EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Implanted ^{7}Be Targets For The Study of Neutron Interactions With ^{7}Be * (The "Primordial ^{7}Li Problem")

June 21, 2014

M. Gai[1,2], M. Paul[3], Th. Stora[4], D. Schumann[5], D. Berkovits[6], R. Dressler[5], G. Feinberg[3], A. Gottberg[4], S. Halfon[3], M. Hass[7], S. Heinitz[5], E. Kading [1], A. Prygarin[7], A.F. Shor[6], L. Weissman[6].

[1] *LNS at Avery Point, Univ. of Connecticut, 1084 Shennecossett Rd, Groton, CT06340, USA.*
[2] *Department of Physics, Yale University, 272 Whitney Ave., New Haven, CT 06520, USA.*
[3] *Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel.*
[4] *ISOLDE, CERN, CH-1211 Geneva, Switzerland.*
[5] *RadWasteAnalytics, Paul Scherrer Institute, CH-5232 Villigen, Switzerland.*
[6] *Soreq Nuclear Research Center, Nuclear Physics Engineering Division, Yavne 81800, Israel.*
[7] *Department of Particle Physics, Weizmann Inst. of Science, Rehovot 7610, Israel.*

Spokesperson: Moshe Gai: <moshe.gai@yale.edu>, <moshe.gai@cern.ch>
Contact person: Thierry Storra: <thierry.stora@cern.ch>

* Funded in part by the US-Israel Binational Science Foundation
co-PI: M. Paul, Hebrew University, Jerusalem

UConn-40870-00XX/ April 18, 2013

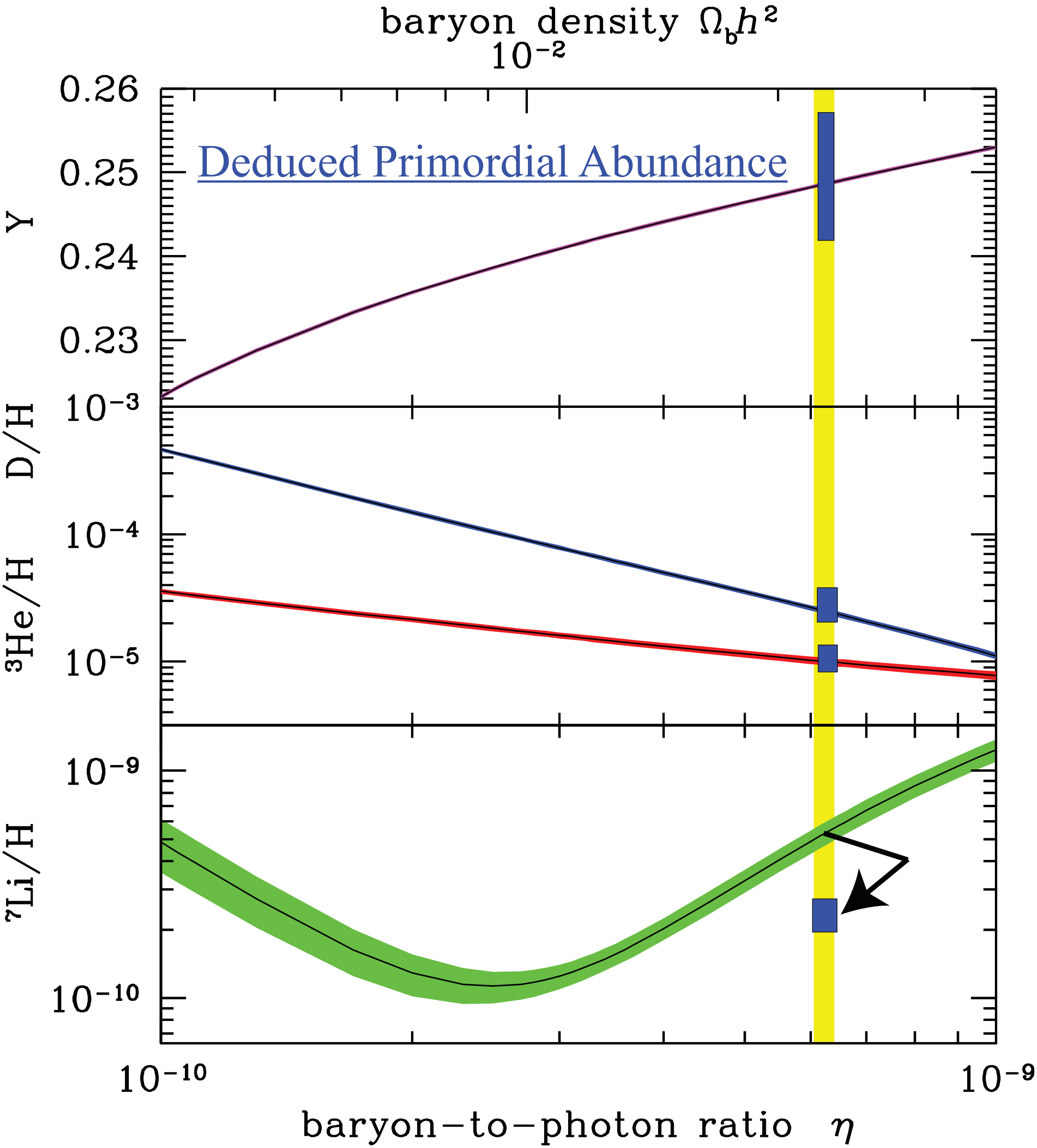
Letter of Intent: Collaboration Between the n_TOF and ISOLDE at CERN,

the Paul Scherrer Institute, Switzerland and the Israel-US SARAF Collaboration

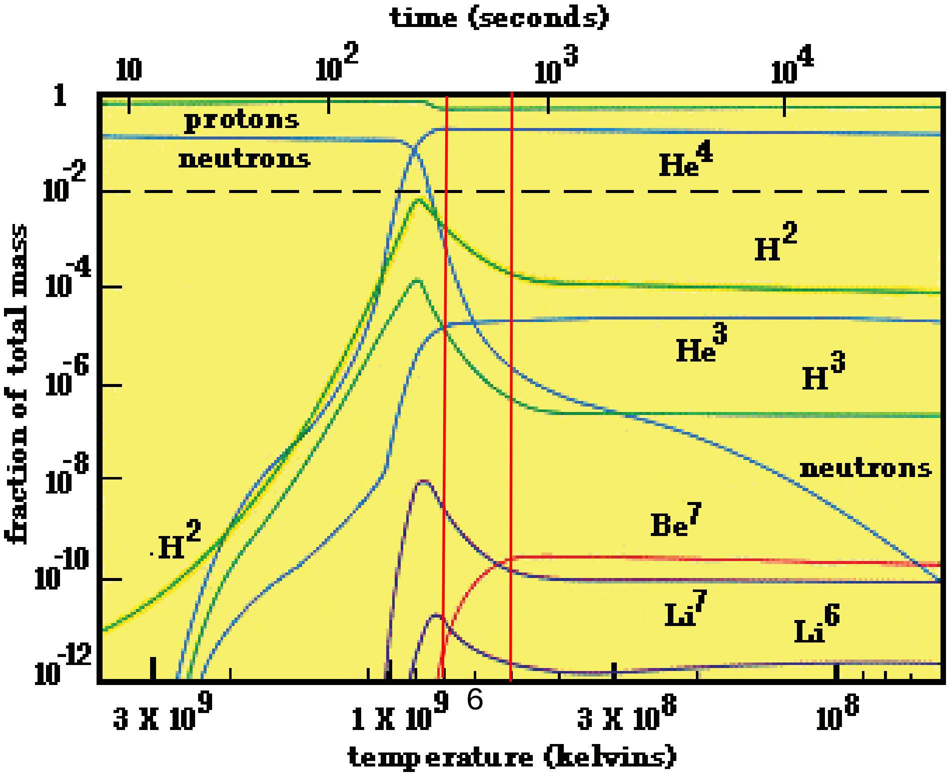
Measurements of Neutron Interactions With ^{7}Be and the "Primordial ^{7}Li Problem"

D. Berkovits[1], E. Berthoumieux[2], M. Borge[3], E. Chiaveri[2], N. Colonna[4], G. Feinberg[1,5], S. Halfon[1,5], M. Gai[6], G.M. Hale[7], M. Hass[8], K.M. Nollett[9], M. Paul[5], A. Prygarin[8], D. Schumann[10], C. Seiffert[3], A.F. Shor[2], Th. Stora[3], L. Weissman[1]

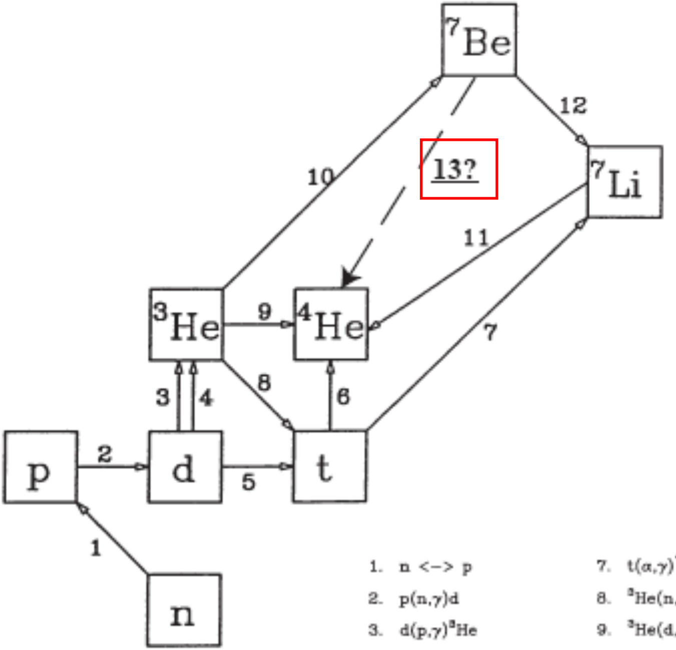
1. Soreq Nuclear Research Center, Nuclear Physics and Engineering Division, Yavne 81800, Israel.
2. European Organization for Nuclear Research (CERN), CH-1211 Geneva, Switzerland and Commissariat a l'Energie Atomique (CEA) Saclay-Irfu, 91191 Gif-sur-Yvette, France, for the n_TOF collaboration, CERN, CH-1211 Geneva, Switzerland.
3. ISOLDE, CERN, CH-1211 Geneva, Switzerland.
4. Istituto Nazionale di Fisica Nucleare, 70125 Bari, Italy; for the n_TOF Collaboration, CERN, CH-1211 Geneva, Switzerland.
5. Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel.
6. LNS at Avery Point, University of Connecticut, 1084 Shennecossett Rd, Groton, CT06340, USA and Department of Physics, Yale University, 272 Whitney Ave., New Haven, CT 06520-8124, USA.
7. Theoretical Division, Los Alamos National Lab, Los Alamos, NM 87545, USA
8. Department of Particle Physics, Weizmann Inst. of Science, Rehovot 7610, Israel.
9. Department of Physics and Astronomy, Ohio University, Athens, OH 45701,USA.
10. RadWasteAnalytics, Paul Scherrer Institute, CH-5232 Villigen, Switzerland.



baryon density $\Omega_b h^2$
10^{-2}
0.26
0.25
0.24
0.23
Y
Deduced Primordial Abundance
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio η



time (seconds)
10
10^2
10^3
10^4
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
fraction of total mass
protons
neutrons
He^4
H^2
He^3
H^3
neutrons
Be^7
H^2
Li^7
Li^6
3×10^9
1×10^9
6
3×10^8
10^8
temperature (kelvins)



1. n <–> p
2. p(n,γ)d
3. d(p,γ)^{3}He
4. d(d,n)^{3}He
5. d(d,p)t
6. t(d,n)^{4}He
7. t(α,γ)^{7}Li
8. ^{3}He(n,p)t
9. ^{3}He(d,p)^{4}He
10. ^{3}He(α,γ)^{7}Be
11. ^{7}Li(p,α)^{4}He
12. ^{7}Be(n,p)^{7}Li
13. **^{7}Be(n,α)^{4}He?**

THE ASTROPHYSICAL JOURNAL, Vol. 148, April 1967

ON THE SYNTHESIS OF ELEMENTS AT VERY HIGH TEMPERATURES*

ROBERT V. WAGONER, WILLIAM A. FOWLER, AND F. HOYLE
California Institute of Technology, Pasadena, California, and Cambridge University

Received September 1, 1966

ABSTRACT

A detailed calculation of element production in the early stages of a homogeneous and isotropic expanding universe as well as within imploding-exploding supermassive stars has been made. If the recently measured microwave background radiation is due to primeval photons, then significant quantities of only D, He^3, He^4, and Li^7 can be produced in the universal fireball. Reasonable agreement with solar-system abundances for these nuclei is obtained if the present temperature is 3° K and if the present density is $\sim 2 \times 10^{-31}$ gm cm^3, corresponding to a deceleration parameter $q_0 \approx 5 \times 10^{-3}$. However, massive stars "bouncing" at temperatures $\sim 10^9$ ° K can convert the universal D and He^3 into C, N, O, Ne, Mg, and some heavier elements in amounts observed in the oldest stars. The mass gaps at $A = 5$ and 8 are bridged by the reactions $He^3(He^4,\gamma)Be^7(He^4,\gamma)C^{11}$. Bounces at higher temperatures bridge the mass gaps through $3\,He^4 \rightarrow C^{12}$ and mainly produce metals of the iron group, plus a small amount of heavier elements synthesized by a new kind of *r*-process (rapid neutron capture). It is found that very low abundances of He^4, as recently observed in some stars, can be produced in a universe in which the electron neutrinos are degenerate.

Bassi *et al.*; IL Nuvo Cimento 28(1963)1049

(^{7}Be + Thermal Neutrons)

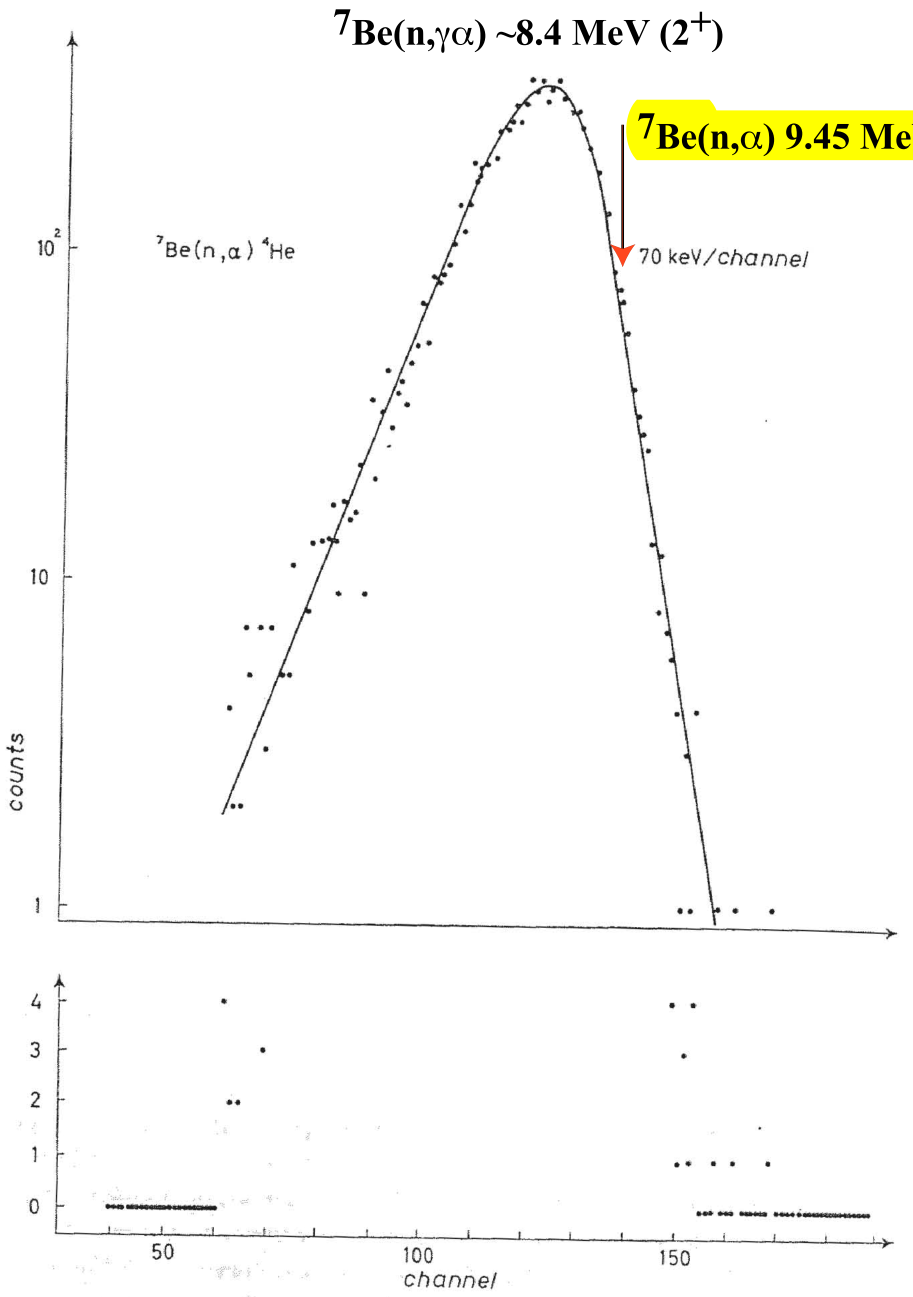
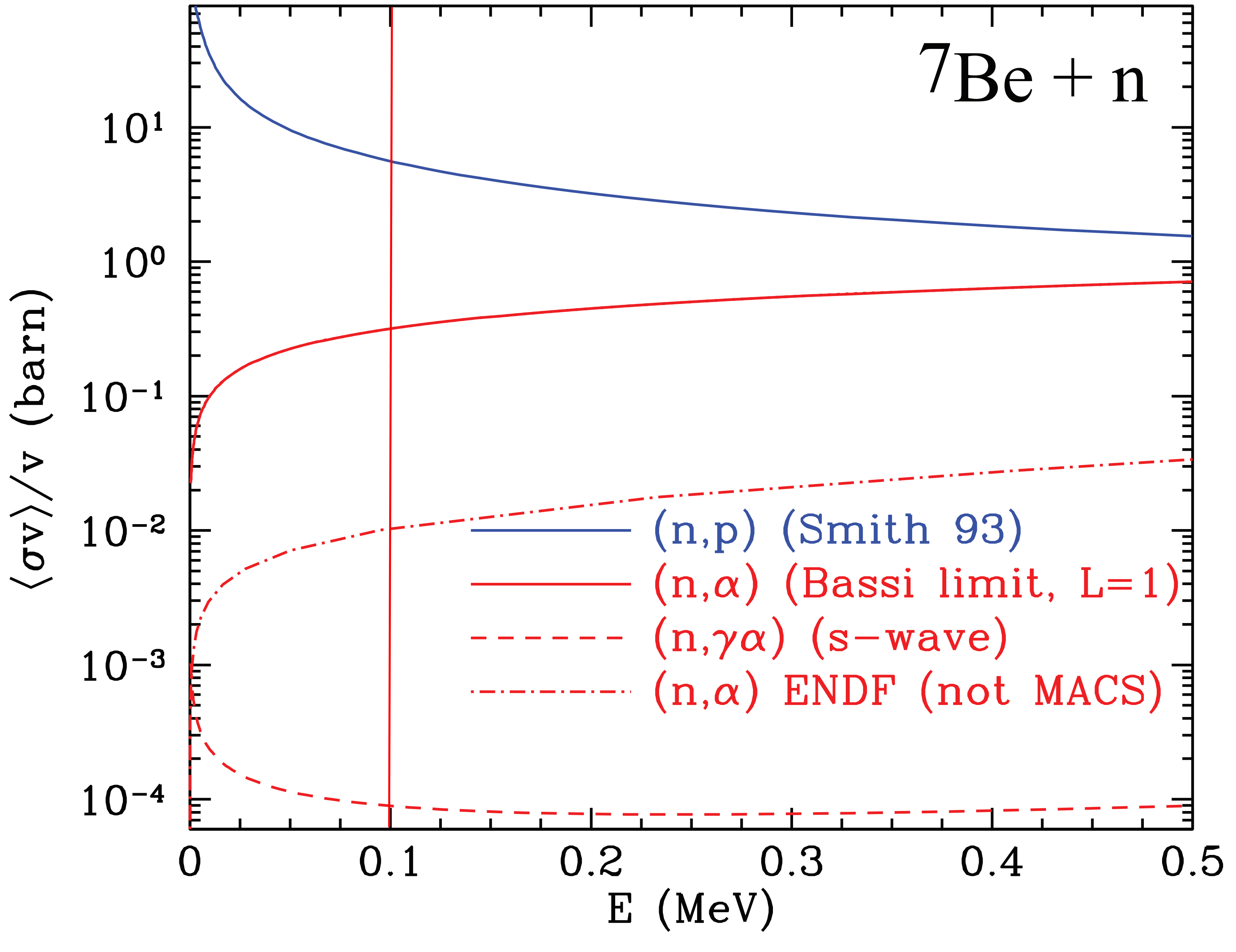


Fig. 5.

3.5.4. Reaction be7nα: $^7Be + n \leftrightarrow {}^4He + {}^4He$. To our knowledge, evaluations for the rate of this reaction have only been published in [9] and [23], without information on the sources of the data and error estimate. We did not find further analysis in the subsequent compilations by Fowler *et al* [10]. The two data sets of the reverse process published in [163, 164] refer to centre of mass energies of the direct one greater than 0.6 MeV, thus leaving a great uncertainty in the BBN window. They seem to be roughly consistent with the old estimate of the rate, and a new one in view of so scarce data would make little sense. For this reason we adopted Wagoner's rate, assuming a factor of ten uncertainty, as he suggested as a typical conservative value. Within this allowed range, this reaction could play a non-negligible role in *direct* ^{7}Be destruction, so it would be fruitful to have a new experimental determination. Apart from the role of unknown or little known ^{8}Be resonances, it is however unlucky that the used extrapolation may underestimate the rate by more than one order of magnitude, as this process mainly proceeds through a p-wave.

Kenneth M. Nollett, ANL, Private Communication, 2011



Destruction of ^{7}Be: ^{7}Be(n,p)^{7}Li(p,a)

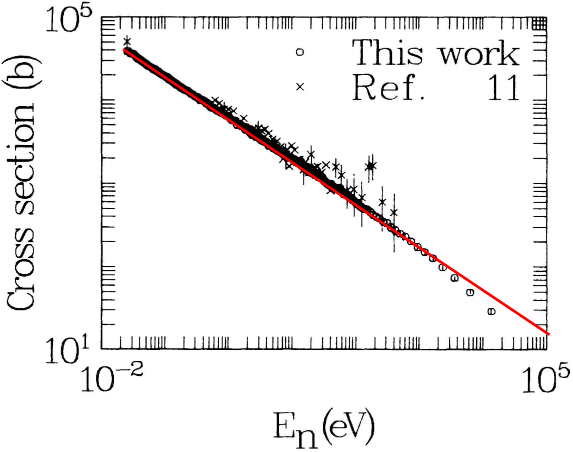


FIG. 4. The $\boxed{^7\mathrm{Be(n,p)}^7\mathrm{Li}\ (p_0+p_1)}$ cross section. Data from 25 meV to 13.5 keV are results of the present work (circles). Also shown are the data for this reaction from Ref. 11 (crosses).

P.E. Koehler *et al.*; Phys. Rev. C 37(1988)917.

$^{7}Be(n,p)^{7}Li$

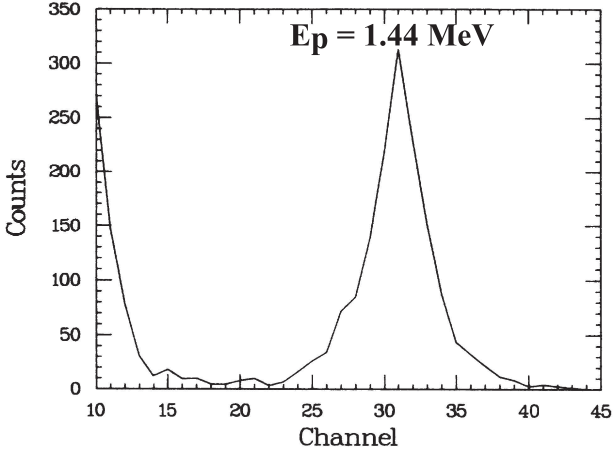


FIG. 3. Pulse-height spectrum taken at the highest energy measured in the present work, $\boxed{\text{13.5 keV.}}$ This spectrum represents just a small part of the data taken during the measurements at the LANSCE.

E_α = 9.45 MeV ???

The Astrophysical Journal, 630:L105–L108, 2005 September 10

THE ^{7}Be(d, p)2α CROSS SECTION AT BIG BANG ENERGIES AND THE PRIMORDIAL ^{7}Li ABUNDANCE

C. Angulo, E. Casarejos, M. Couder,[1] P. Demaret, P. Leleux,[2] and F. Vanderbist
Centre de Recherches du Cyclotron and Institut de Physique Nucléaire, Université catholique de Louvain, Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium; angulo@cyc.ucl.ac.be
A. Coc, J. Kiener, and V. Tatischeff
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS, Université Paris-Sud, Bâtiment 104, F-91405 Orsay Campus, France
T. Davinson and A. S. Murphy
School of Physics, James Clerk Maxwell Building, King's Buildings, University of Edinburgh, Mayfield Road, Edinburgh EH9 3JZ, UK
N. L. Achouri and N. A. Orr
Laboratoire de Physique Corpusculaire, ENSICAEN, and Université de Caen, IN2P3-CNRS, 6 boulevard du Maréchal Join, F-14050 Caen Cedex, France
D. Cortina-Gil
Departamento de Física de Partículas, Universidad de Santiago de Compostela, E-15782 Santiago de Compostela, Spain
P. Figuera
Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, via Santa Sofia 62, I-95123 Catania, Italy
B. R. Fulton
Department of Physics, University of York, Heslington, York YO10 5DD, UK
I. Mukha[3]
Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
and
E. Vangioni
Institut d'Astrophysique de Paris, 98bis boulevard Arago, F-75014 Paris, France
Received 2005 April 27; accepted 2005 August 1; published 2005 August 26

ABSTRACT

The *WMAP* satellite, devoted to observations of the anisotropies of the cosmic microwave background radiation, has recently provided a determination of the baryonic density of the universe with unprecedented precision. Using this, big bang nucleosynthesis calculations predict a primordial ^{7}Li abundance that is a factor of 2–3 higher than that observed in Galactic halo dwarf stars. It has been argued that this discrepancy could be resolved if the ^{7}Be(d, p)2α reaction rate were around a factor of 100 larger than has previously been considered. We have now studied this reaction, for the first time at energies appropriate to the big bang environment, at the CYCLONE radioactive-beam facility at Louvain-la-Neuve. The cross section was found to be a factor of 10 *smaller* than derived from earlier measurements. It is concluded therefore that nuclear uncertainties cannot explain the discrepancy between observed and predicted primordial ^{7}Li abundances, and an alternative astrophysical solution must be investigated.

Subject headings: cosmological parameters — early universe — nuclear reactions, nucleosynthesis, abundances — stars: Population II

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **84**, 042801(R) (2011)

Search for a resonant enhancement of the ^{7}Be + d reaction and primordial ^{7}Li abundances

P. D. O'Malley,[1] D. W. Bardayan,[2] A. S. Adekola,[1] S. Ahn,[3] K. Y. Chae,[2,4] J. A. Cizewski,[1] S. Graves,[5] M. E. Howard,[1] K. L. Jones,[3] R. L. Kozub,[5] L. Lindhardt,[6] M. Matos,[6] B. M. Moazen,[6] C. D. Nesaraja,[2] S. D. Pain,[2] W. A. Peters,[7] S. T. Pittman,[3] K. T. Schmitt,[3] J. F. Shriner Jr.,[5] M. S. Smith,[2] I. Spassova,[7] S. Y. Strauss,[1] and J. L. Wheeler[5]

[1]*Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903*

[2]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

[3]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996*

[4]*Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea*

[5]*Department of Physics, Tennessee Technological University, Cookeville, Tennessee 38505*

[6]*Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803*

[7]*Oak Ridge Associated Universities, Oak Ridge, Tennessee 37830*

(Received 26 July 2011; revised manuscript received 9 September 2011; published 17 October 2011)

Big Bang nucleosynthesis calculations, constrained by the Wilkinson Microwave Anisotropy Probe results, produce ^{7}Li abundances almost a factor of four larger than those extrapolated from observations. Since primordial ^{7}Li is believed to be mostly produced by the beta decay of ^{7}Be, one proposed solution to this discrepancy is a resonant enhancement of the $^7\mathrm{Be}(d,\ p)2\alpha$ reaction rate through the $5/2^+$ 16.7-MeV state in ^{9}B. The $^2\mathrm{H}(^7\mathrm{Be},d)^7\mathrm{Be}$ reaction was used to search for such a resonance; none was observed. An upper limit on the width of the proposed resonance was deduced.

DOI: 10.1103/PhysRevC.84.042801 PACS number(s): 26.35.+c, 25.10.+s, 25.30.Bf, 24.30.−v

PHYSICAL REVIEW C **84**, 058801 (2011)

One fewer solution to the cosmological lithium problem

O. S. Kirsebom[1,2,*] and B. Davids[1]
[1] *TRIUMF, Vancouver, British Columbia, Canada, V6T 2A3*
[2] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*
(Received 29 August 2011; published 9 November 2011)

Data from a recent ^{9}Be(^{3}He,t)^{9}B measurement are used to rule out a possible solution to the cosmological lithium problem based on conventional nuclear physics.

DOI: 10.1103/PhysRevC.84.058801 PACS number(s): 26.35.+c, 98.80.Ft

Search for new resonant states in ^{10}C and ^{11}C and their impact on the cosmological lithium problem

F. Hammache[1],* A. Coc[2], N. de Séréville[1], I. Stefan[1], P. Roussel[1], S. Ancelin[1], M. Assié[1], L. Audouin[1], D. Beaumel[1], S. Franchoo[1], B. Fernandez-Dominguez[3], S. Fox[4], C. Hamadache[2], J. Kiener[2], A. Laird[4], B. Le Crom[1], A. Lefebvre-Schuhl[2], L. Lefebvre[1], I. Matea[1], A. Matta[1],† G. Mavilla[1], J. Mrazek[5], P. Morfouace[1], F. de Oliveira Santos[6], A. Parikh[7], L. Perrot[1], A.M. Sanchez-Benitez[8],‡ D. Suzuki[1], V. Tatischeff[2], P. Ujic[6],§ and M. Vandebrouck[1]

[1] Institut de Physique Nucléaire d'Orsay, UMR8608, IN2P3-CNRS, Université Paris Sud, 91406 Orsay, France
[2] CSNSM, IN2P3-CNRS, Université Paris Sud, 91405 Orsay, France
[3] Universidade de Santiago de Compostela, E-15786 Santiago, Spain
[4] Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom
[5] Nuclear Physics Institute ASCR, 250 68 Rez, Czech Republic
[6] GANIL, CEA/DSM-CNRS/IN2P3, Caen, France
[7] Departament de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain and
[8] Departamento de Física Aplicada, Universidad de Huelva, E-21071 Huelva, Spain

(Dated: 07/11/2013)

The observed primordial ^{7}Li abundance in metal-poor halo stars is found to be lower than its Big-Bang nucleosynthesis (BBN) calculated value by a factor of approximately three. Some recent works suggested the possibility that this discrepancy originates from missing resonant reactions which would destroy the ^{7}Be, parent of ^{7}Li. The most promising candidate resonances which were found include a possibly missed 1^- or 2^- narrow state around 15 MeV in the compound nucleus ^{10}C formed by ^{7}Be+^{3}He and a state close to 7.8 MeV in the compound nucleus ^{11}C formed by ^{7}Be+^{4}He. In this work, we studied the high excitation energy region of ^{10}C and the low excitation energy region in ^{11}C via the reactions ^{10}B(^{3}He,t)^{10}C and ^{11}B(^{3}He,t)^{11}C, respectively, at the incident energy of 35 MeV. Our results for ^{10}C do not support ^{7}Be+^{3}He as a possible solution for the ^{7}Li problem. Concerning ^{11}C results, the data show no new resonances in the excitation energy region of interest and this excludes ^{7}Be+^{4}He reaction channel as an explanation for the ^{7}Li deficit.

PACS numbers: 26.35.+c, 25.55.Kr, 24.30.-v, 29.30.-h, 29.30.-h

ELSEVIER

Nuclear Physics A718 (2003) 398c–400c

NUCLEAR PHYSICS A

www.elsevier.com/locate/npe

Destruction of ^{7}Li and ^{7}Be in astrophysical environments *

R.H. France III[a,b], L.T. Baby[c], C. Bordeanu[c†], Th. Delbar[d], J.A. Dooley[a], M. Gai[a], M. Hass[c], J.E. McDonald[e], A. Ninane[d], and C.M. Przybycien[e]

[a]Department of Physics, Unit 3046, University of Connecticut, Storrs, CT 06269, USA

[b]Department of Chemistry & Physics, Georgia College & State University, CBX 82, Milledgeville, GA 31061, USA

[c]Department of Particle Physics, Weizmann Institute, Rehovot 76100, Israel

[d]Institut de Physique Nucleaire, Universite Catholique de Louvain, Chemin du Cyclotron 2, B-1348-Louvain-la-Neuve, Belgique

[e]Physics Department, 200 Bloomfield Ave., University of Hartford, West Hartford, CT 06117-1599, USA

We Need a Thin and Clean ^{7}Be Target Implanted into thin foil(!)

Similar to the ^{7}Be target Produced at ISOLDE/PSI for Weizmann Inst *

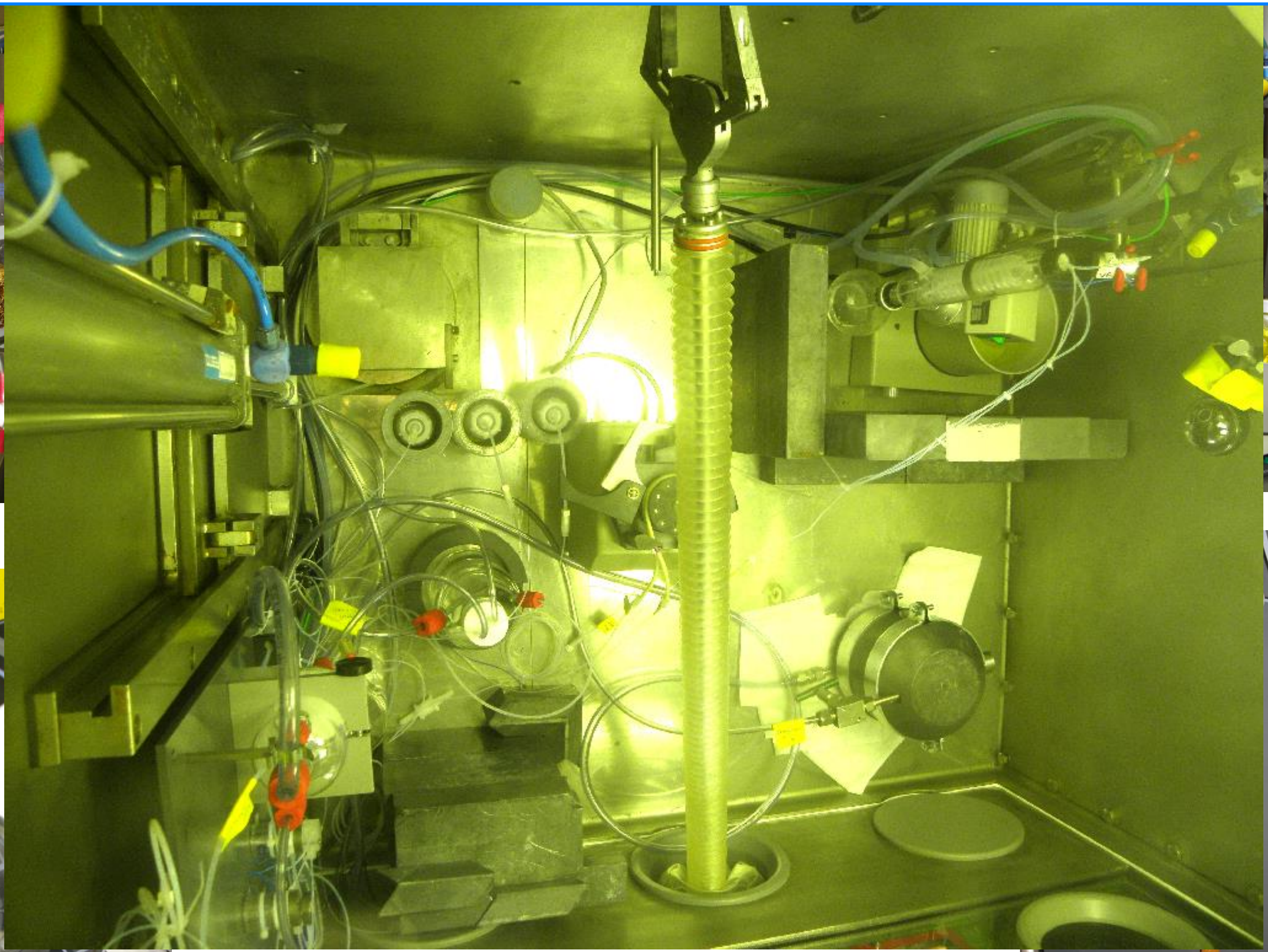
(~300 mCi/ 30 mCi 478 keV gamma, 8 mm diameter)

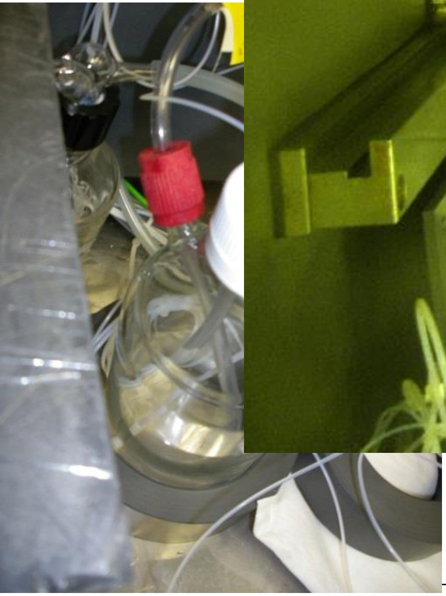
target: ~ 1.0 x10^{17} ^{7}Be/cm^2
Beam: ~10^9 /sec (30-100 keV)
$\mathcal{L}$ = 10^{26} /cm^2 sec (2.8 μb^{-1} HR^{-1})
$\varepsilon/2\pi$ = ~100% (M=2)
$\mathcal{L}\sigma\varepsilon$ > 70 CPD
σ > 1 μb (One Day)

Design Goal Sensitivity = 1 μb

* L.T. Baby *et al.*; Phys. Rev. C 67(2003)065805.

Separation Scheme for the ^{7}Be separation



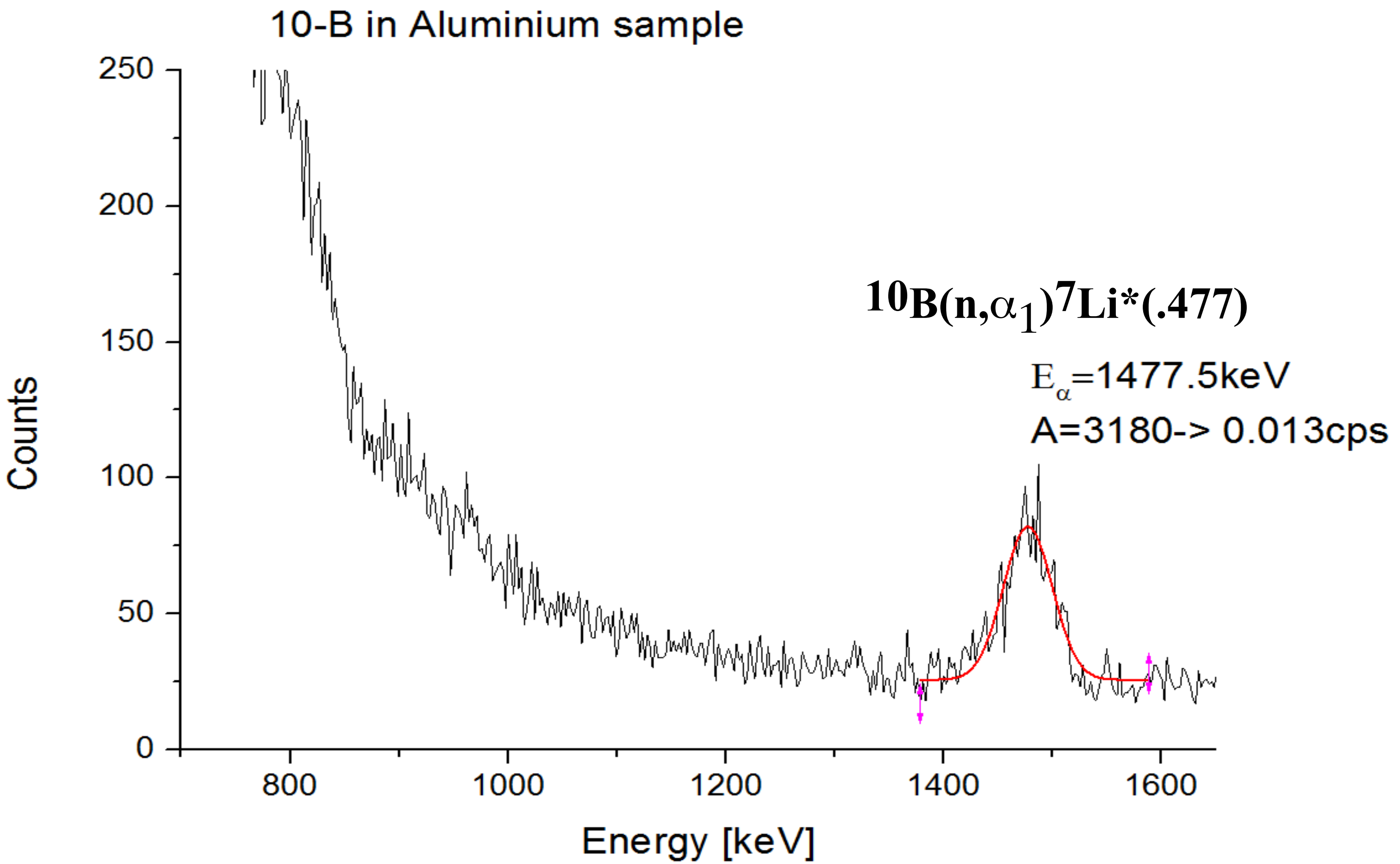


~ 200 GBq ^{7}Be can be processed in one batch
Contains comparable amounts of $^{9/10}Be$

^{10}B Implantation Chamber at the ISOLDE Off Line Ion Separator

Christoph Seiffert *et al.*; CERN/ISOLDE

Implanted ^{10}B target

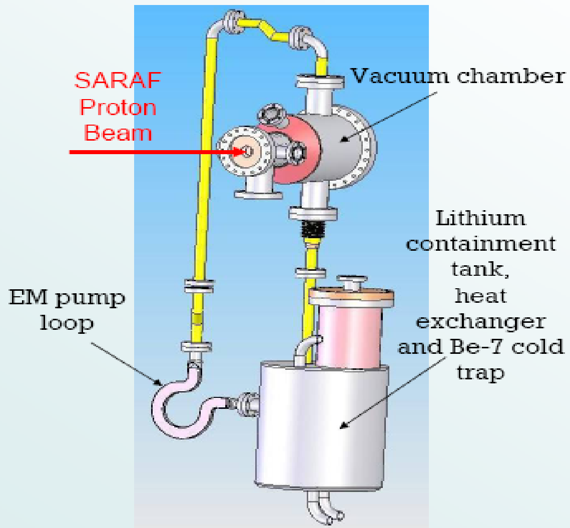


Michael Paul, Hebrew University, Jerusalem, P.I.

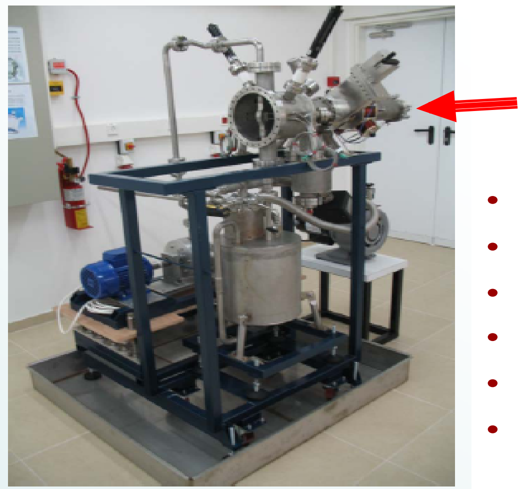
S. Halfon et al., Rev. Sci. Inst. 84(2013)123507; Rev. Sci. Inst. 85(2014)056105.

SOREQ

LiLiT



LiLiT : artist view (D. Kijel and A. Arenshtam)



- Liquid lithium jet target
- Proton energy: ~2 MeV.
- Proton current: <3.5 mA.
- Up to 8×10^{10} n/sec
- $T \approx 230^{0}$C.
- $T_{max} \approx 350^{0}$C.

Feinberg et al,
Nucl Phys A827
(2009) 590C

Ralph H. France III, Ph.D. thesis, Yale, 1995

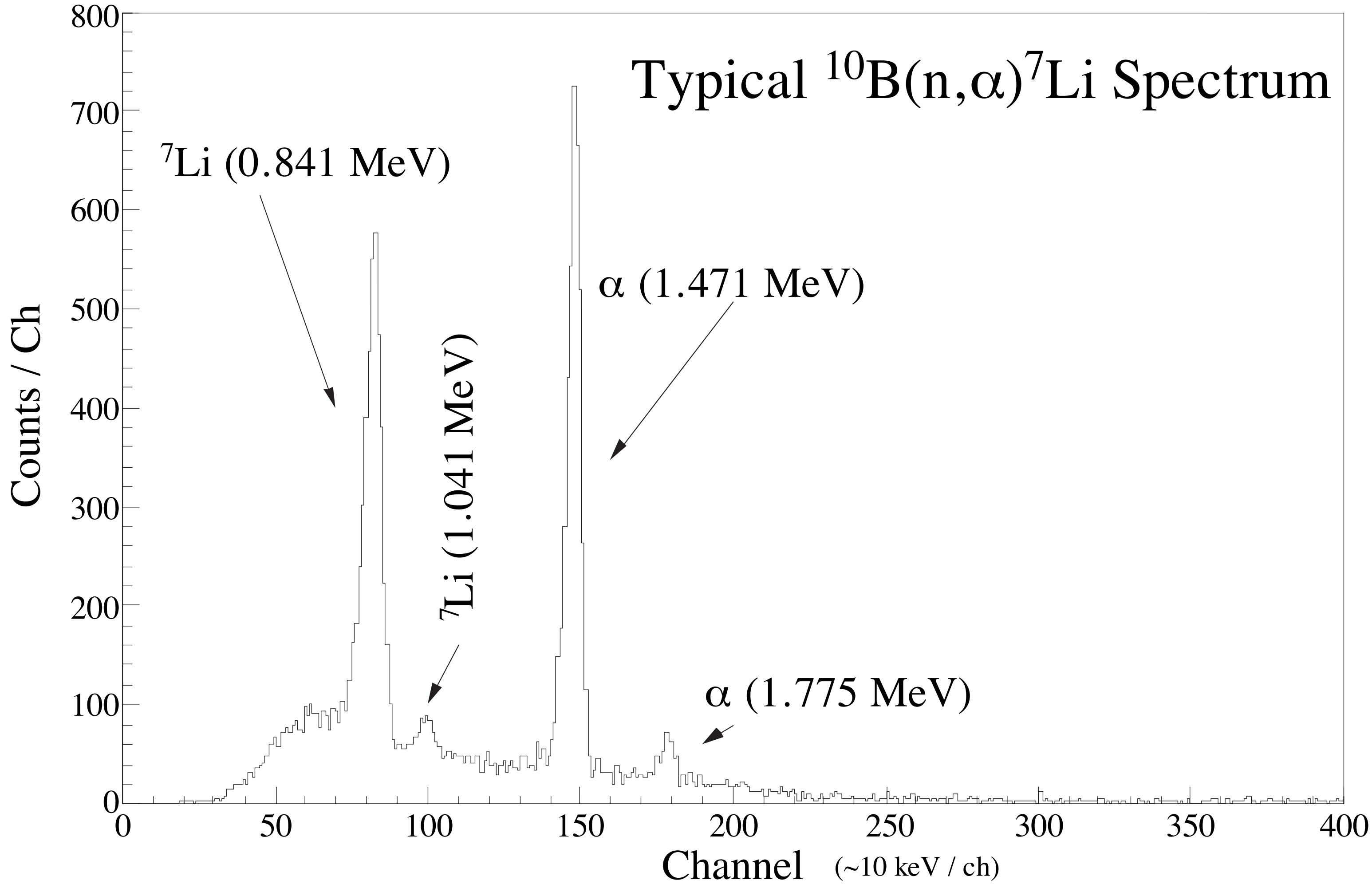
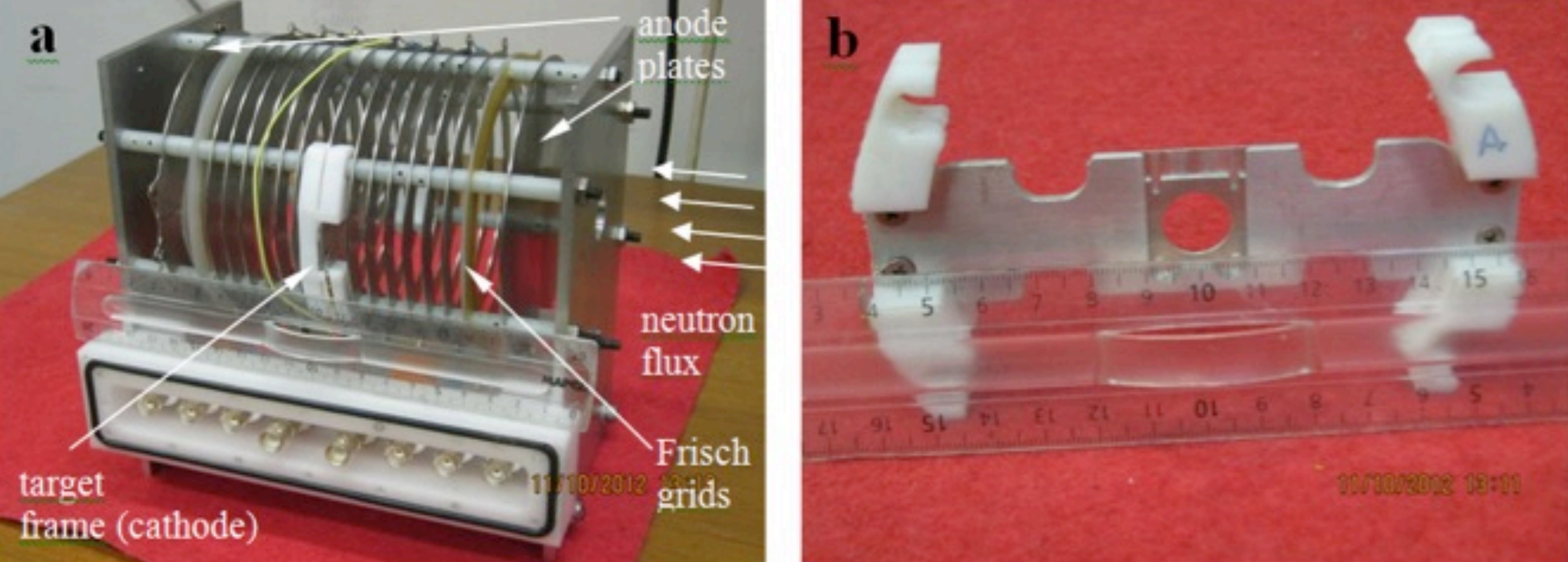


Figure 4.6: Typical Spectrum from the $^{10}B(n,\alpha)^7Li$ Reaction used to calibrate our alpha array at low energies exhibiting energy resolution of FWHM = 55 keV at 1.5 MeV.


RAMP EXIT


a
anode plates
neutron flux
Frisch grids
target frame (cathode)
b
A
11/10/2012 13:11

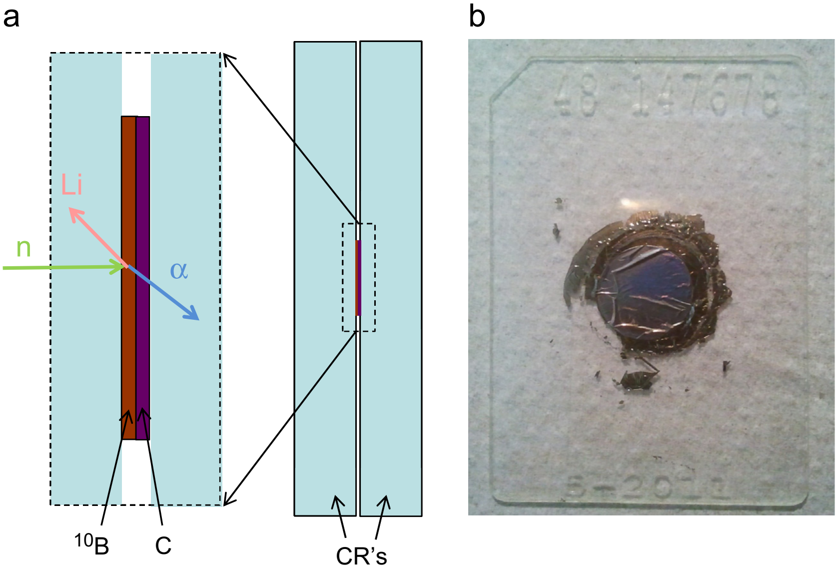
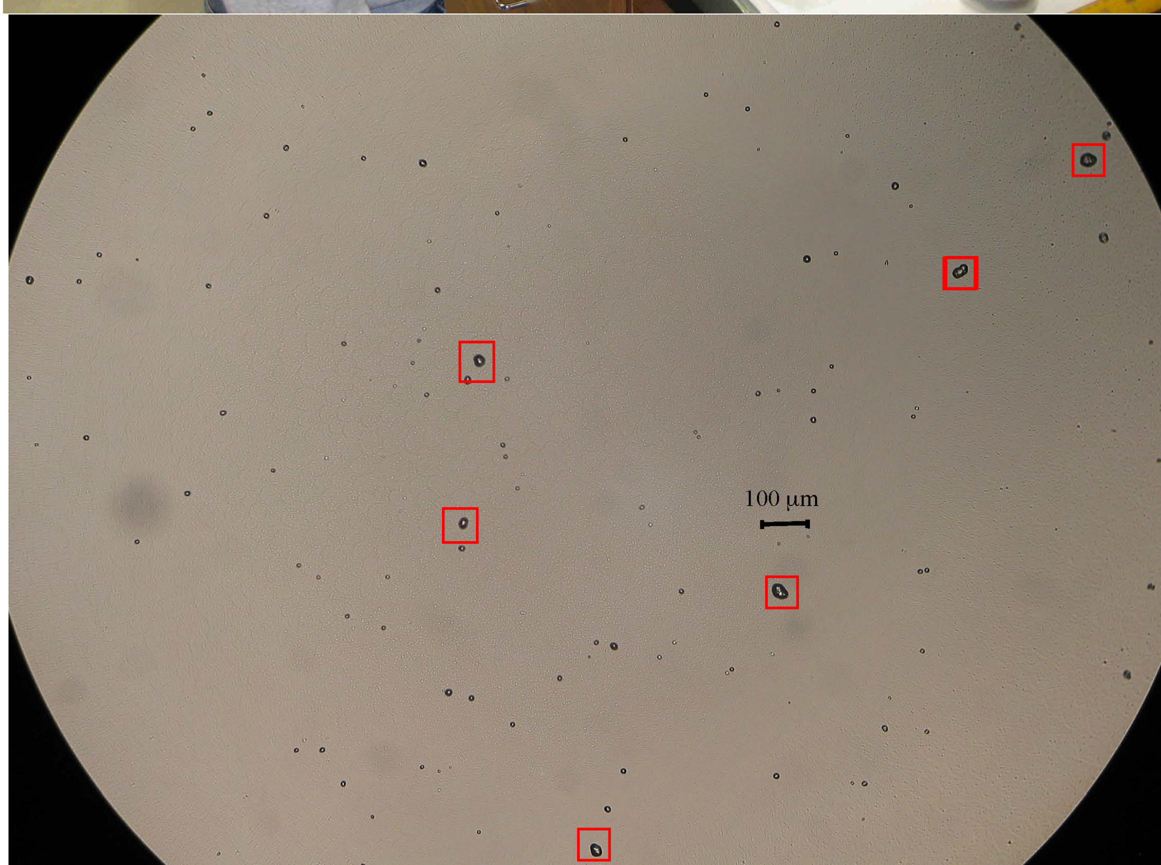


Fig. 3. (a) ^{10}B dosimeter design, based on a pair of CR-39 detectors sandwiching a thin (20 μg/cm^2) ^{10}B target on a 20 μg/cm^2 C backing. (b) 20 μg/cm^2 enriched ^{10}B target on 20 μg/cm^2 C backing attached to CR-39.

Emily E. Kading, LNS at Avery Point, June 16, 2014

Soreq, IL: TASLIMAGE Computer Scanning System



M. Izerrouken *et al.; Radiation Measurements 31(1999)141*

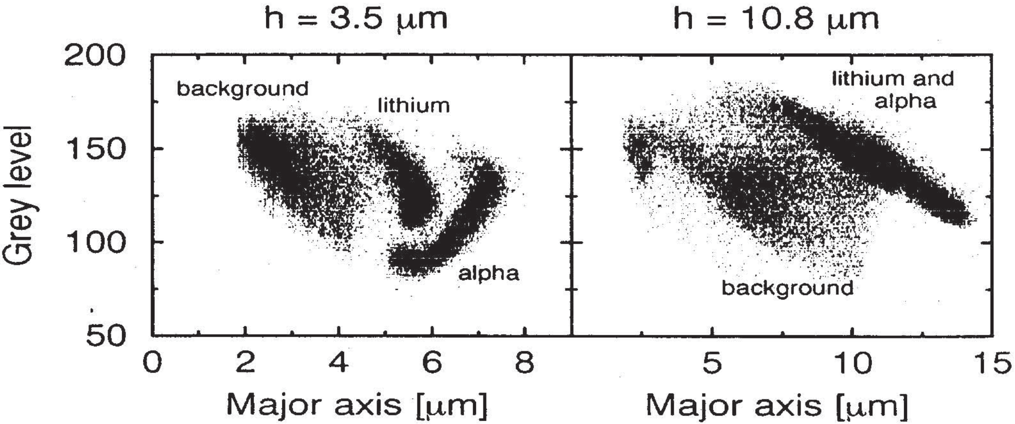


Fig 2. Grey level vs major axis of $^{10}B(n, \alpha)^{7}Li$ reaction product tracks in CR-39 detector obtained at a removed detector layer thickness of 3.5 μm and 10.8 μm. Si wafer was doped by implantation of ^{10}B of 35 keV at 5×10^{15} ions/cm^2.

Interactions of Neutrons with ^{7}Be

(US-Israel-Switzerland Collaboration)

1) **^{7}Be sample at PSI up to 200 GBq √**

2) **Implantation setup at ISOLDE √**

3) **Neutron beam at SARAF/ LiLiT √**

4) **Develop CR-39, Summer/Fall 2014**
   Measure ^{10}B(n,α)^{7}Li with CR-39, Fall/Spring 2015
   Implant ^{7}Be, Spring/Summer 2015
   Measure with CR-39: σ[^{7}Be (n,α)]/σ[^{7}Be(n,p)]

5) **Develop Twin Ionization Chamber Gas Detector**
   Measure ^{10}B(n,α)^{7}Li with IC, Fall 2015
   Implant ^{7}Be, Spring 2016
   Measure ^{7}Be(n,α) with Split IC