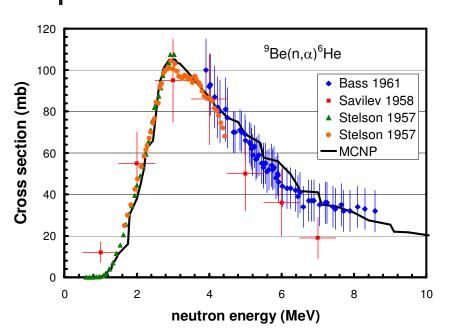


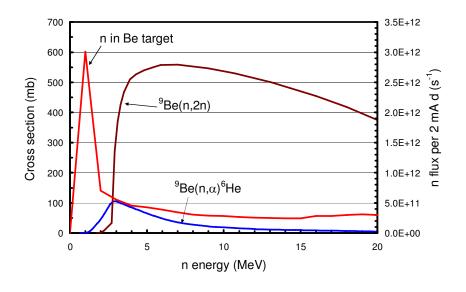






## <sup>6</sup>He production (n, $\alpha$ ) cross section





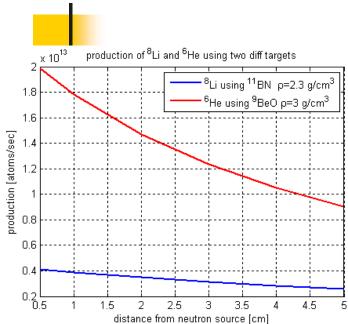
Production yield of the order of 10<sup>13</sup> <sup>6</sup>He per 1 mA d@40 MeV

Remember also <sup>11</sup>B(n, α)<sup>8</sup>Li









# <sup>6</sup>He vs. <sup>8</sup>Li Production using SARAF/SPIRAL2 40 MeV d on Lithium neutrons

SARAF/SPIRAL2 d-Li neutron flux is more suitable for <sup>6</sup>He production than <sup>8</sup>Li

11 B(n,α)<sup>8</sup>Li and <sup>11</sup>B(n,2n)<sup>10</sup>B from ENDFB6.8

70

11 B(n,α)<sup>8</sup>Li

11 B(n,2n)<sup>10</sup>B

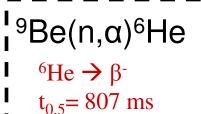
40

20

10

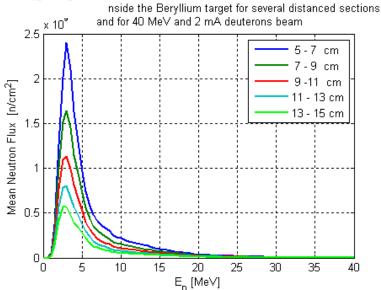
5 10 15 20

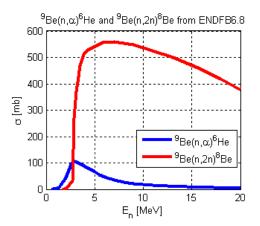
E<sub>n</sub> [MeV]



<sup>11</sup>B(n,α)<sup>8</sup>Li <sup>8</sup>Li → β<sup>-</sup>

 $t_{0.5} = 838 \text{ ms}$ 



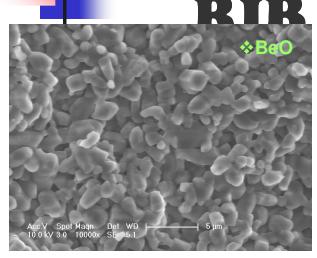


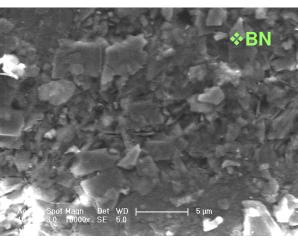


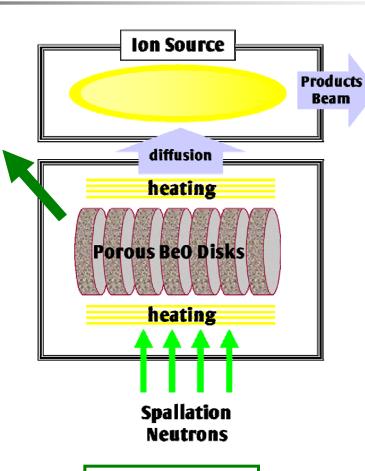




## **Extraction of**







❖ISOLDE Exp. T. Stora at al. 17.4.2009



<sup>6</sup>He









#### **Schematics and pictures of ISOLDE setup**

#### **Courtesy of Tierry Stora and the ISOLDE Ion-Source group**





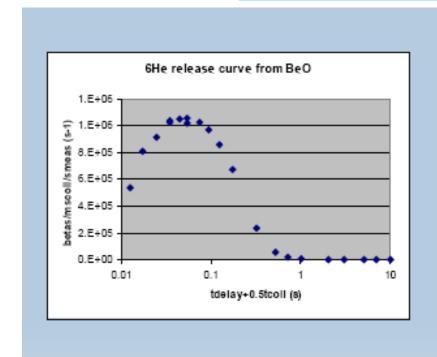


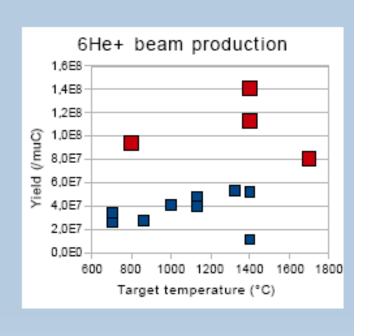




#### **♦• Preliminary results of ISOLDE BeO run – April 2009**

#### **♦** See talk by Thierry Stora – this WORKSHOP





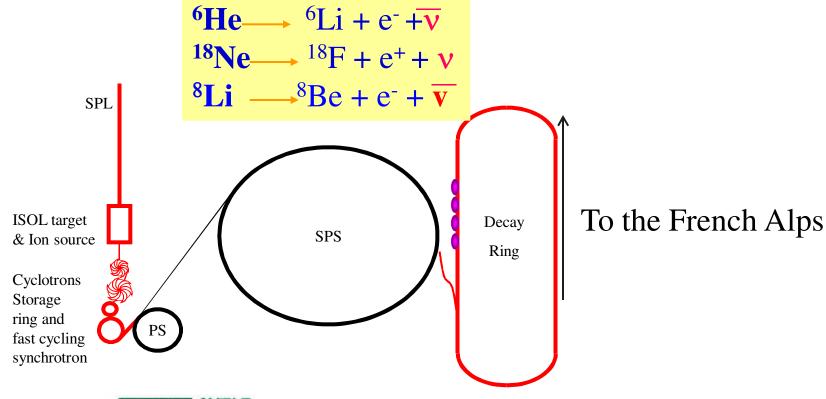






## The $\beta$ beam (from Mats Lindroos – CERN)

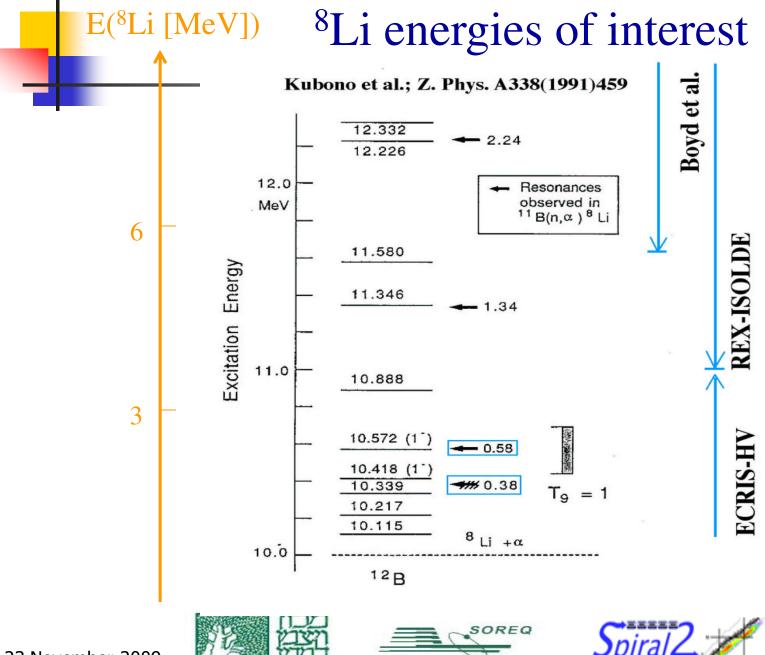
Production of an intense collimated neutrino (antineutrino) beam directed at neutrino detectors via β decay of accelerated radioactive ions











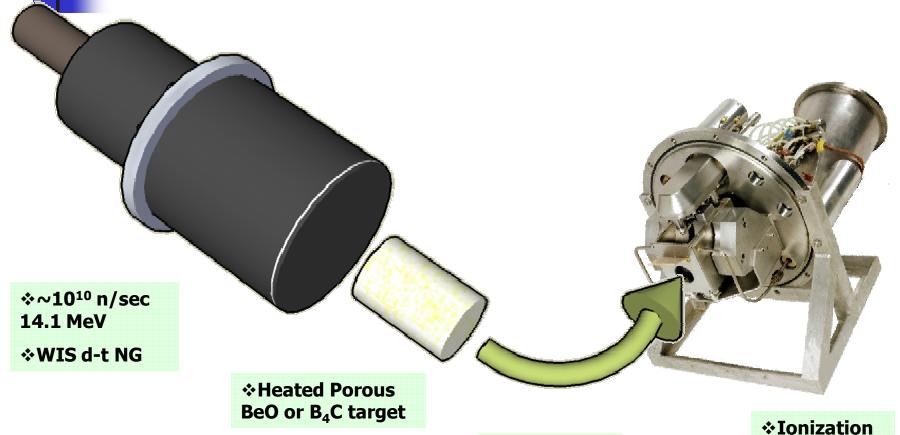








## <sup>6</sup>He and <sup>8</sup>Li beams in WIS



**\***~6·10<sup>7</sup> <sup>6</sup>He/s ~2·10<sup>7</sup> <sup>8</sup>Li/s Extraction by diffusion

**\*Efficiency?** 







## **β-Decay Physics**

- Transition rate W (inverse lifetime)
  - In case of nonoriented nuclei

$$dW \propto \xi \left(1 + a \frac{\vec{p}_e \cdot \vec{p}_v}{E_e E_v} + b \frac{m}{E_e} + \dots\right)$$

**❖Beta-neutrino correlation coefficient** 

• In case of oriented nuclei  $(\vec{J}$  - nuclear polarization)

$$dW \propto \xi \left(1 + A \frac{\vec{p}_e}{E_e} \cdot \vec{J} + D \vec{J} \cdot \frac{(\vec{p}_e \times \vec{p}_v)}{E_e E_v} + R \vec{\sigma}_e \cdot \frac{(\vec{J} \times \vec{p}_e)}{E_e} + \dots \right)$$

 J. D. Jackson, S. B. Treiman and H. W. Wyld, Nucl. Phys. 4, 206 (1957)







## Why RNB's in Traps?

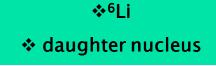
- No possibility for detection of neutrinos
- Small effects measurements low energy of ions, multiple scattering, angle resolution
- Atoms/Ions are pin-point in a trap
- → Increase of accuracy in measurements:
  - Angular correlations
  - Energy





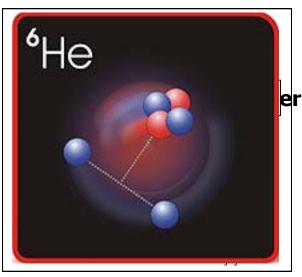


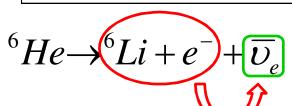
### Example: <sup>6</sup>He beta decay See, e.g, Flechard et al, PRL (2008)

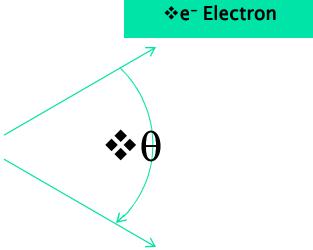


$$dW \propto a\xi \left(\frac{p_e}{E_e}\cos\theta\right)$$

$$dW_{SM}(^{6}He) \propto -\frac{1}{3} \left(\frac{p_{e}}{E_{e}} \cos \theta\right)$$







❖ν<sub>e</sub> Electron

anti-neutrino

- New physics beyond the Standard Model's
- ❖ V-A structure









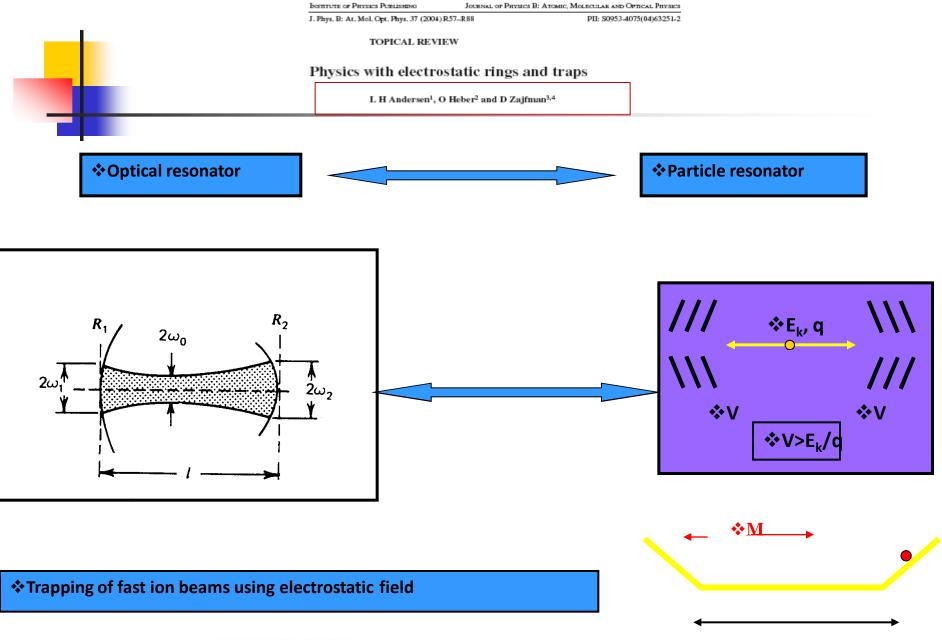
### Current Status on <sup>6</sup>He

- **❖** ~2 % limit on any possible deviation hence improve limit
- Statistics + systematic limitations
- ❖ Flechard et al: "....MOT" (Magneto Optical Trap)"
- ❖ But He is noble gas metastable state for MOT
- Statistics













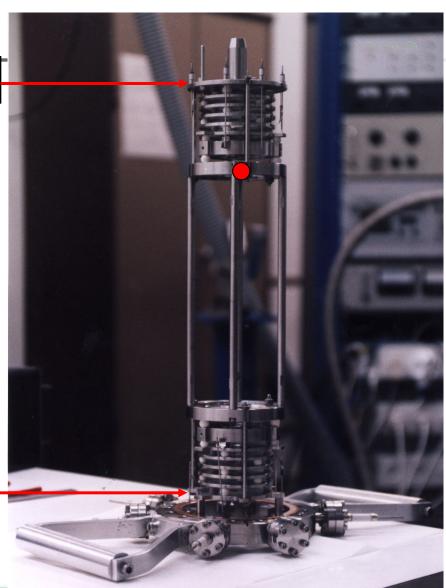






**❖** Field free region

**❖**Exit mirror



**❖L=407 mm** 

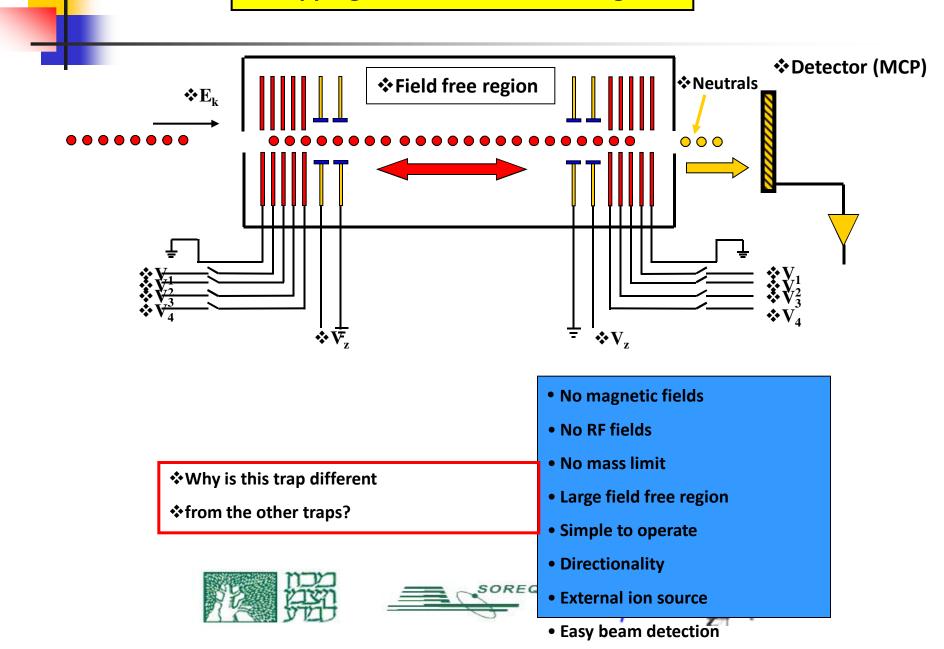




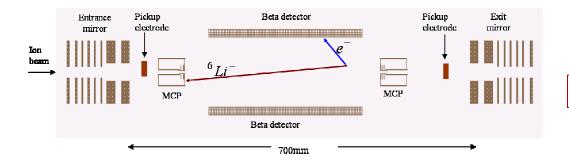




#### **❖**Trapping ion beams at keV energies

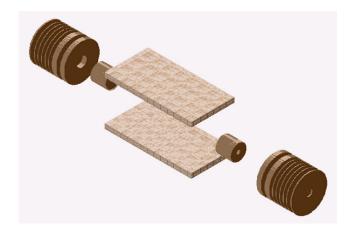






**♦ MPI – HD Participation** 

**♦ Fig. 2** A schematic view of the EST for β-decay studies. The radioactive ion, like  $^6$ He, moves with  $E_k$ -4.2 keV between the reflecting electrodes. The β electrons are detected in position sensitive counters while the recoiling ions, due to kinematic focusing, are detected with very high efficiency in either one (determined by the instantaneous direction) of the annular MCP counters.













### R&D steps at the WI

- **❖** <sup>6</sup>He (+ ions) and <sup>8</sup>Li (neutrals) production and extractions
- EIBT parameters (bunching (pre-trapping), bunch size, timing

(with <sup>4</sup>He) --- Re-use hardware from the 14 UD Pelletron

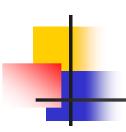
- ❖ RNB in Trap and detection system
- First measurements
- **❖ SARAF...**



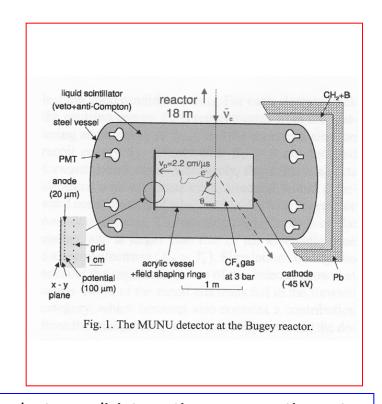












Model dependence of the neutrino-deuteron disintegration cross sections at low energies
 http://il.arxiv.org/abs/nucl-th/0702073v1











#### Prospects for Detecting a Neutrino Magnetic Moment with a Tritium Source and

Beta-beams

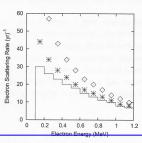
#### G. C. McLaughlin

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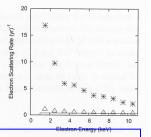


Fig. 3. BETA-BEAMS: Number of neutrino-electron scattering events from a Helium-6 ion source produced at the rate  $10^{15}$  per second, and a  $4\pi$  detector of 10 m in radius. The diamonds show the number of scatterings if the neutrino has a magnetic moment of  $\mu_{\nu} = 10^{-10} \mu_{B}$ , the stars present the number of events if  $\mu_{\nu} = 5 \times 10^{-11} \mu_{B}$ , and the triangles give the number of events if the neutrino has a magnetic moment of  $\mu_{\nu} = 10^{-11} \mu_{B}$ . The histogram shows the expected number of events for a vanishing neutrino magnetic moment.

$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi} \left[ (g_V + g_A)^2 + (g_V - g_A)^2 \left( 1 - \frac{T}{E_\nu} \right)^2 + (g_A^2 - g_V^2) \frac{m_e T}{E_\nu^2} \right] + \frac{\pi \alpha^2 \mu_\nu^2}{m_e^2} \frac{1 - T/E_\nu}{T} \tag{1}$$

where  $g_V = 2 \sin^2 \theta_W + 1/2$ ,  $\theta_W$  is the Weinberg angle,  $g_A = 1/2$  (-1/2) for  $\nu_e$  ( $\bar{\nu}_e$ ),  $m_e$  is the electron mass and  $G_F$  is the Fermi coupling constant. Following Eq. (1) we consider scattering of neutrino on free electrons. The effect of atomic binding is discussed in [13]. These cross sections have to be averaged by the neutrino flux from the relevant source :

$$\left\langle \frac{d\sigma}{dT} \right\rangle = \frac{\int \frac{dN_{\nu}}{dE_{\nu}} \frac{d\sigma(E_{\nu})}{dT} dE_{\nu}}{\int \frac{dN_{\nu}}{dE_{\nu}} dE_{\nu}} \tag{2}$$

where  $dN_{\nu}/dE_{\nu}$  is the number of neutrinos per unit energy emitted by the neutrino source. Note that the electron recoil energy is restricted to the values :

$$T \lesssim \frac{2E_{\nu}^2}{2E_{\nu} + m_e} \tag{3}$$

 $\mu_{sm} = 3 \bullet 10^{-19} [\mu_{\nu}/eV], but.....$ 

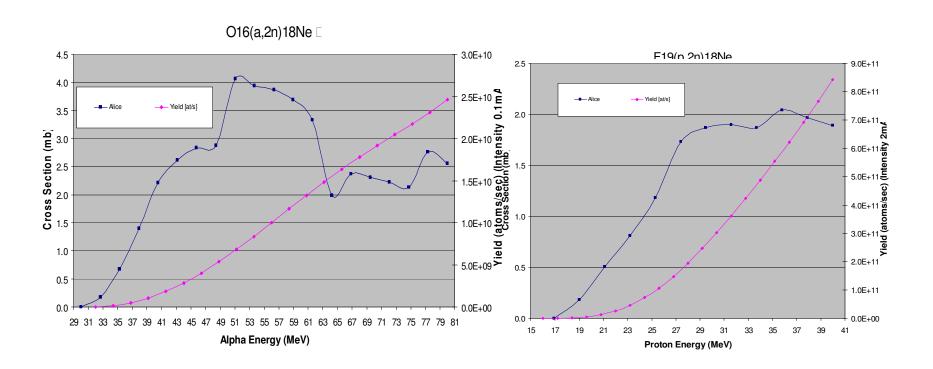








#### **Tentative results**



#### Lower yield, but, better extraction..











#### <u>Via neutron converter – <sup>6</sup>He, <sup>8</sup>Li, ...</u>

- **❖ Simulations Geant4, MCNP PRODUCTION rate of ~10<sup>13</sup>/mA!!!**
- Converter design
- \*Target design Diffusion & Extraction (BeO fibers,

**Boron Nitrite fibers)** 

<u>Direct production – 14,150, 18Ne,...</u>

- Design of targets (heat) for direct production (O and Ne); materials (gas?), ...
- Extraction. Nitrogen is "bad". Perhaps CO<sub>2</sub>? M. Loiselet, LLN <sup>12</sup>C(<sup>3</sup>He,n)<sup>14</sup>O and <sup>12</sup>C(<sup>4</sup>He,n)<sup>15</sup>O

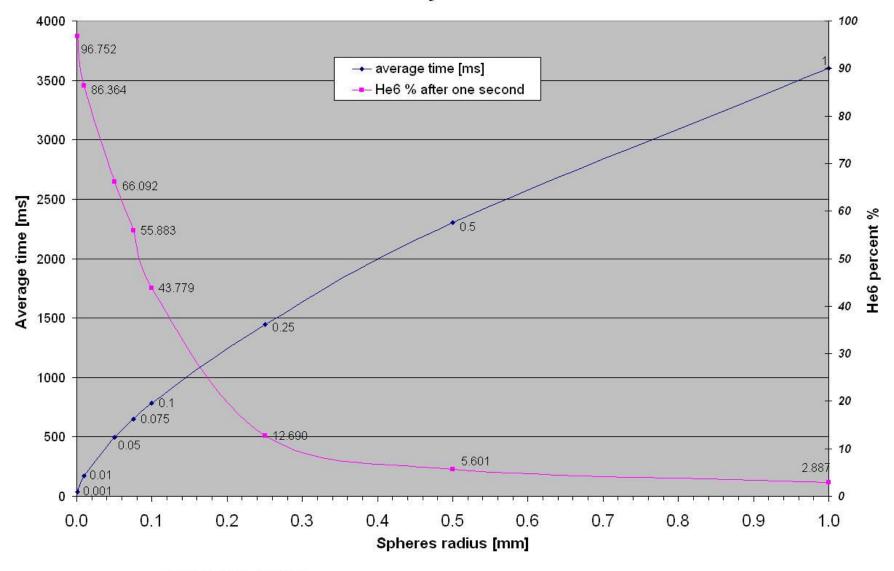
**Experiment:** Beam, Team, Detectors (RMS-like, Si ball, EXOGAM..)...







#### Diffusion & Decay of He6 in BeO











#### Towards a full proposal – objectives and milestones.

**Soreq neutron generator** 

**Soreq Phase I** 

**GANIL** (neutrons from C+C)

**ISOLDE** (neutrons from 1 GeV spallation)

2009-2011 Target (s) manufacturing. Parameters for experimental setup, synergy with detector (particle, gamma, separator) projects

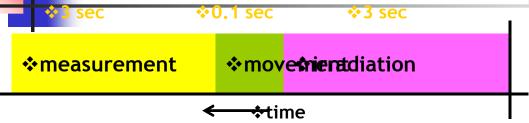
- **❖ 2012-.....** SPIRAL-II
- \* 2012-..... SARAF??...





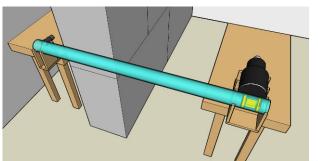


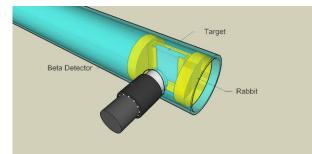
## <sup>8</sup>Li Production Experiment

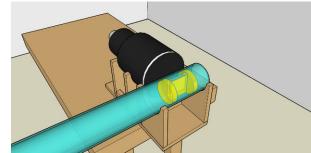






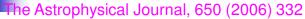








#### **Partial sample of representative papers**



J.L. Fisker et al.

The Importance of  $^{15}O(\alpha,\gamma)$   $^{19}Ne$  to X-Ray Bursts and Superbursts

Arxive-ph/0702412 Feb. 2007

J.L. Fisker et al.

Experimental measurements of the  $^{15}O(\alpha,\gamma)^{19}Ne$  reaction rate vs. observations of type I X-ray bursts

Nuclear Physics A 718, (2003) 605

B. Davids et al.

Alpha-decay branching ratios of near-threshold states in  $^{19}$ Ne and the astrophysical rate of  $^{15}$ O( $\alpha,\gamma$ ) $^{19}$ Ne

PRC 67 065809 (2003)

K. E. Rehm et al.

Branching ration  $\Gamma_{\alpha}/\Gamma_{\gamma}$  of the 4.033 MeV 3/2+ state in <sup>19</sup>Ne

Nuclear Physics A 688 (2001)465c.

S. Cherubini et al.

The  $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$  reaction using a  $^{18}\text{Ne}$  radioactive beam









# 4

#### **SUMMARY**

- Scientific Case
- ❖ Calculations and simulations exist but much more R&D needed

Presented at several recent scientific conferences.

**Funds: EC (infrastructure), Local** 

- ❖ "Road Map" towards a full experiment test experiments!
- **❖ OPEN COLLABORATION** participation welcome!!







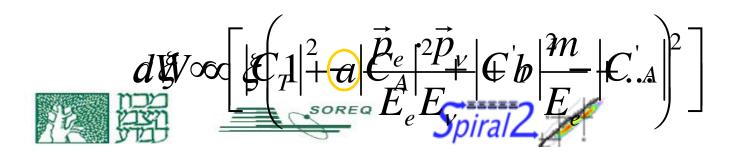


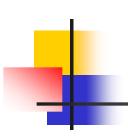
## **β-Decay Physics**

For pure Fermi or pure Gamow-Teller (GT) transitions the correlations coefficients become independent of the nuclear matrix elements

The correlations coefficients depends on scalar, yector, axial- $\beta$  vector and tensor coefficients in  $\beta$ -decay Hamiltonian i=S,P,V,A,T

For example, <sup>6</sup>He β-decay (pure GT) beta-neutrino correlation coefficient can be measured in order to check the presence of tensor interactions





## X-Ray Bursts and the "rp" process

These movies simulate an x-ray burst and the rapid-proton capture ("rp") process.

The calculation begins at T9=T/10^9 K=40 with only neutrons and protons. As time progresses and the temperature drops below T9=10, nucleons assemble into 4He nuclei then into heavier mass nuclides. Once T9 falls below about 4, the QSE among the heavy nuclei begins to break down. Charged-particle reactions freeze out, and flow to higher mass number occurs via nuclear beta decay. This is the classical r-process phase.

The rp process

 and x-ray bursts site of nucleo synthesis







❖A new class of ion trapping devices: The Electrostatic Linear Ion Beam Trap **❖** Physical Principle: **❖** Photon Optics and Ion Optics **❖**are Equivalent **∜**V<sub>1</sub>  $V_1 < V_2$ **⊹**R **❖**Photons can be Trapped in an **❖Optical Resonator ⊹**L **⇔**E<sub>k</sub>, q **❖**lons can be Trapped in an **❖** Electrical Resonator? **\***V **\***V **∜** V>E<sub>k</sub>/c

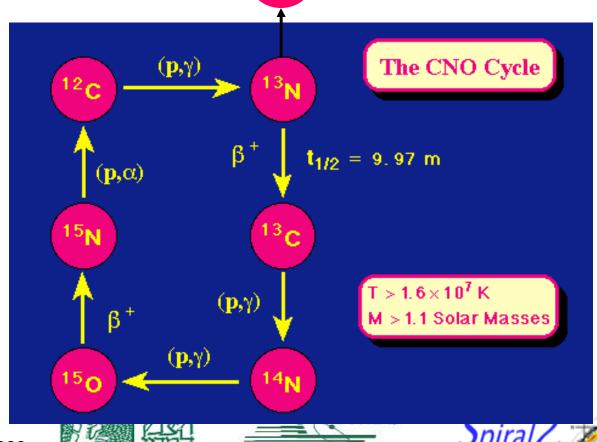


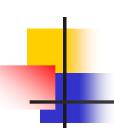
Fusion Reactions in the Sun:
The CNO cycler

<sup>14</sup>O

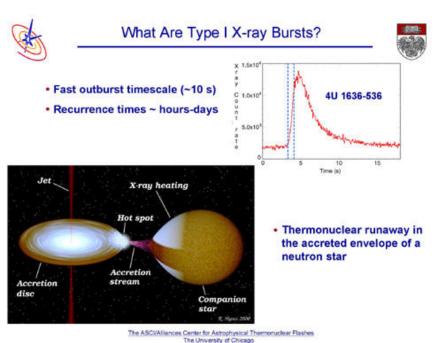
 $(\alpha,p)$ 

❖ Proposed at GANIL





# Mass accretion from a companion into a neutron star (black hole).

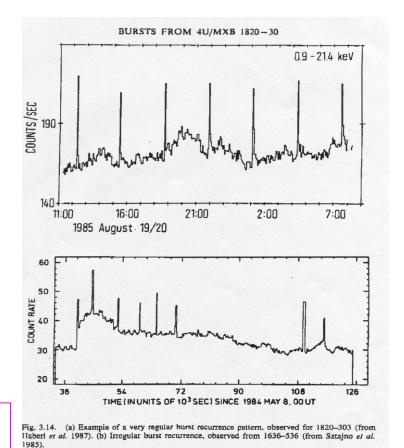


 Role of <sup>14</sup>O, <sup>15</sup>O and <sup>18</sup>Ne in the physics of x-ray bursts

<sup>4</sup>He(<sup>15</sup>O,γ)<sup>19</sup>NE

M. Wiescher et al. Erice Conference, 2007

J.L. Fisker et al., arXiv:astro-ph/070241









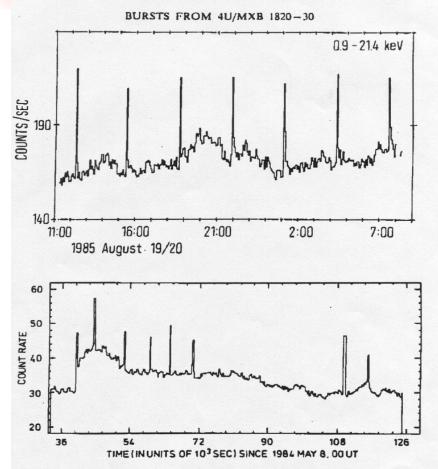


Fig. 3.14. (a) Example of a very regular burst recurrence pattern, observed for 1820–303 (from Haberl *et al.* 1987). (b) Irregular burst recurrence, observed from 1636–536 (from Sztajno *et al.* 1985).

### **Typical X-ray bursts:**

- $10^{36}$ - $10^{38}$  erg/s
- duration 10 s 100s
- recurrence: hours-days
- regular or irregular

Frequent and very bright phenomenon!

 $(\text{stars } 10^{33}\text{-}10^{35} \text{ erg/s})$ 

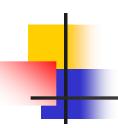




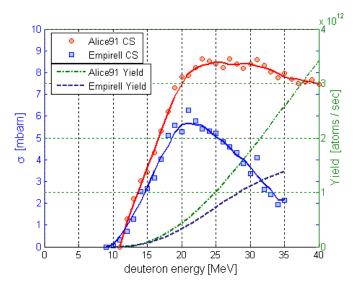


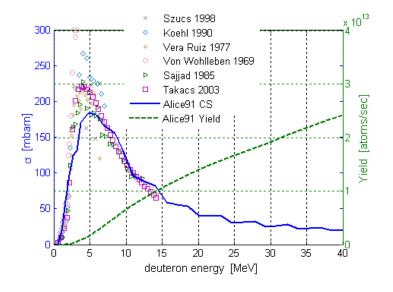


### Long-learned lesson:



"orders-of-magnitude improvement in sensitivity of measurement – enhanced understanding and possibilities".





<sup>14</sup>N(d,2n)<sup>14</sup>O cross section and yield for a 2 mA deuteron beam

<sup>14</sup>N(d,n)<sup>15</sup>O cross section and yield for a 2 mA deuterons beam

But, extraction of atomic oxygen...











A first experimental approach to the  $^{15}O$  +  $\alpha$  elastic scattering - Eur. Phys. J. A27, 183 (2006)

F. Vanderbist, P. Leleux, C. Angulo, E. Casarejos, M. Couder, M. Loiselet, G. Ryckewaert,

P. Descouvement, M. Aliotta, T. Davinson, Z. Liu, and P.J. Woods

Recent experiments have determined  $\Gamma_{\alpha}$  (or put limits to  $\Gamma_{\alpha}$ ) for levels in <sup>19</sup>Ne up to 5.092 MeV excitation energy. A conclusion is that a direct measurement of the <sup>15</sup>O( $\alpha$ ,  $\gamma$ )<sup>19</sup>Ne reaction in the region of astrophysical interest is <u>currently impossible</u>: <sup>15</sup>O beams of intensity larger than 10<sup>11</sup> pps on target would be required indeed to measure the <sup>15</sup>O(a,  $\gamma$ )<sup>19</sup>Ne cross-section in inverse kinematics in the energy region surrounding the first state above threshold, at 4.033 MeV....





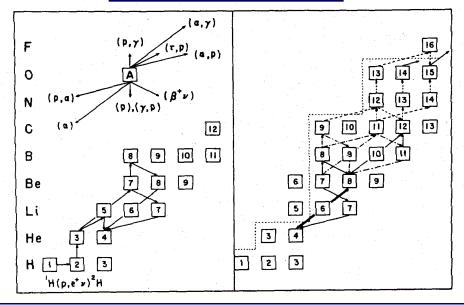




### Examples of Reactions with RNB's for Astrophysics

- ${}^{8}B(p,\gamma){}^{9}C$
- ${}^{8}B(\alpha,p)^{11}C$
- ${}^{9}C(\alpha,p)^{12}N$
- ${}^{11}C(p,\gamma){}^{12}N$

#### HOT PROTON-PROTON CHAINS







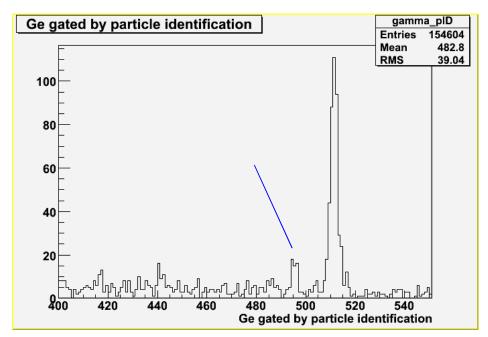




#### **ISOLDE experiment IS424 (Sept. '07):** (in collaboration with P.J. Woods et al.).

The use of a  $^{17}$ F beam from the upgraded REX-ISOLDE facility to study the astrophysically important  $^{14}$ O(a,p) $^{17}$ F reaction in time reverse kinematics.

- REX-ISOLDE + MINIBALL
- Only  $\sim 10^{3} \, ^{17} \text{F/s}$

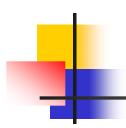


On-line data of p- $\gamma$  coincidences – Indicating the 1<sup>st</sup> excited state of <sup>17</sup>F









#### **EURISOL INTERNATIONAL ADVISORY PANEL:**

".... no progress has been made with the study of alternative production schemes of <sup>6</sup>He and <sup>18</sup>Ne using low energy beams and strongly recommends that this study be completed....
The outcome of this study is an essential ingredient for the analysis whether it is technically feasible to decouple EURISOL and the beta-beams completely



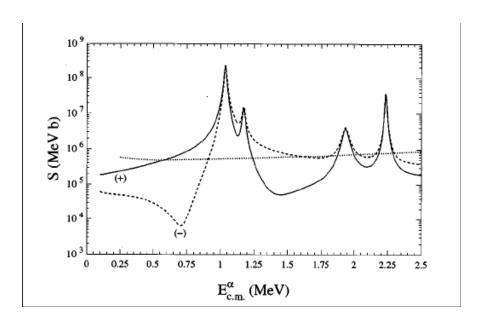






#### **GANIL** experiment – accepted by GANIL PAC: (in collaboration with Marialuisa Aliotta et al.)

Plan to investigate the *direct*  $^{14}O(\alpha,p)^{17}F$  reaction at four different energies in the energy region  $E_{cm}=1.0-2.5$  MeV



Calculated total S(E) factor.

Constructive (+) and destructive (-)
interference between the Jpp=1<sup>-</sup>
6.15 MeV state and the direct l=1
partial wave contribution are shown.

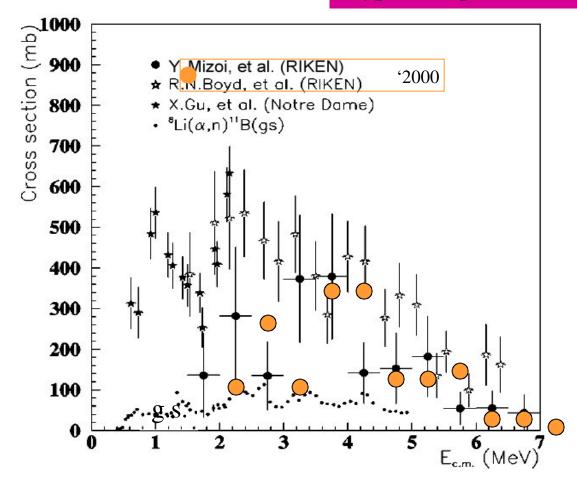








### Type II Supernovae ${}^{8}\text{Li}(\alpha,n)^{11}\text{B}$

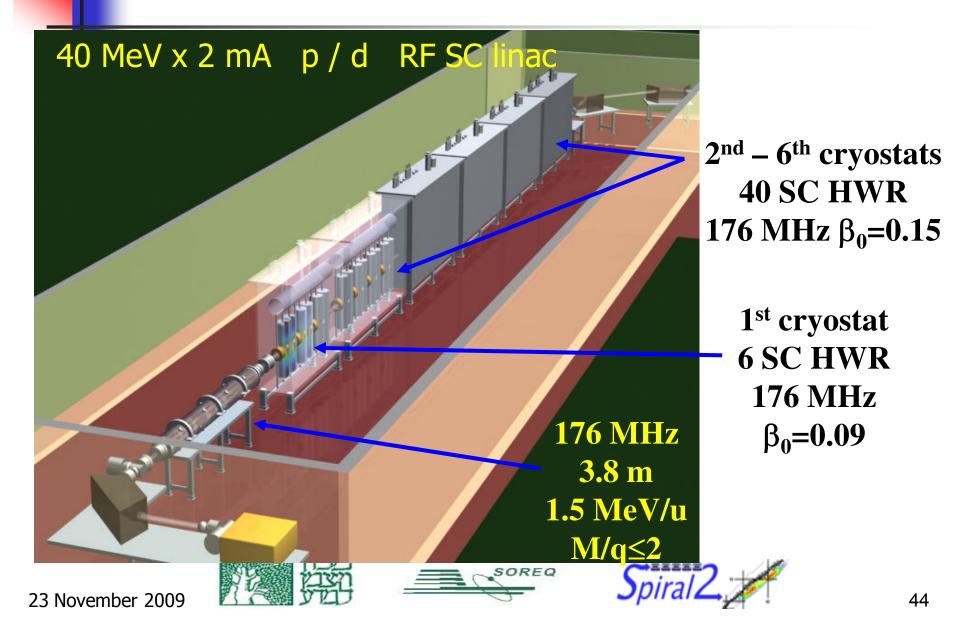




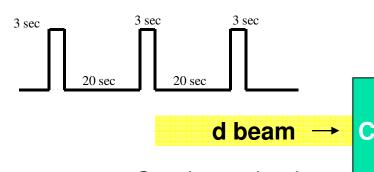




## Accelerator artist view



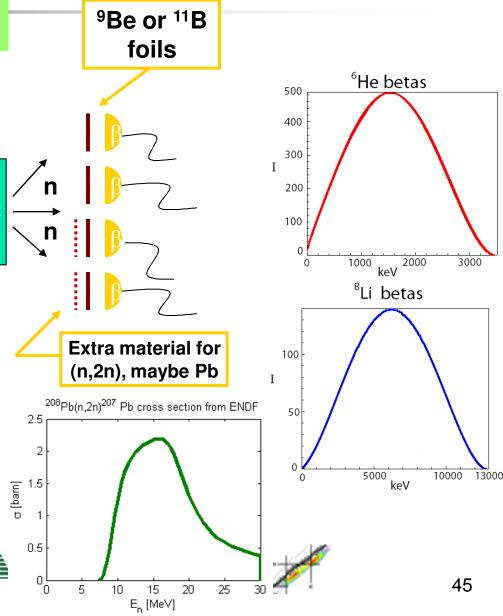
## <sup>6</sup>He or <sup>8</sup>Li production measurements by betas



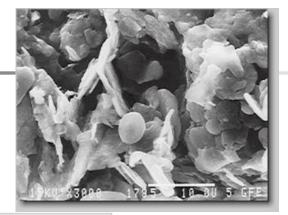
Or other pulsed neutron source

- **★** Easy experiment
- All cross sections are already known
- ★ Measuring <sup>6</sup>He and <sup>8</sup>Li betas is hard
- Only very thin 23 November 2009





## <sup>11</sup>BN



## SEM picture of BN

#### **Properties**

General	
Name	Boron nitride
Chemical formula	BN
Appearance	White solid
CAS Number	10043-11-5
Physical	
Formula weight	24.818 g/mol
Melting Point	2967 °C
Boiling point	3273 °C
Density	2.18×10 <sup>3</sup> kg/m <sup>3</sup>
Crystal structure	hexagonal or tetrahedral- cubic
Solubility	insoluble



A scanning electron microscope image of the boron nitride nanotube (enriched with boron 10). They were produced by grinding a powder of the isotope boron 10 in a ball mill for many hours and then heating the crushed powder to around 1100 °C for 6 hours in an atmosphere of ammonia.

- ✓ Exists in fibers and nanotubes forms
- ✓ Could be bought in any shape and form.







### Available online at www.sciencedirect.com

Beam Interactions with Materials & Atoms

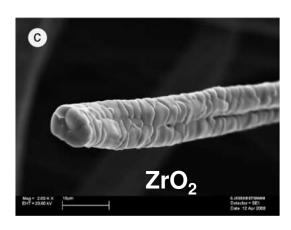
Nuclear Instruments and Methods in Physics Research B 204 (2003) 303-313

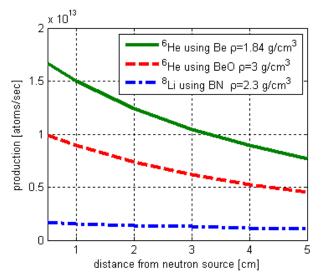
www.elsevier.com/locate/nimb

#### Oxide fiber targets at ISOLDE

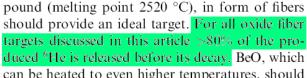
U. Köster <sup>a,\*</sup>, U.C. Bergmann <sup>a</sup>, D. Carminati <sup>a</sup>, R. Catherall <sup>a</sup>, J. Cederkäll <sup>a</sup>, J.G. Correia <sup>a</sup>, B. Crepieux <sup>a</sup>, M. Dietrich <sup>a</sup>, K. Elder <sup>a,b</sup>, V.N. Fedoseyev <sup>a,c</sup>, L. Fraile <sup>a</sup>, S. Franchoo <sup>a</sup>, H. Fynbo <sup>a</sup>, U. Georg <sup>a</sup>, T. Giles <sup>a</sup>, A. Joinet <sup>a</sup>, O.C. Jonsson <sup>a</sup>, R. Kirchner <sup>d</sup>, Ch. Lau <sup>a</sup>, J. Lettry <sup>a</sup>, H.J. Maier <sup>e</sup>, V.I. Mishin <sup>c</sup>, M. Oinonen <sup>a</sup>, K. Peräjärvi <sup>a</sup>, H.L. Ravn <sup>a</sup>, T. Rinaldi <sup>a,f</sup>, M. Santana-Leitner <sup>a</sup>, U. Wahl <sup>g</sup>, L. Weissman <sup>a</sup>, the ISOLDE Collaboration <sup>a</sup>







- ✓ Could be made in fibers form.
- No need of enrichment
- Very toxic.23 November 2009



duced <sup>6</sup>He is released before its decay. BeO, which can be heated to even higher temperatures, should thus guarantee an efficient release also from large volume targets.

BeO, the most refractory Be com-

Beryllium oxide		
Other names	Beryllia	
Identifiers		
CAS number	1304-56-9	
Pro	perties	
Molecular formula	BeO	
Molar mass	25.01	
Appearance	white solid	
Density	3.0 g/cm³ (solid)	
Melting point	2530 °C	
Boiling point	3900 °C	
Hazards		
MSDS	External MSDS	
EU classification	Highly toxic ( <b>T+</b> )	
	Carc. Cat. 2	
NFPA 704	4 4	

4/