Lack of "Standard Solution" to the "Primordial ^{7}Li Problem"

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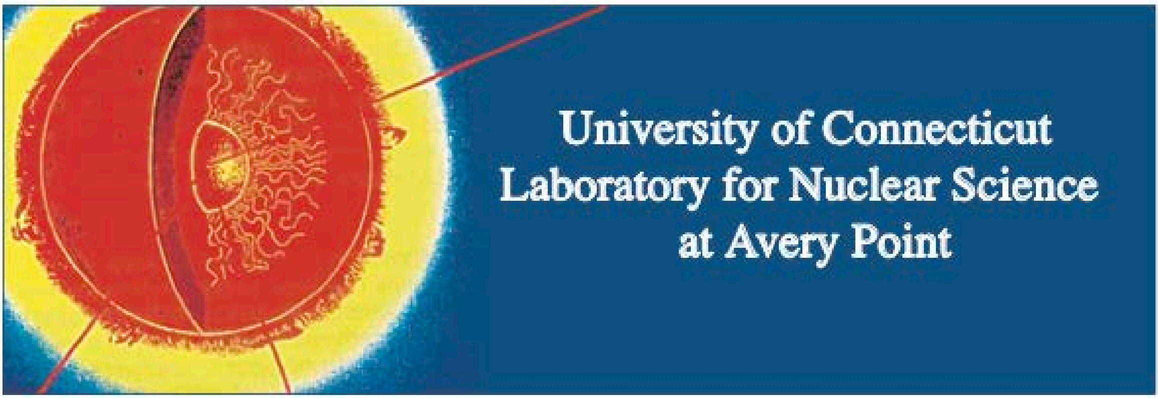


1) The Primordial ^{7}Li Problem

2) The SARAF neutron facility

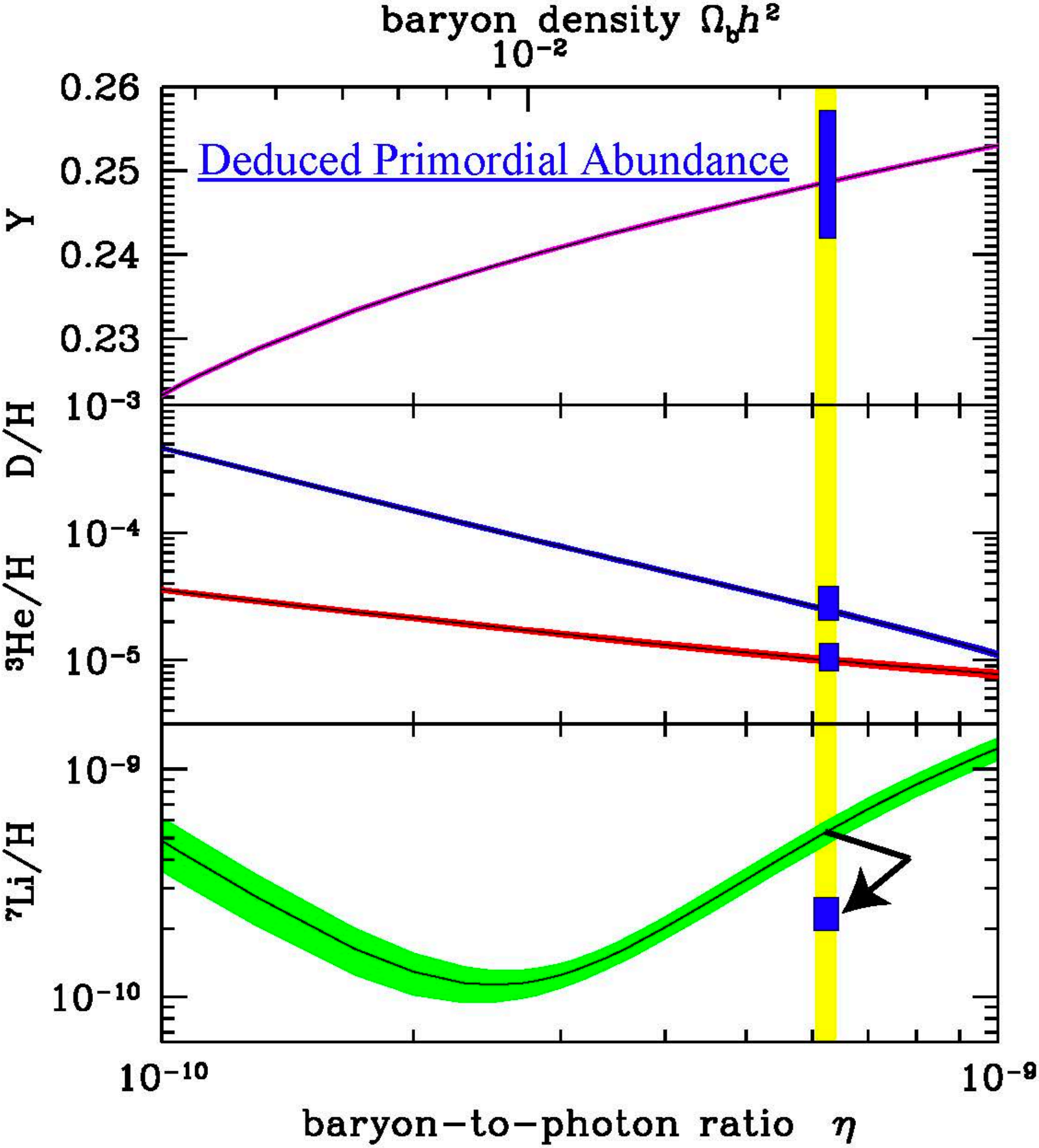
3) CR39 Nuclear Track Detectors

4) n + ^{7}Be: n_TOF, Kyoto, SARAF

5) Lack of Standard Solution to the ^{7}Li Problem

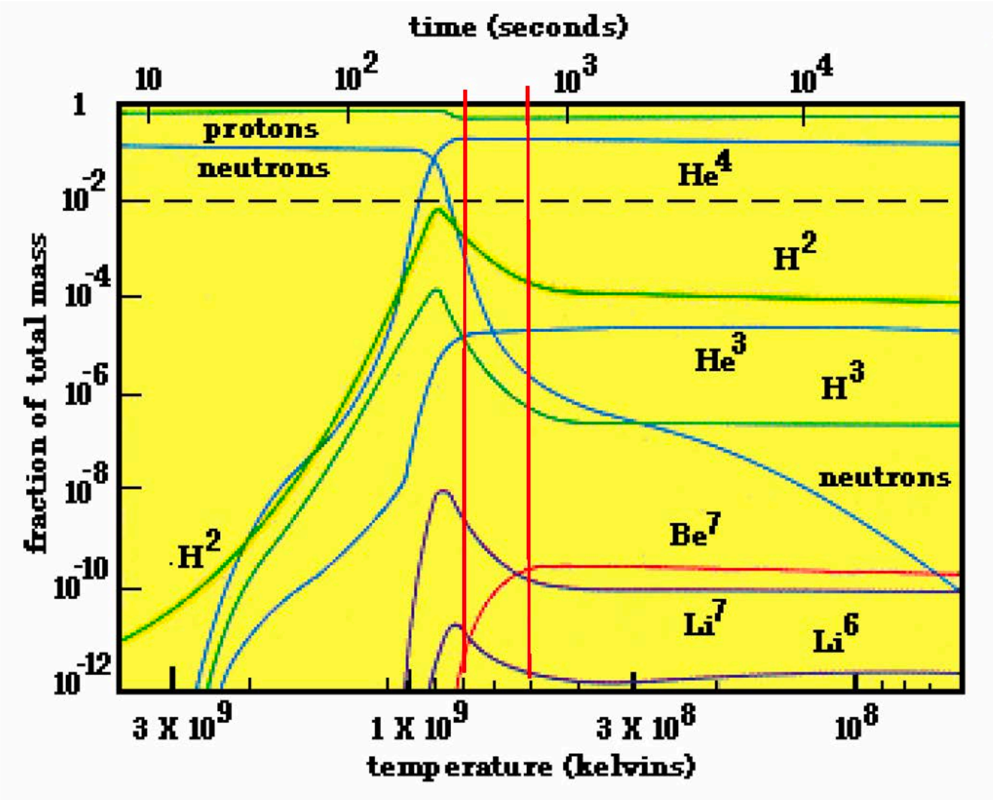
NPA8, June 20, 2017

^{7}Li Problem: Cybrut-Fields-Olive; 0808.2818

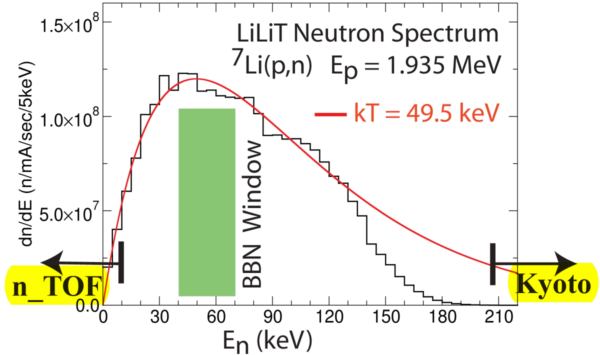


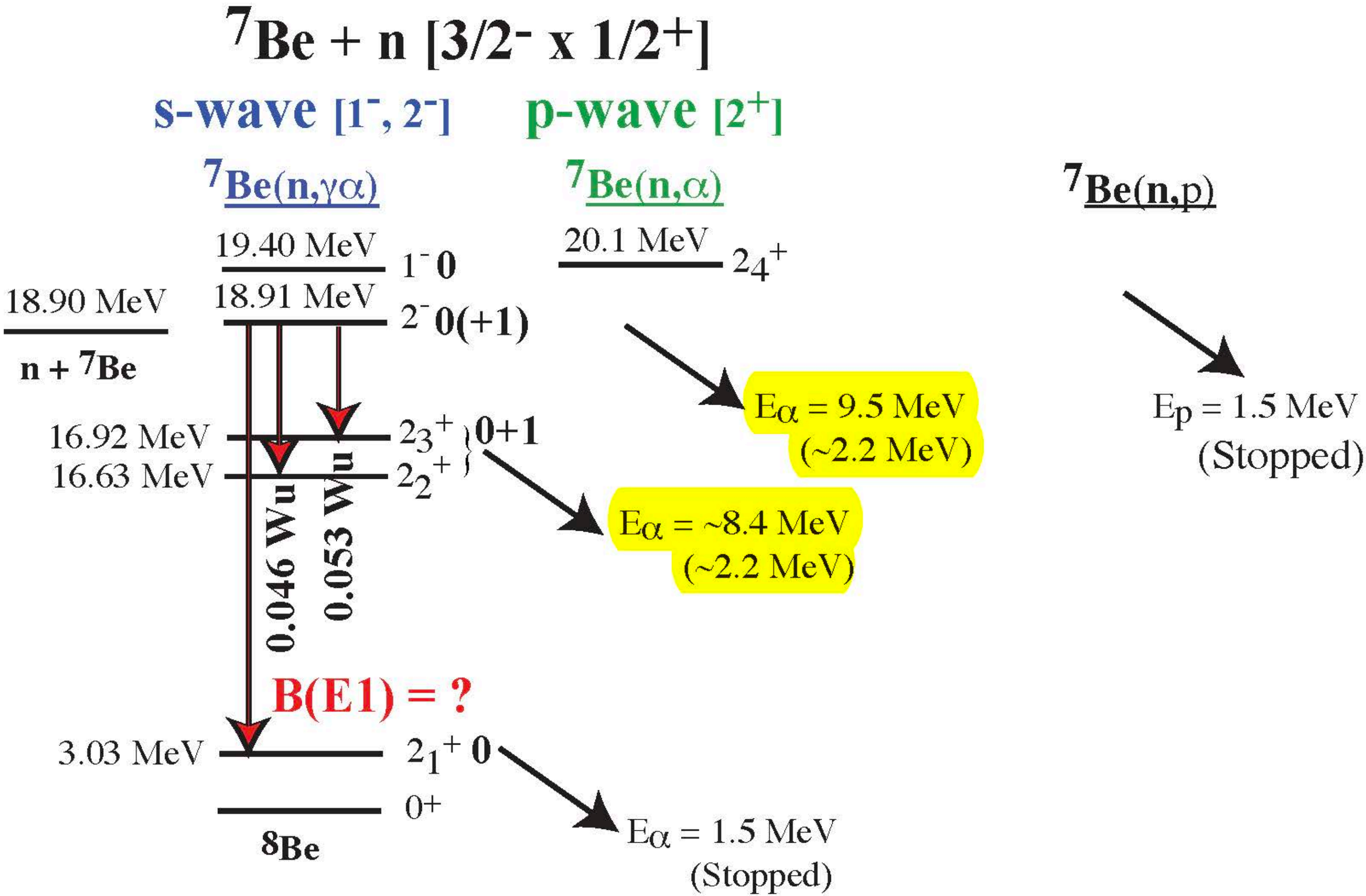
Big Bang Nucleosynthesis

T = 0.5 - 0.8 GK (43 - 69 keV)



Soreq Applied Research Facility (SARAF)
~10^{10} n/cm^2/sec + Gamma-Background




7Be + n [3/2- x 1/2+]
s-wave [1-, 2-]
p-wave [2+]
7Be(n,γα)
7Be(n,α)
7Be(n,p)
19.40 MeV
1- 0
20.1 MeV
24+
18.90 MeV
n + 7Be
18.91 MeV
2- 0(+1)
16.92 MeV
23+
0+1
16.63 MeV
22+
0.046 Wu
0.053 Wu
Eα = 9.5 MeV
(~2.2 MeV)
Ep = 1.5 MeV
(Stopped)
Eα = ~8.4 MeV
(~2.2 MeV)
B(E1) = ?
3.03 MeV
21+ 0
0+
8Be
Eα = 1.5 MeV
(Stopped)

UConn-40870-00XX

Alpha-Particles and Protons Calibration and Tests of CR39 Nuclear Track Detectors For Operation in High Neutron Flux

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Emily E. Kading; Poster tonight

Alpha-Particles and Protons Calibration and Tests of CR39 Nuclear Track Detectors For Operation in High Neutron Flux

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Moshe Tessler (Hebrew U, Jerusalem) and Aryeh Weiss (Bar Ilan U)

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Michael Hass, Ish Mukul, Yigal Shachar (Weizmann Inst, Israel)

Christoph Seiffert and Thierry Stora (CERN/ISOLDE, Switzerland), Ulli Koester (ILL)

M. Ayranov, Rugard Dressler, Stephan Heinitz, N. Kivel, Emilio A. Maugeri, and Dorothea Schumann (PSI, Switzerland)

David Ticehurst, Calvin R. Howell (TUNL)

Why CR-39?

The Primordial Lithium Problem:

- **Soreq Applied Research Accelerator Facility (SARAF):** Quasi-Maxwellian energy distribution at kT = 49.5 keV Inside Big Bang Nucleosynthesis (BBN) window, mimics BBN conditions.
- BBN over-predicts ^{7}Li by a factor of ~3 (see Fig. 1), The "Primordial Lithium Problem".
- SARAF ^{7}Be(n,α) Challenge: high flux neutron beam and background gamma-rays. The use of spectroscopic devices is not possible.
- Developing Diamond Detectors.
- CR-39 Nuclear Track Detector (NTD) have been calibrated for detection of alpha-particles and protons resulting from neutrons + ^{7}Be.

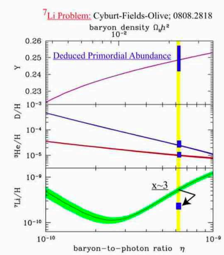


Fig. 1: BBN predicted abundances as a function of the baryon to photon ratio. The value of the ratio measured by WMAP is indicated in yellow and the observed primordial abundances are shown in blue.

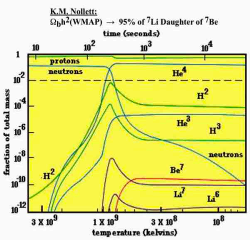


Fig. 2: BBN prediction of the production of light elements as function of time after the Big Bang and temperature.

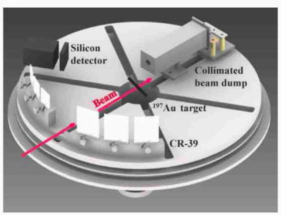
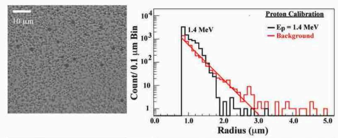


Fig 3: Schematic diagram of the experimental setup used at the TUNL at Duke University and the 3 MV van de Graaff accelerator at the Weizmann Institute of Sciences.

Calibration process

- The CR-39 NTD were calibrated with alpha-particles from standard radioactive sources: ^{148}Gd (3.18 MeV), ^{241}Am (5.49 MeV) and ^{228}Th (5.34 - 8.78 MeV).
- They were also calibrated using Rutherford Backscattering of alpha-particles (1.5 - 9.0 MeV) and protons (1.5 MeV) from a thin (100 μg/cm^2 gold foil).
- The plates were etched in a standard 6.25 N NaOH solution for 30 minutes at 90°C to produce micron size circular pits.
- The short etching time enabled us to distinguish the pits produced by 1.5 MeV protons from the alpha-pits of interest; proton tracks require several hours of etching to produce a well developed pit.
- Plates were scanned with a fully motorized microscope at Bar Ilan University in Israel.
- A segmentation algorithm that addressed the challenges posed by the intense neutron beam and gamma-ray background was developed.

Fig. 4 (below): Left: Typical pits observed for 1.4 MeV proton from the RBS calibration. Right: The measured radii (~ 1.0 μm) of pits observed in 0.15 mm^2 from irradiation with protons. The background was measured behind a thick aluminum foil that stopped the protons.



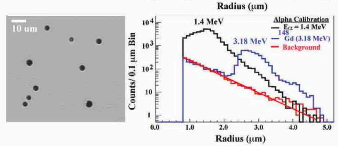


Fig. 5 (above): Left: Typical pits observed after etching CR39 plates exposed to 3.18 MeV alpha-particles from a ^{148}Gd source. Right: The measured radii of pits in 6.7 mm^2 from irradiation with alpha-particles from a ^{148}Gd source (3.18 MeV) and RBS (1.4 MeV). The background shown of the ^{148}Gd source data was measured behind a thick (50 μm) aluminum foil that stopped the 3.18 MeV alpha-particles.

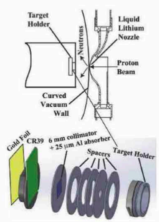


Fig. 6: Schematic diagram of the experimental setup used at SARAF including the secondary Be target holder and the primary LiLiT target.

Our Results

The calibration defines a conservative radii region of interest (RRI) for detecting the alpha-particles of interest with average energy of ~2.2 MeV; RRI = 1.4 - 3.4 microns.

- A ("phantom") ^{9}Be target was used to measure the background from irradiation with an intense (~ 10^{10} n/cm^2/sec) neutron beam (Fig. 8).
- Cold neutrons were used to measure "the background" ^{17}O(n,α) reaction inside the CR-39 and background gamma-ray (2.2 MeV) (Fig. 9).
- **Our RRI is dominated by alpha-particles from ^{17}O(n,α) inside CR-39.**

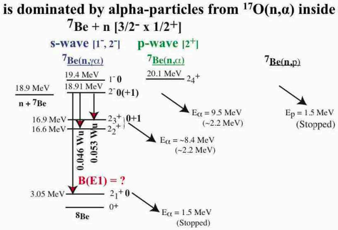


Fig. 7: States in ^{8}Be from s-wave (shown in blue) and p-wave (shown in green) interactions of neutrons with ^{7}Be and the charged particles from the decay of these states. In parentheses we show the average energy of the charged particles after traversing a 25 micron aluminum foil.

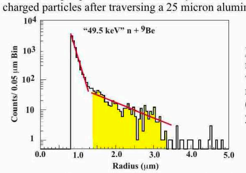


Fig. 8: The radii of pits measured over 16.36 mm^2 from the in-beam SARAF measurement with epithermal neutrons and ^{9}Be target. The radii region of interest for alpha-particles (RRI = 1.4 - 3.4 μm) is shown in hashed yellow.

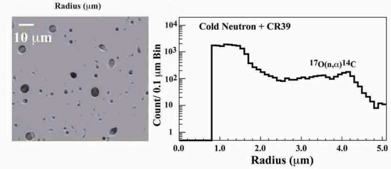


Fig. 9: Left: Pits observed from cold neutrons on CR-39 plate. Right: The measured "effective radii" of pits observed in 4.435 mm^2 from 1.82 MeV from the ^{17}O(n,α) reaction and 2.2 MeV capture gamma-rays inside CR39.

Acknowledgement

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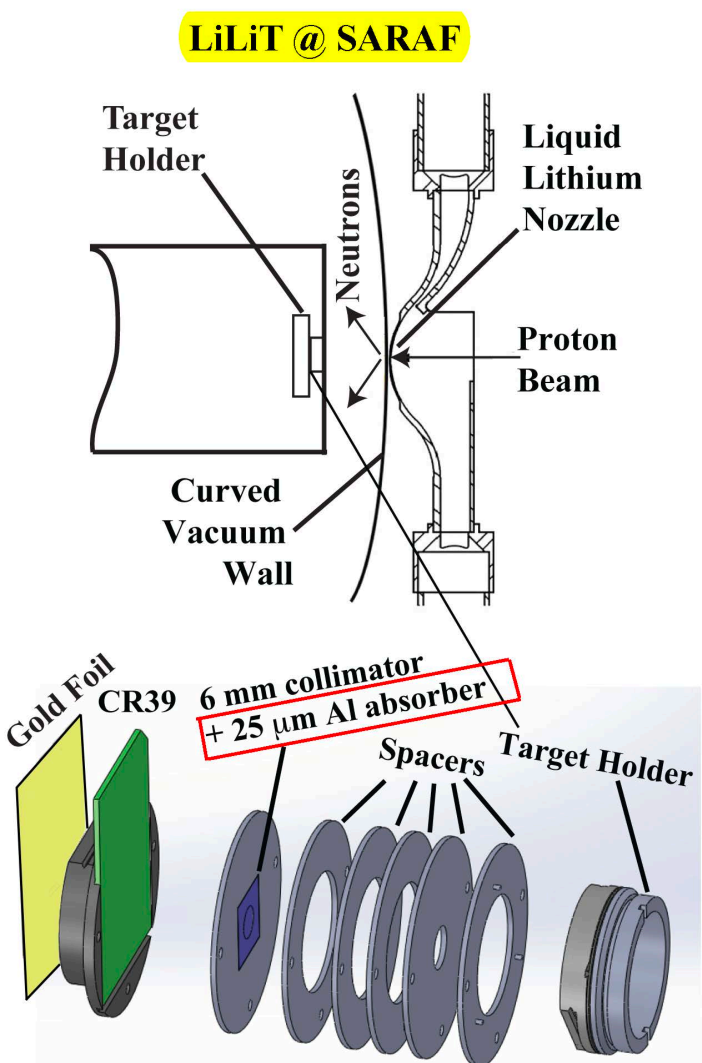
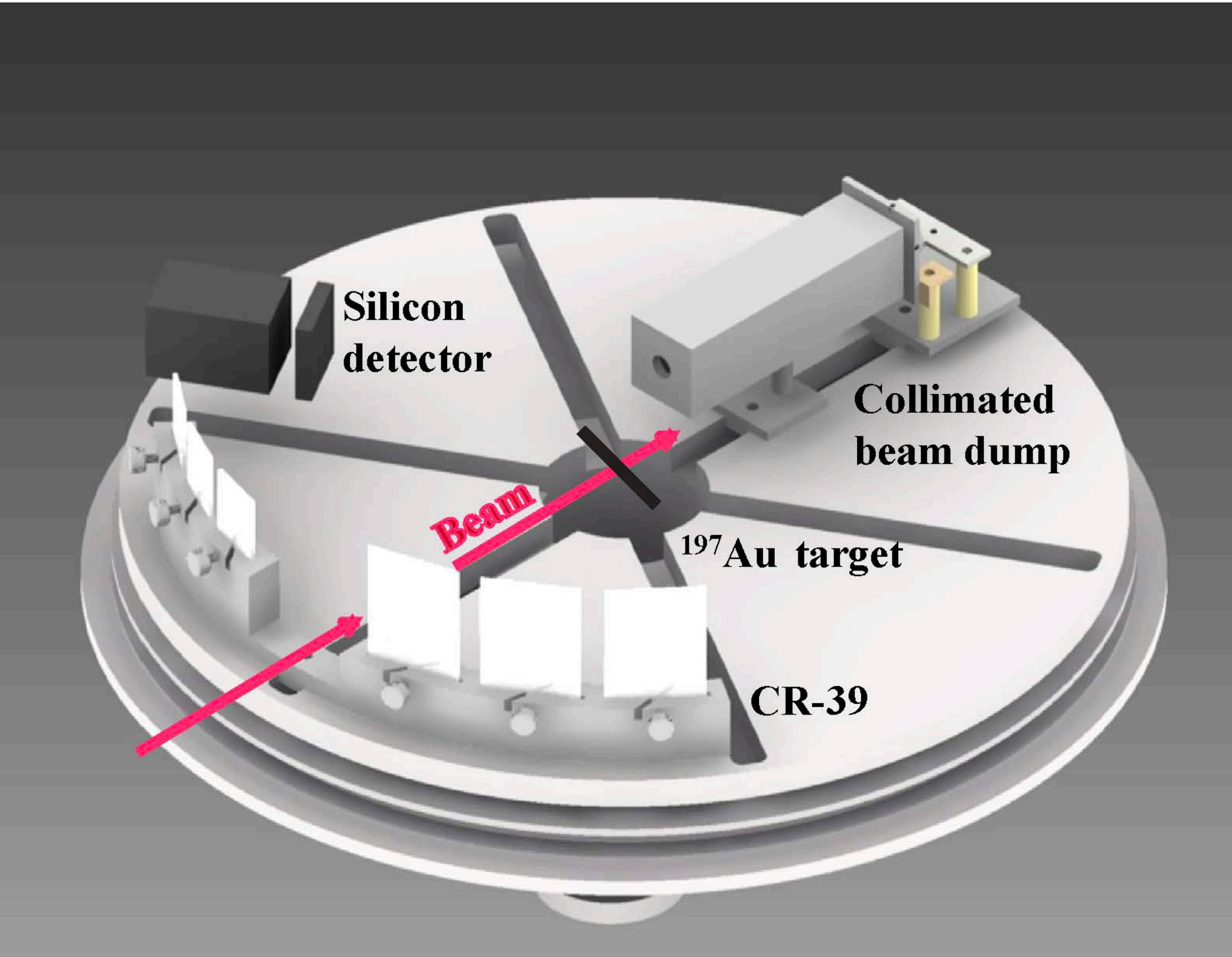
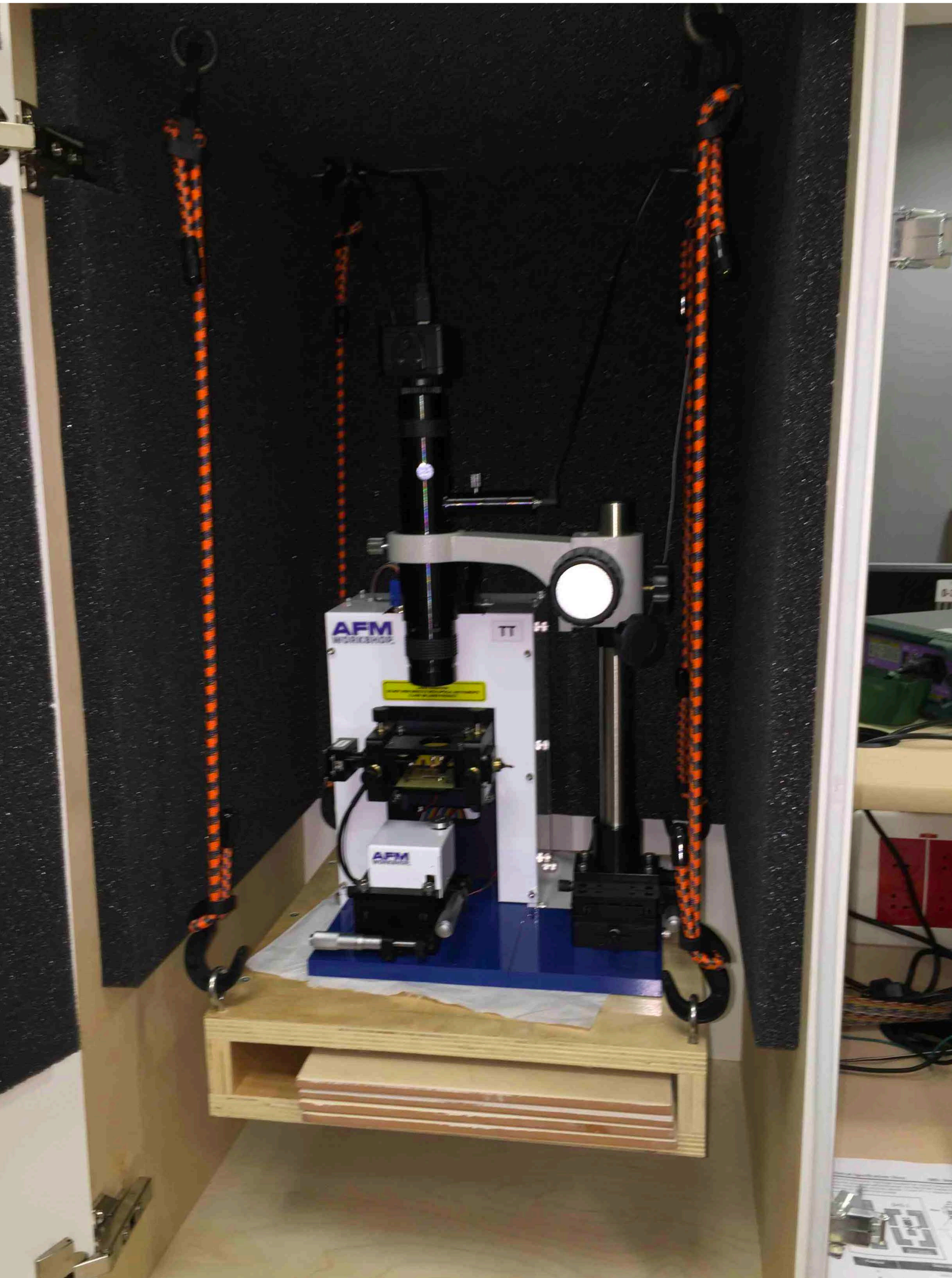


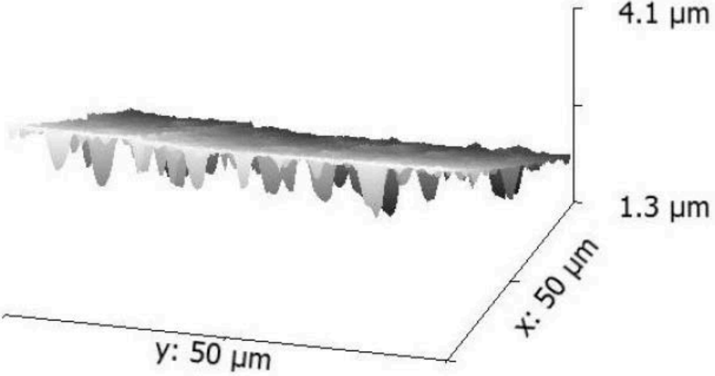
LiLiT @ SARAF
Target Holder
Neutrons
Liquid Lithium Nozzle
Proton Beam
Curved Vacuum Wall
Gold Foil
CR39
6 mm collimator
+ 25 μm Al absorber
Spacers
Target Holder

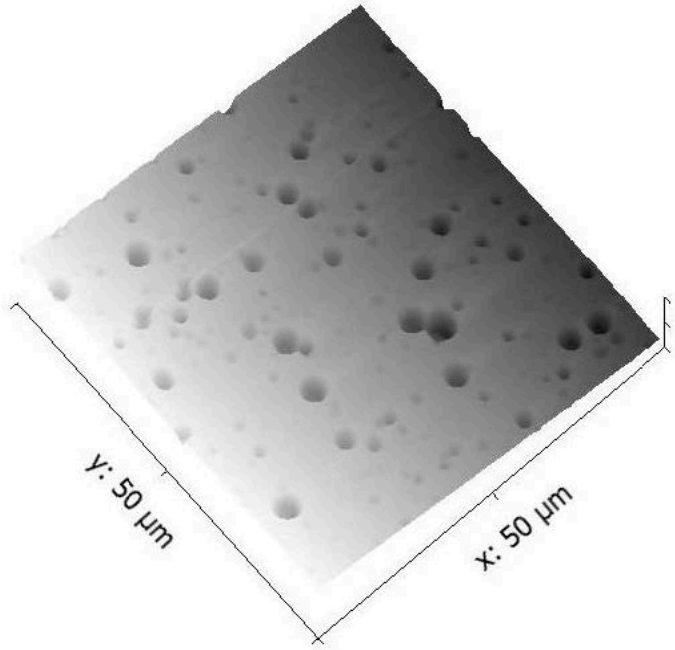
CR-39 Calibration Setup @ TUNL/Duke and Weizmann



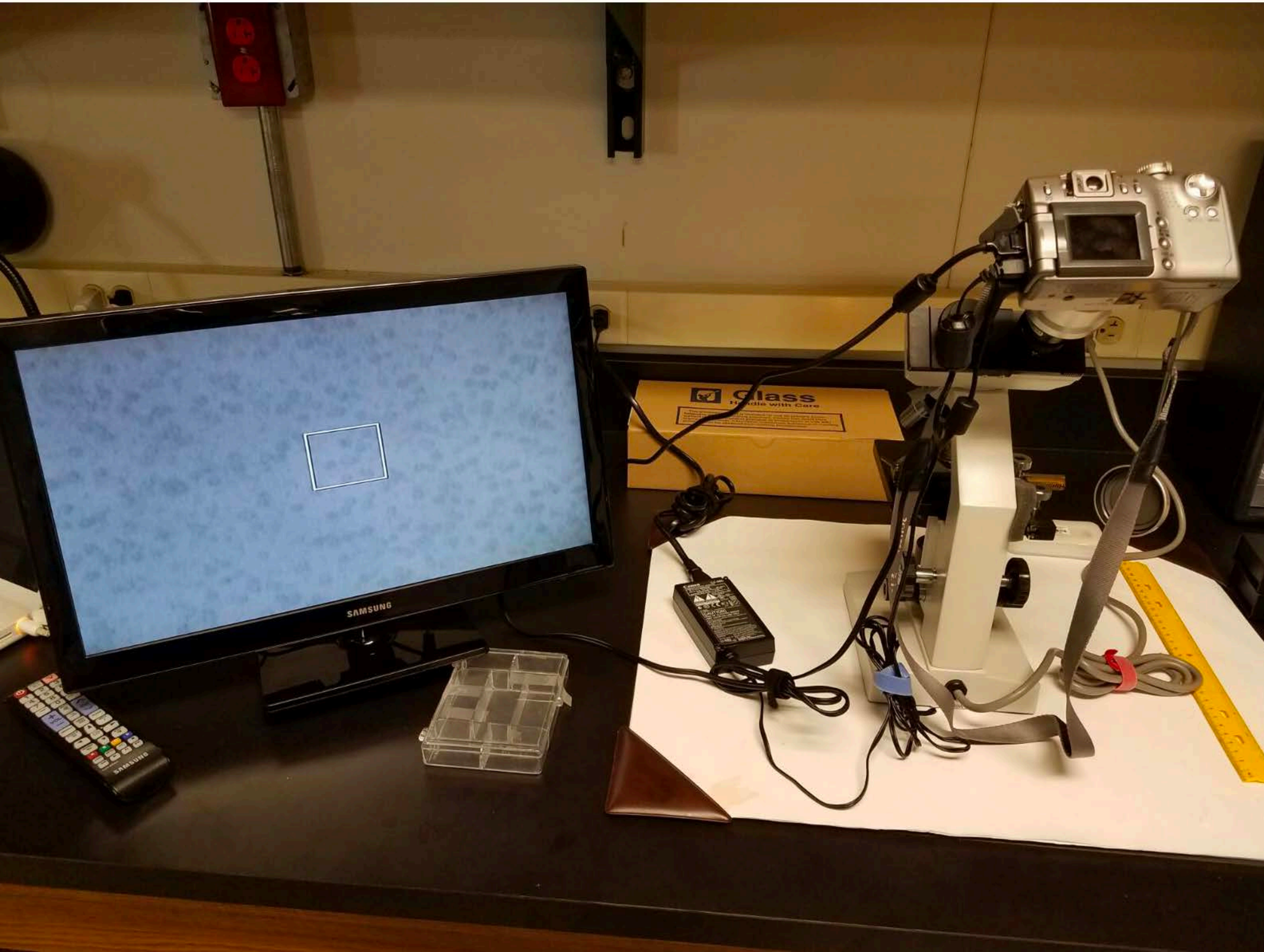
Atomic Force Microscope @ Bar Ilan University




4.1 µm
1.3 µm
x: 50 µm
y: 50 µm


y: 50 µm
x: 50 µm

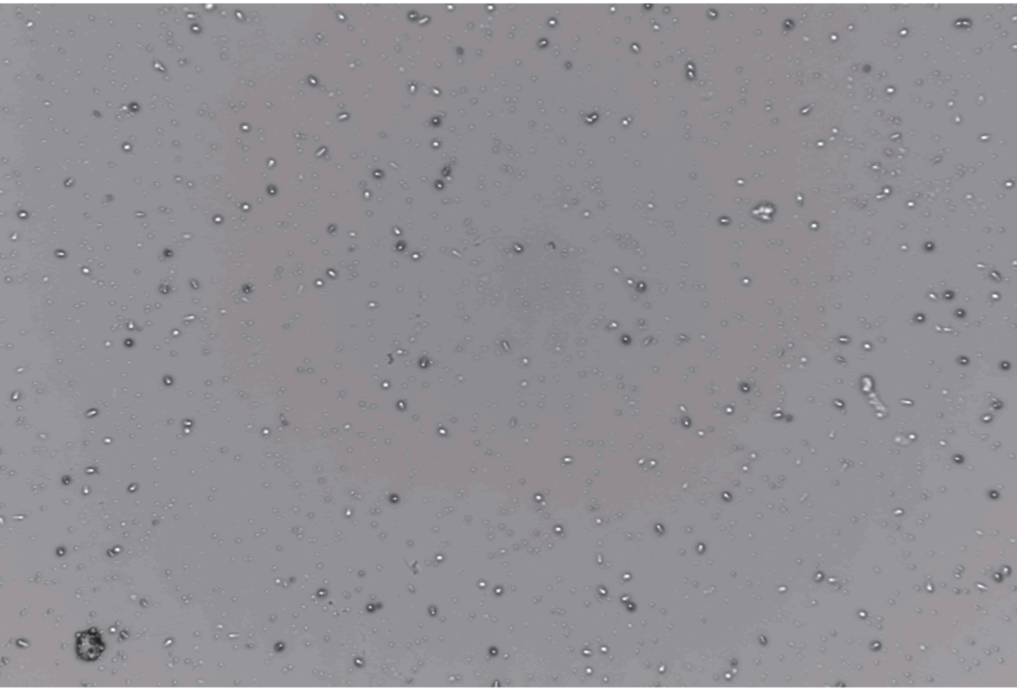
Microscope System at UConn



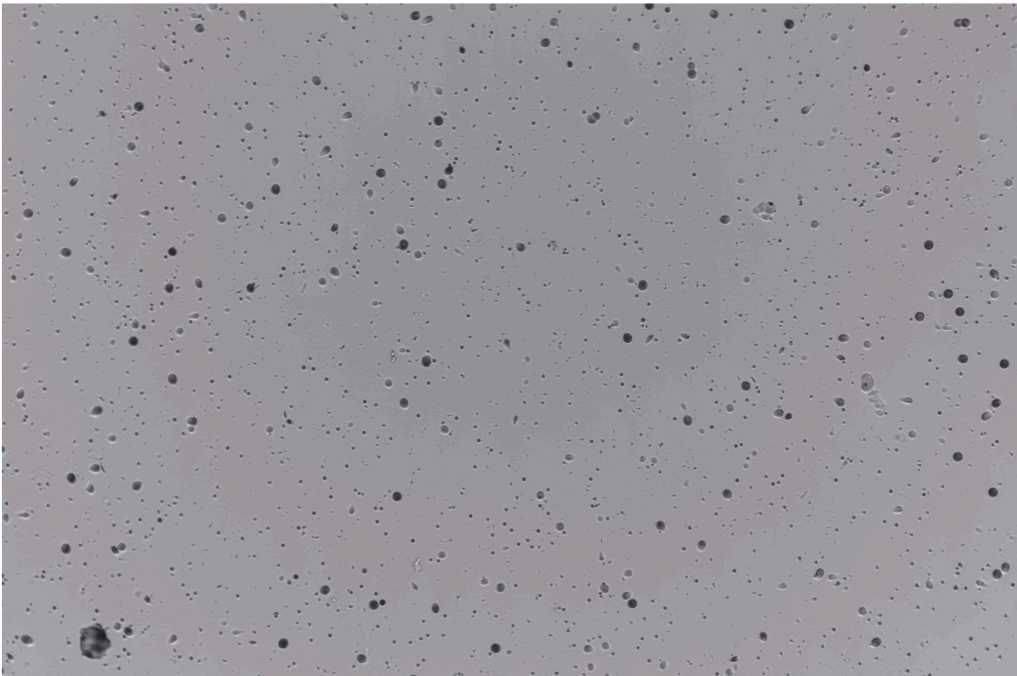
Microscope System at Bar Ilan University

ILL Data (cold neutrons)

Upper CR39



Lower CR39

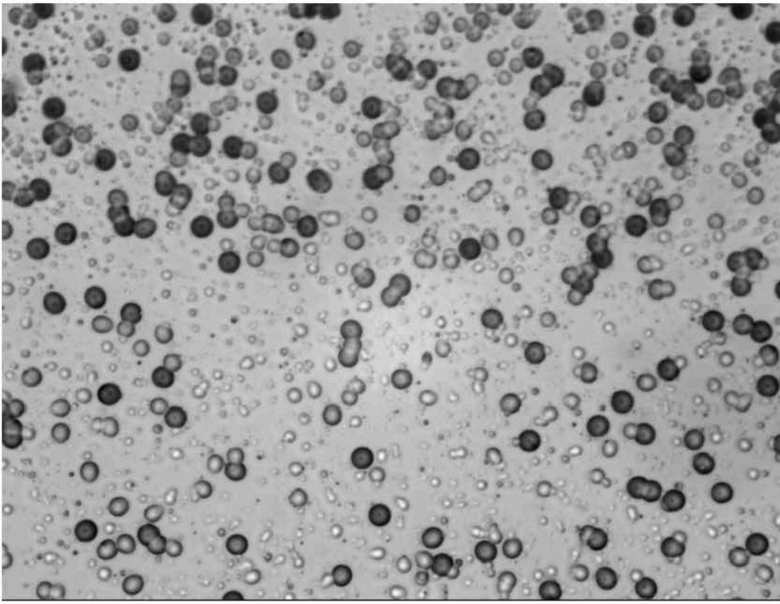


^{10}B(n,α) Reaction @ SARAF

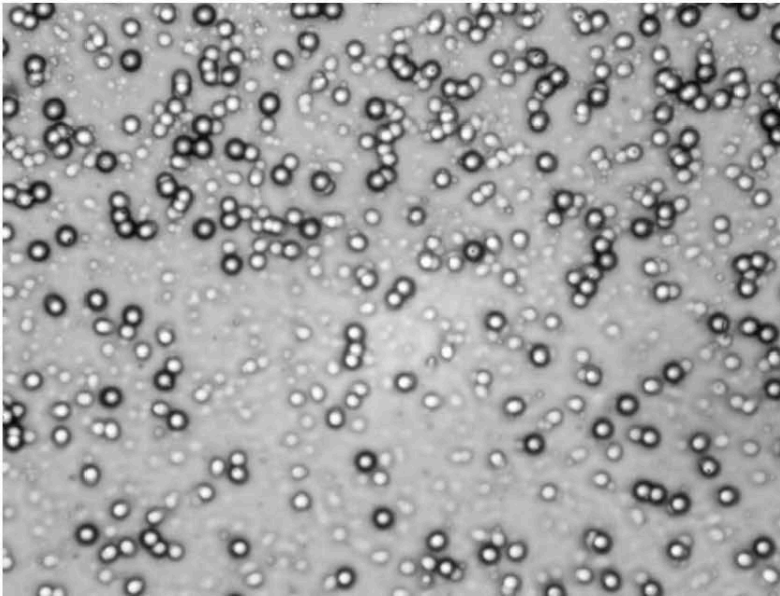
Measured = 3.3 ± 0.3 b

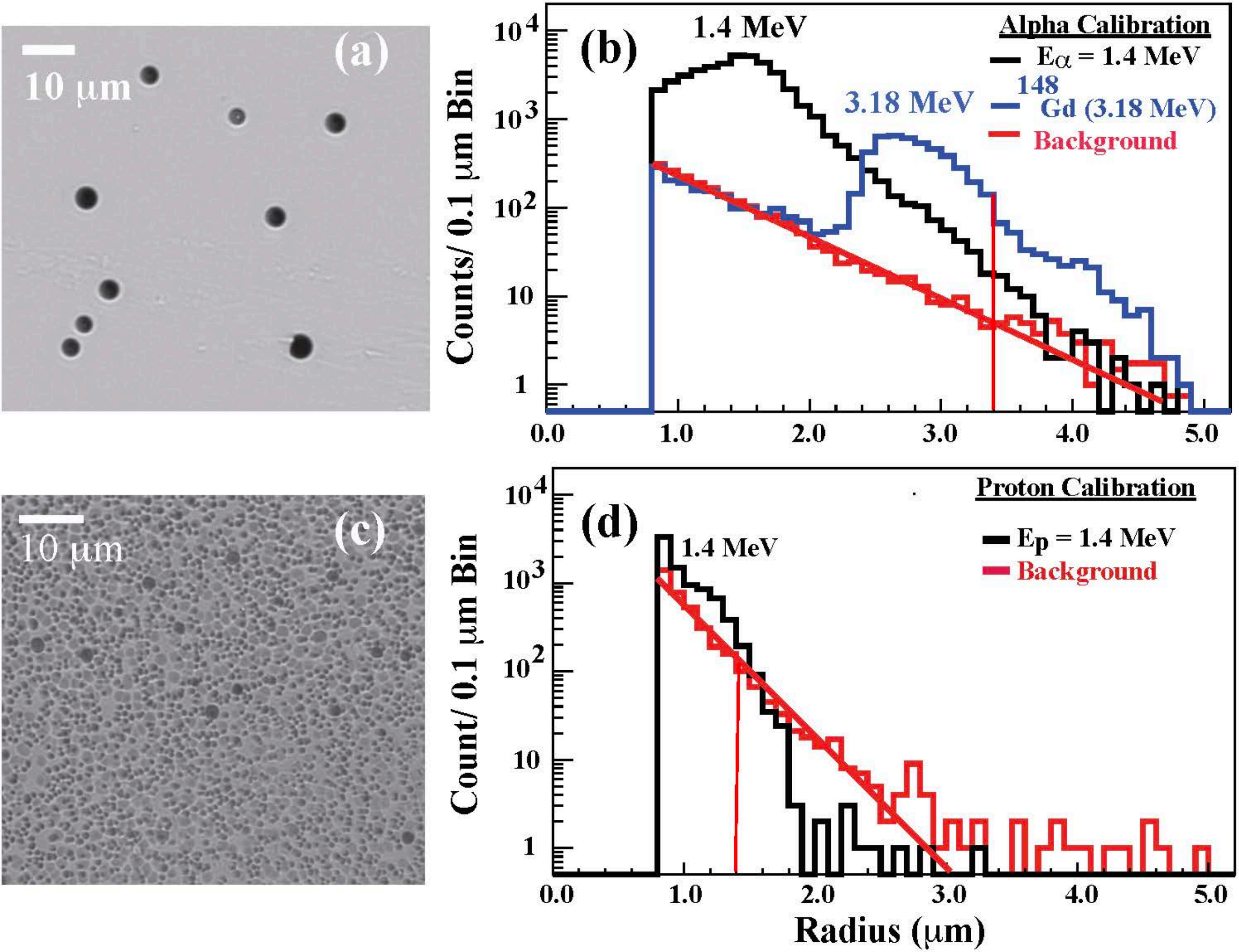
Known MACS = 3.35 b

Before focus point:



After focus point:

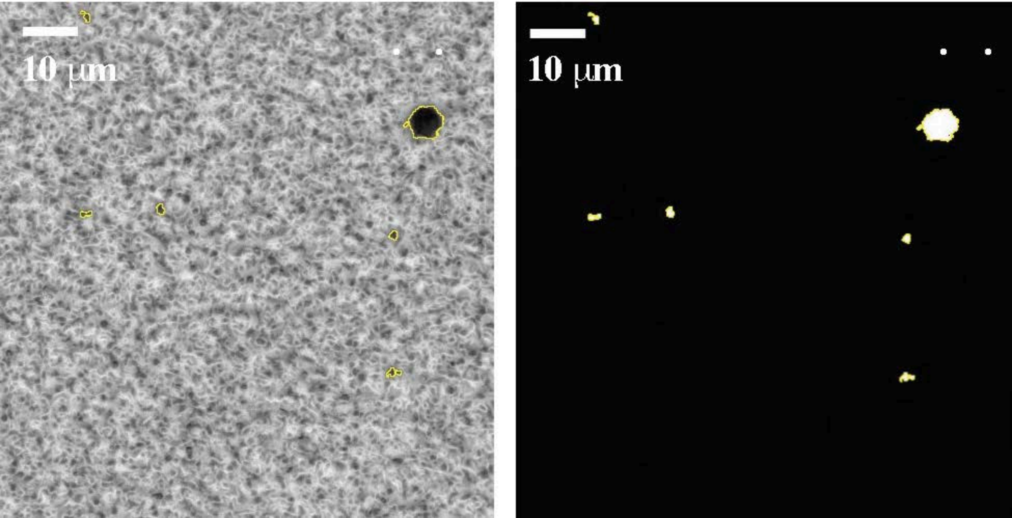


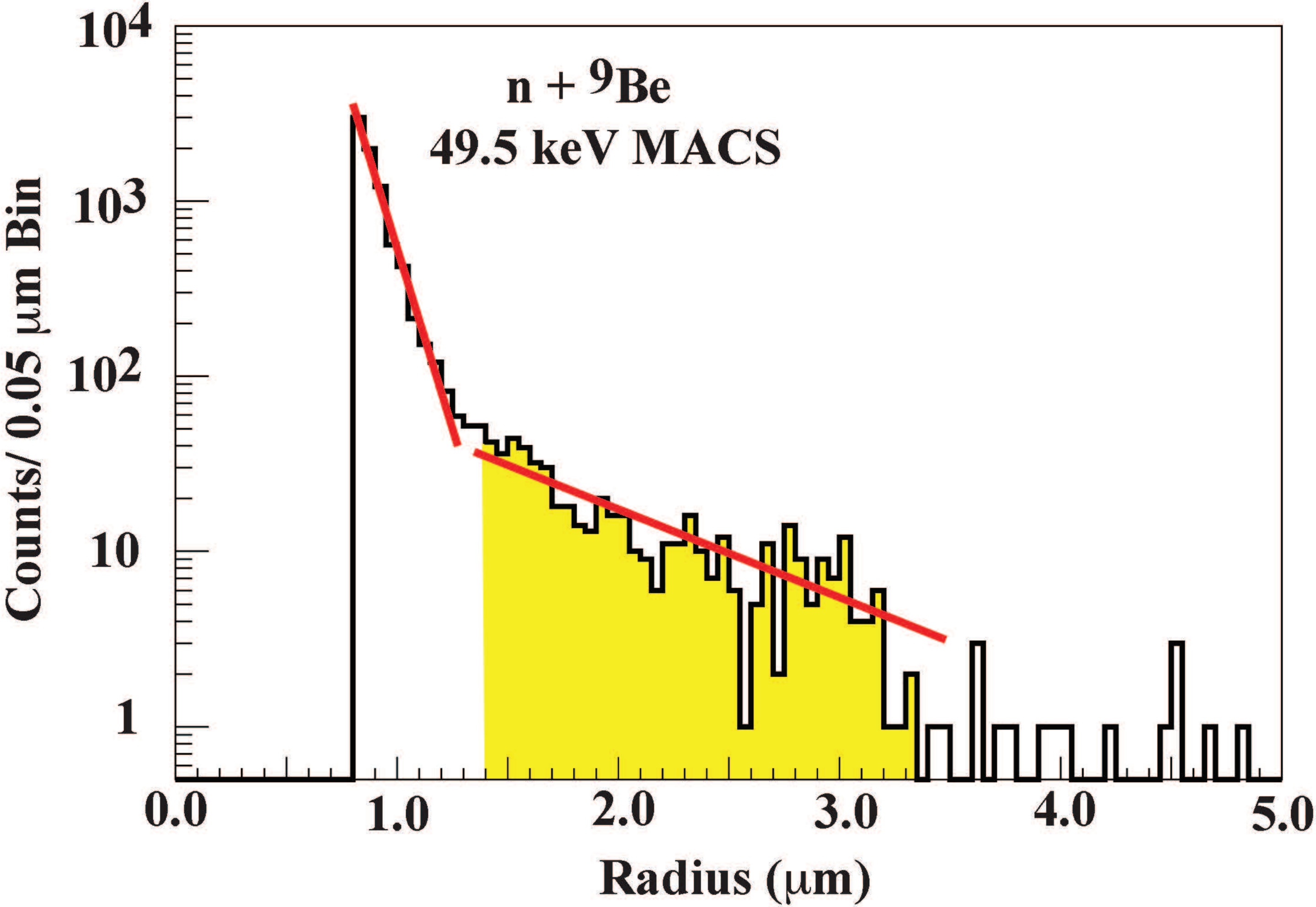


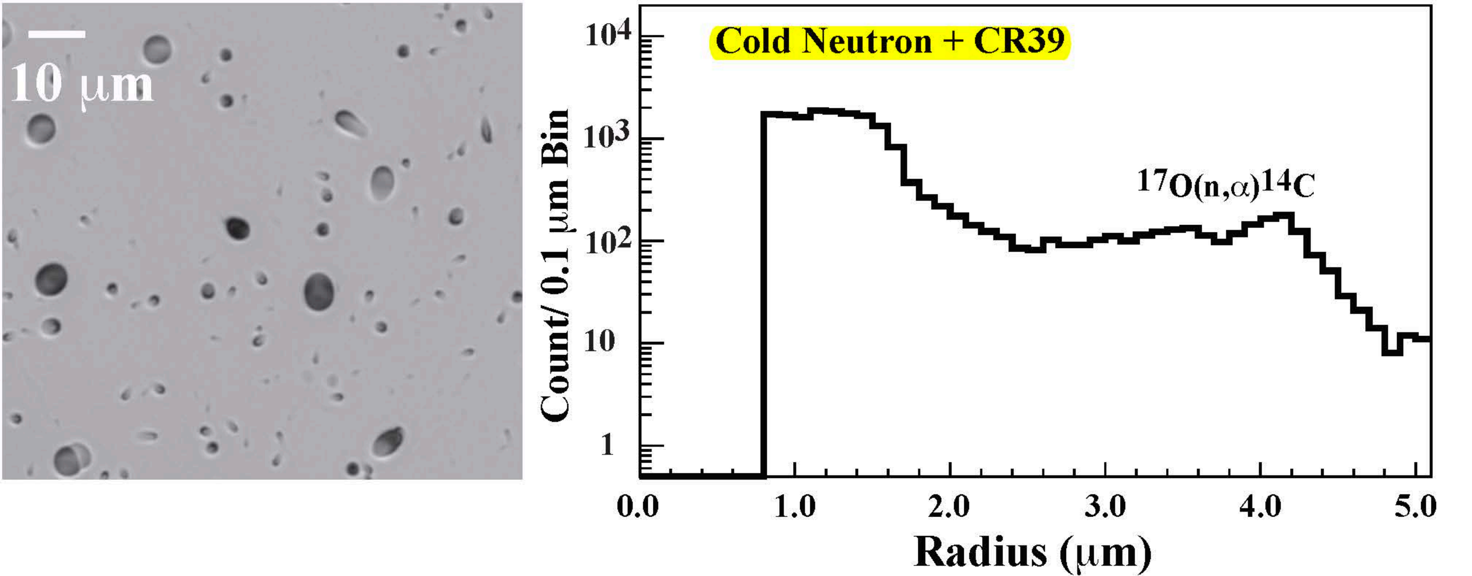
10 μm
(a)
(b)
1.4 MeV
Alpha Calibration
Eα = 1.4 MeV
148 Gd (3.18 MeV)
3.18 MeV
Background
Counts/ 0.1 μm Bin
0.0
1.0
2.0
3.0
4.0
5.0
10 μm
(c)
(d)
Proton Calibration
Ep = 1.4 MeV
1.4 MeV
Background
Count/ 0.1 μm Bin
Radius (μm)

n + ^{9}Be 49.5 keV MACS

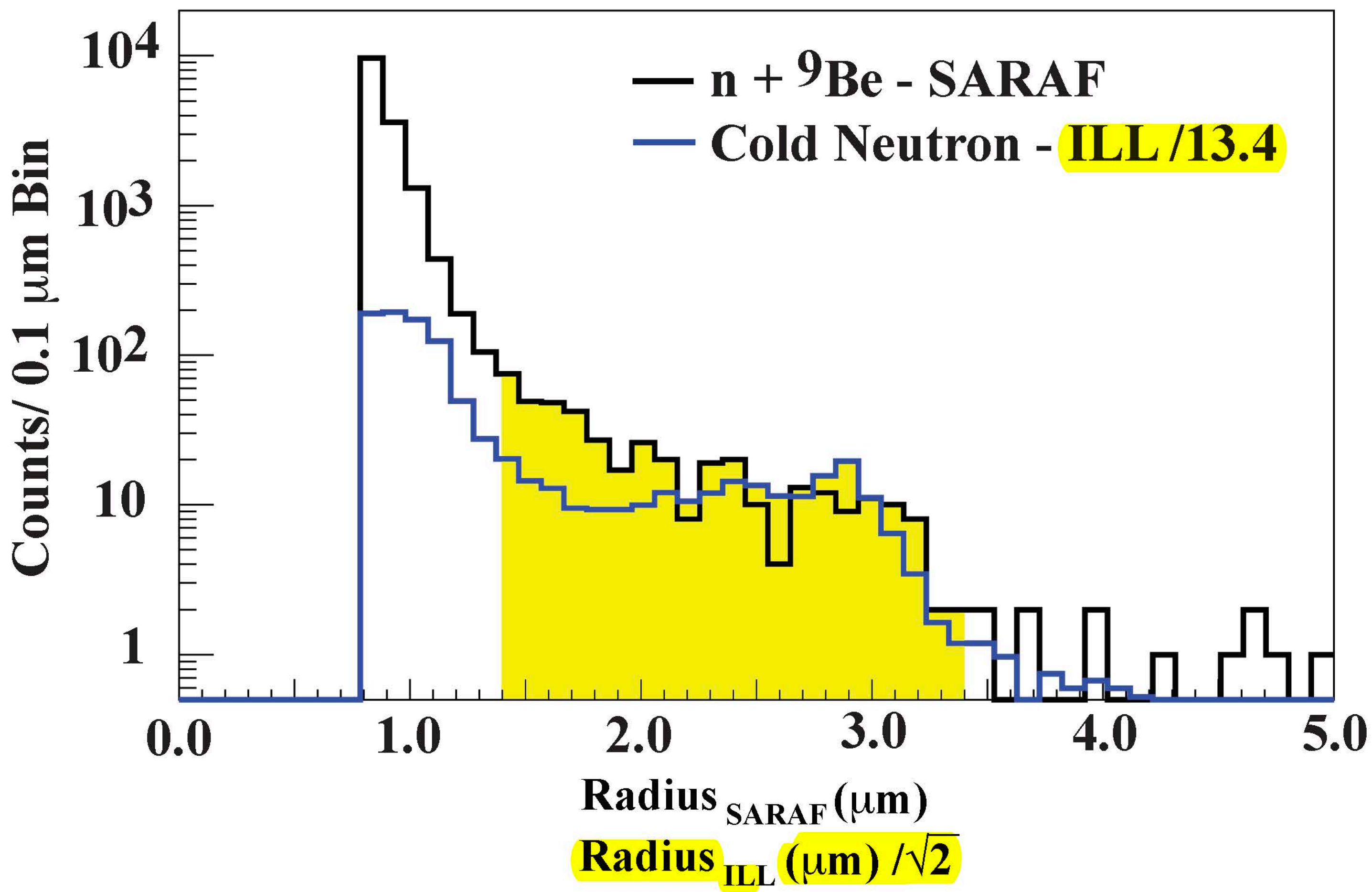
SARAF Data + Binary (Algorithm)



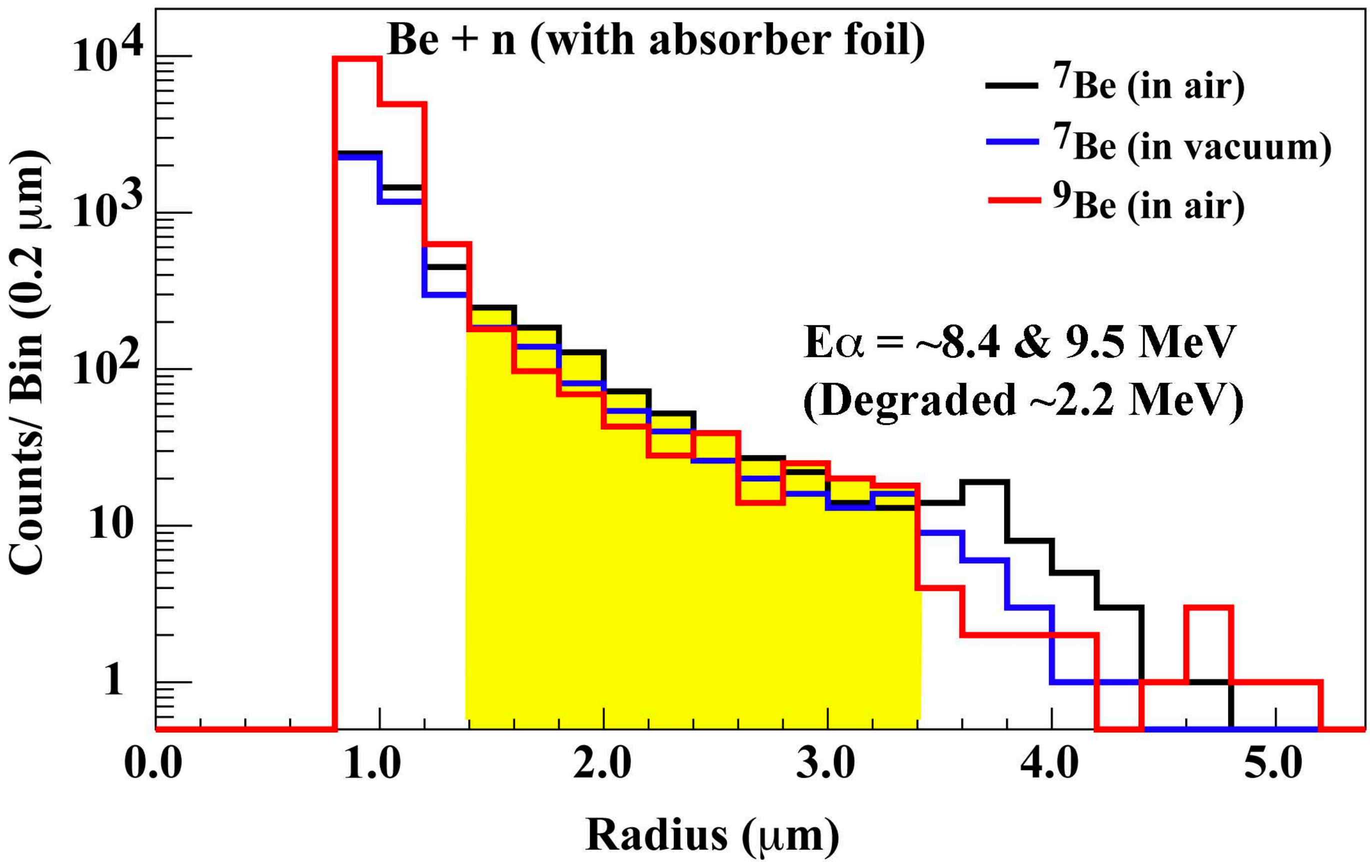

n + ^{9}Be
49.5 keV MACS
Counts/ 0.05 μm Bin
Radius (μm)
10^4
10^3
10^2
10
1
0.0
1.0
2.0
3.0
4.0
5.0

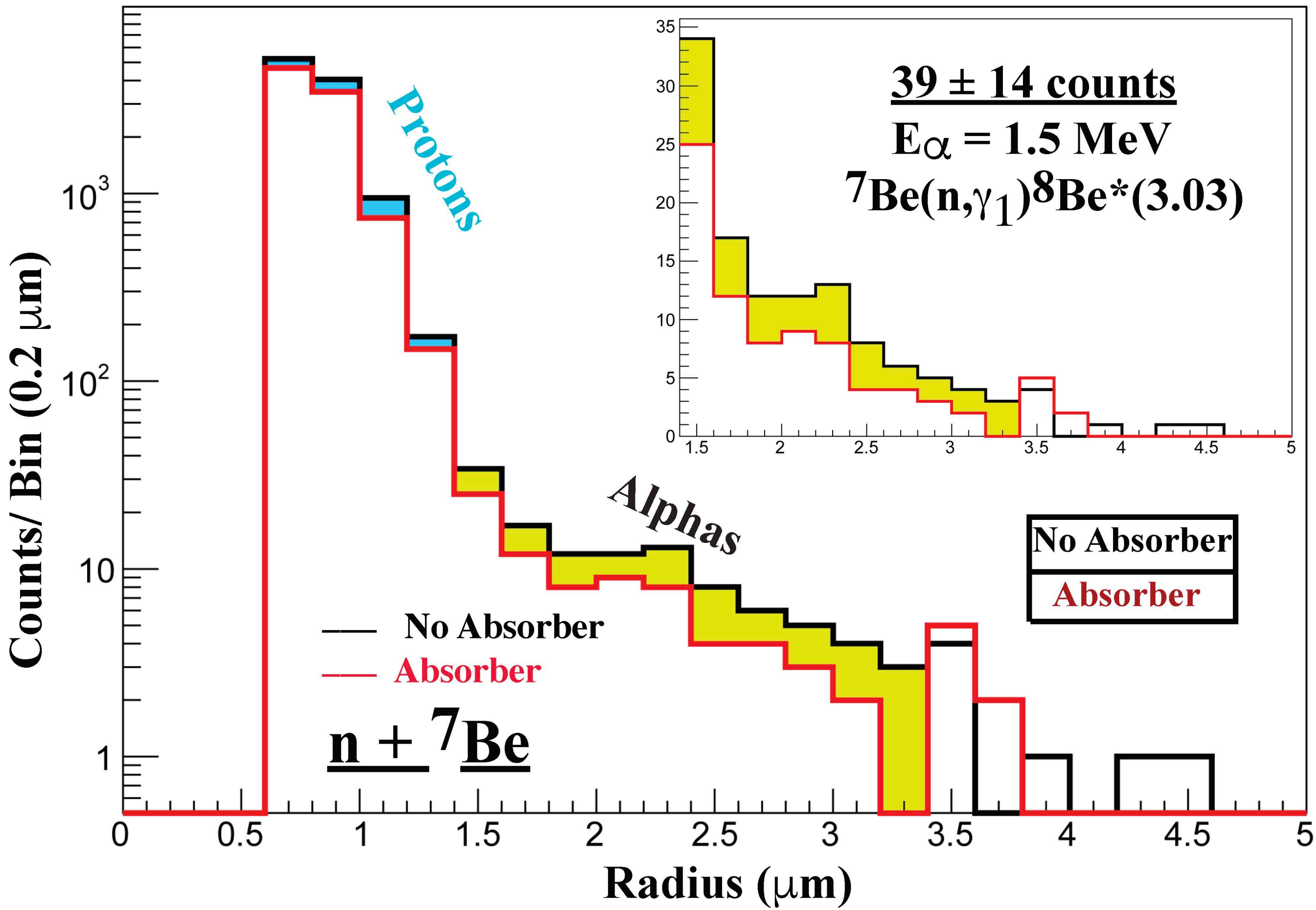


10 μm
Cold Neutron + CR39
$^{17}O(n,\alpha)^{14}C$
Count/ 0.1 μm Bin
10^4
10^3
10^2
10
1
0.0
1.0
2.0
3.0
4.0
5.0
Radius (μm)



n + ^{9}Be - SARAF
Cold Neutron - ILL /13.4
10^4
10^3
10^2
10
1
Counts/ 0.1 μm Bin
0.0
1.0
2.0
3.0
4.0
5.0
Radius $_{SARAF}$ (μm)
Radius $_{ILL}$ (μm) /√2


Be + n (with absorber foil)
7Be (in air)
7Be (in vacuum)
9Be (in air)
Eα = ~8.4 & 9.5 MeV
(Degraded ~2.2 MeV)
Counts/ Bin (0.2 μm)
Radius (μm)
10^4
10^3
10^2
10
1
0.0
1.0
2.0
3.0
4.0
5.0



39 ± 14 counts
E_α = 1.5 MeV
$^7Be(n,\gamma_1)^8Be^*(3.03)$
Protons
Alphas
No Absorber
Absorber
No Absorber
Absorber
n + ^{7}Be
Counts/ Bin (0.2 μm)
Radius (μm)

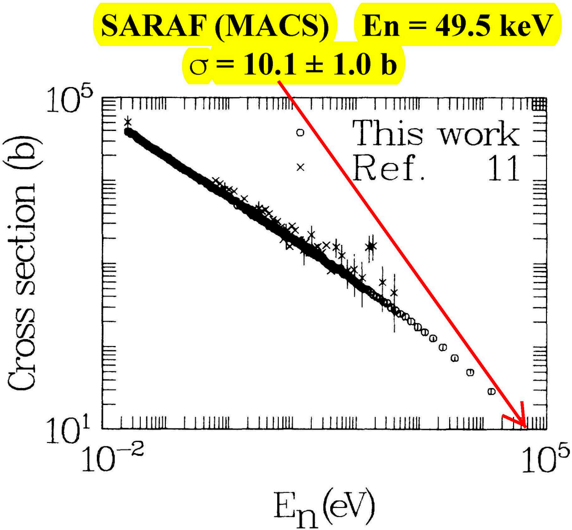
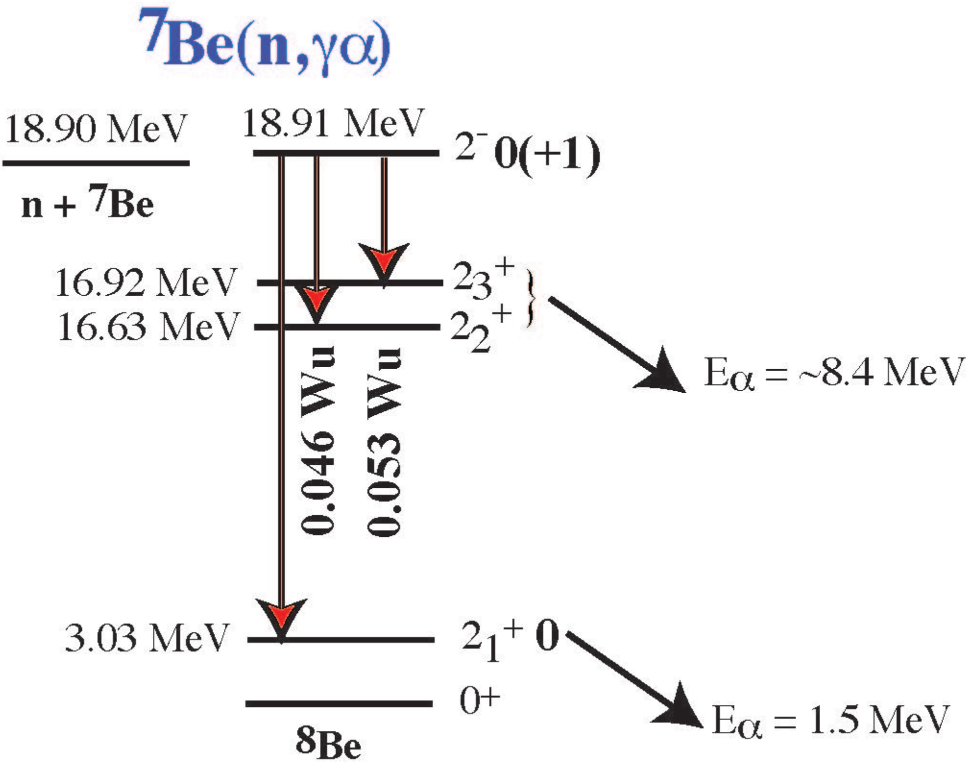


FIG. 4. The $^7Be(n,p)^7Li$ (p_0+p_1) cross section. Data from 25 meV to 13.5 keV are results of the present work (circles). Also shown are the data for this reaction from Ref. 11 (crosses).



7Be(n,γα)
18.90 MeV
n + 7Be
18.91 MeV
2- 0(+1)
16.92 MeV
16.63 MeV
23+
22+
0.046 Wu
0.053 Wu
Eα = ~8.4 MeV
3.03 MeV
21+ 0
0+
8Be
Eα = 1.5 MeV

^{7}Be(n,γ_1)^{8}Be*(3.03 MeV) $\rightarrow \alpha + \alpha$ [E$_\alpha$ = 1.5 MeV]

SARAF: $\sigma(n,\gamma_1)$ = 14.6 mb

B(E1) = ?

$$\sigma(n,\gamma) = \frac{\pi}{k^2} \times \frac{2\ell+1}{(2s_1+1)(2s_2+1)} \times \frac{\Gamma_n\Gamma_\gamma}{(E-E_R)^2+(\Gamma/2)^2}$$

$$\Gamma_\gamma(2^-, 19.91\ MeV) = \Gamma_{\gamma_1} + \Gamma_{\gamma_3} + \Gamma_{\gamma_4}$$

Known: $\Gamma_{\gamma_3} = 0.168\ eV, \Gamma_{\gamma_4} = 0.099\ eV$

For E$_n$ = 49.5 keV Measured SARAF: $\sigma(n,\gamma_1)$ = 14.6 mb

For E$_n$ = 49.5 keV Extrapolated n_TOF: $\sigma(n,\gamma_3) + \sigma(n,\gamma_4)$ = 0.1 mb

$$\frac{\sigma(n,\gamma_1)}{\sigma(n,\gamma_3)+\sigma(n,\gamma_4)} = \frac{14.6\ mb}{0.1\ mb} = 146$$

Hence:

$$\Gamma_{\gamma_1} = 146 \times (\Gamma_{\gamma_3} + \Gamma_{\gamma_4}) = 39.0\ eV \quad [\Gamma(W.u.) = 1.08\ keV]$$

B(E1:2$^-$ $\rightarrow$ 2_1^+) = 0.036 W.u.

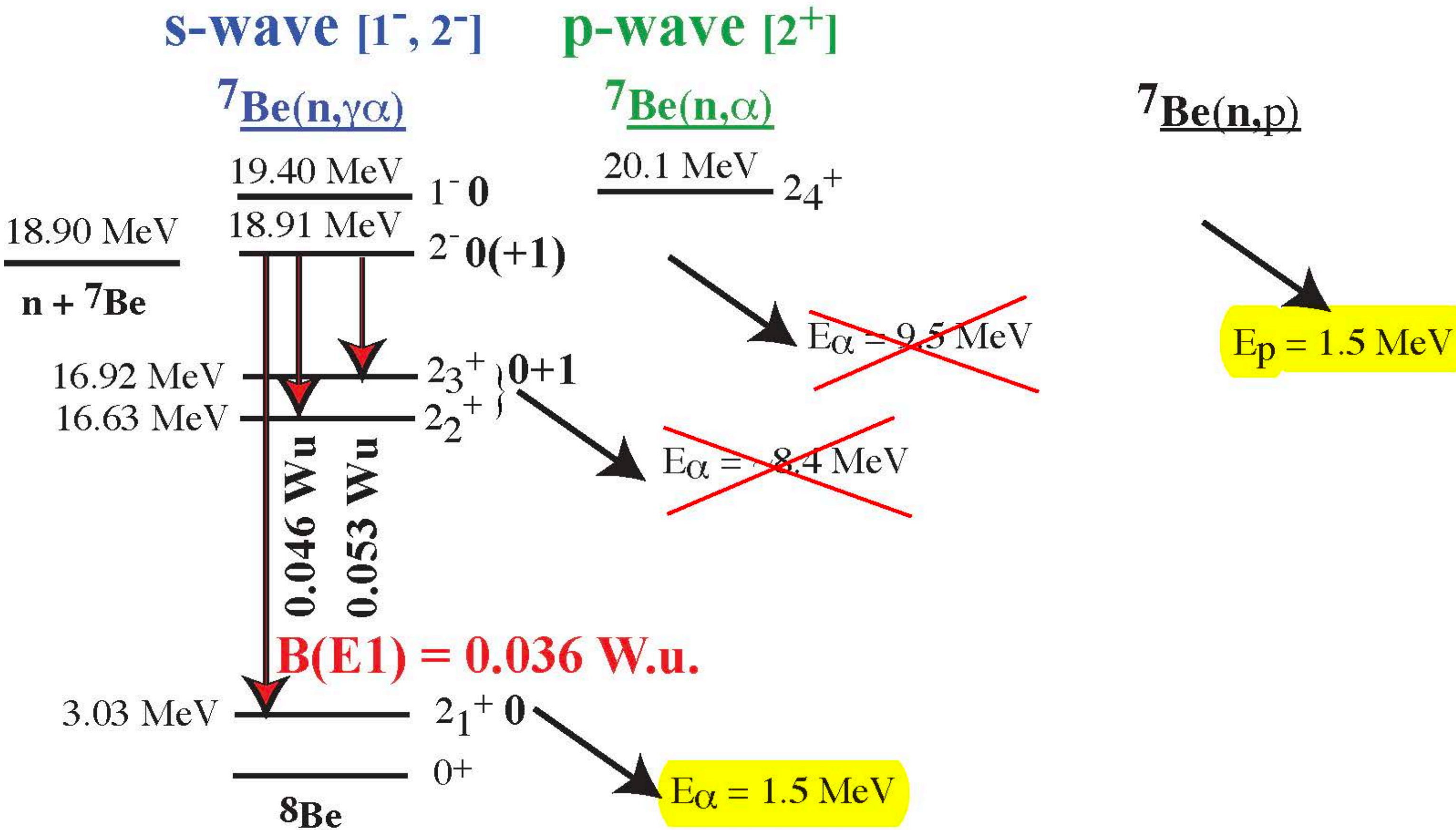
B(E1:2$^-$ $\rightarrow$ 2_2^+) = 0.053 W.u.

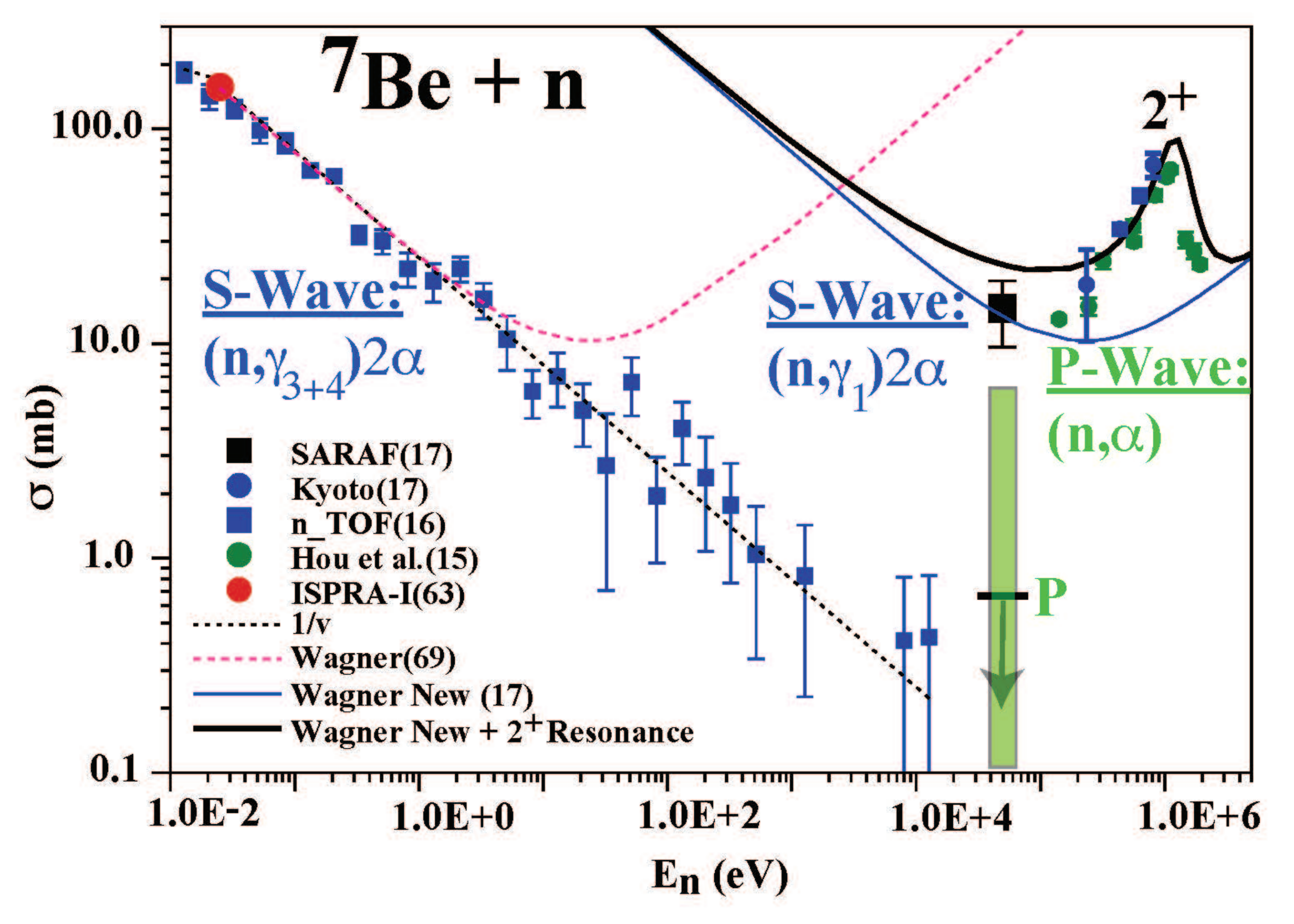
B(E1:2$^-$ $\rightarrow$ 2_3^+) = 0.045 W.u.

SARAF Measured B(E1) in Accordance

With Known B(E1)s of the 2^- state at 19.91 MeV in ^{8}Be

$^{7}Be + n\ [3/2^{-} \times 1/2^{+}]$





^{7}Be + n
2^+
S-Wave:
$(n,\gamma_{3+4})2\alpha$
S-Wave:
$(n,\gamma_1)2\alpha$
P-Wave:
(n,α)
P
SARAF(17)
Kyoto(17)
n_TOF(16)
Hou et al.(15)
ISPRA-I(63)
1/v
Wagner(69)
Wagner New (17)
Wagner New + 2^+Resonance
σ (mb)
100.0
10.0
1.0
0.1
1.0E-2
1.0E+0
1.0E+2
1.0E+4
1.0E+6
E_n (eV)

Wagoner '69: $N_A < \sigma v > = 20,500 \times g_1$

where $g_1 = 1 + 3760$T, with T is in GK.

$$\sigma = \frac{\pi}{k^2} \times \frac{2\ell+1}{(2s_1+1)(2s_2+1)} \times \frac{\Gamma_n \Gamma_\alpha}{(E-E_R)^2+(\Gamma/2)^2}$$

$$\Gamma_\ell = 2P_\ell \gamma^2$$

MACS: $\sigma = \frac{<\sigma v>}{v(kT)}$.

Neutron penetration factor: s-waves $\mathrm{P_0 = kR}$

p-waves $\mathrm{P_1} = (kR)^3/[1+(kR)^2] \approx (kR)^3$

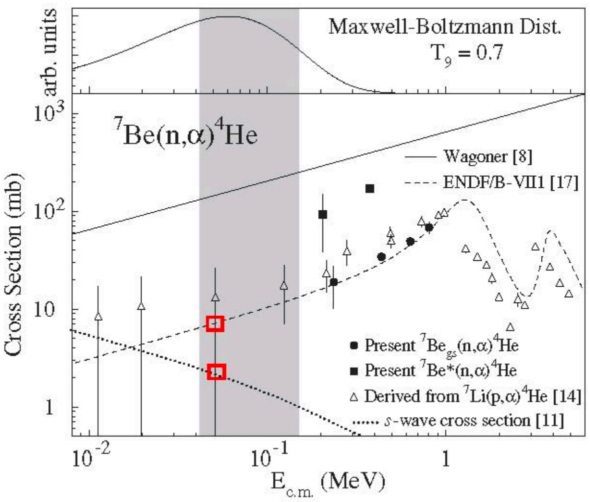
For s-waves $P_0 \times \frac{\pi}{k^2}$ hence $\sigma \propto 1/k \propto 1/v$ and $< \sigma v > =$ constant

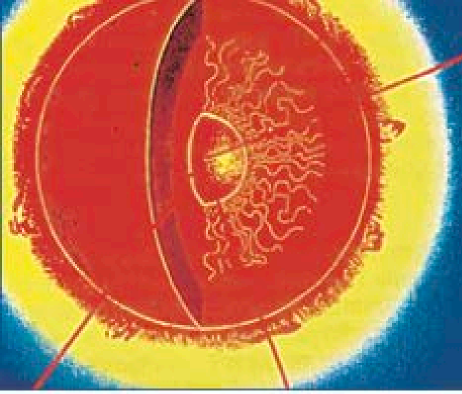
For p-waves $P_1 \times \frac{\pi}{k^2}$ hence $\sigma \propto k \propto v$ and $< \sigma v > \propto v^2 \propto E \propto T$

Data (s-wave dominance) Require $\mathrm{g_1 = 100 + 38T}$

Kyoto: Phys. Rev. Lett. 118(2017)052701

~~(p-wave dominance at BBN Window)~~





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Conclusions:

1. Measured $^{7}Be(n,\alpha)$ $^{7}Be(n,\gamma\alpha)$ in BBN Window.

2. First Measurement of $^{7}Be(n,\gamma)^{8}Be^{*}(3.03\ MeV)$
(Reasonable $B(E1: 2^{-} \rightarrow 2^{+}{}_{1}) = 0.036$ W.u.)

3. Measured $^{7}Be(n,p)$ MACS @ 49.5 keV = 10.1 b.

4. No hitherto unknown Resonance in BBN Window
(that would lead to large cross section).

5. S - wave dominance at BBN Window
(Corrected previous s and p waves extrapolations).

6. New Burning Rate Based on World Data
Updated "Wagoner (2017)".

Lack of Standard Nuclear Solution
To the Primordial ^{7}Li Problem