Laboratory
Underground
Nuclear
Astrophysics

INFN

The seeds of the S-process: experimental issues in the study of $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

Paolo Prati

INFN and Dept. of Physics –Univ. of Genoa, Italy

PHYSICAL REVIEW C **78**, 025803 (2008)

The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process

M. Heil,[1,*] R. Detwiler,[2,†] R. E. Azuma,[2,3] A. Couture,[2,‡] J. Daly,[2,§] J. Görres,[2] F. Käppeler,[1] R. Reifarth,[1,∥] P. Tischhauser,[2,¶] C. Ugalde,[2,**] and M. Wiescher[2]

Current stellar models as well as stellar spectroscopy strongly support the $^{13}C(\alpha, n)^{16}O$ reaction as the dominant neutron source for the main component of the *s* process in thermally pulsing, low-mass, asymptotic giant branch (TP-AGB) stars [1]. The energy generation in such stars occurs in the H and He burning shells surrounding the inert C/O core.

VOLUME 87, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 2001

$^{22}Ne(\alpha,n)^{25}Mg$: The Key Neutron Source in Massive Stars

M. Jaeger,[1] R. Kunz,[1] A. Mayer,[1] J. W. Hammer,[1] G. Staudt,[2] K. L. Kratz,[3] and B. Pfeiffer[3]

The reaction $^{22}Ne(\alpha, n)^{25}Mg$ is the dominant source of neutrons for the *s* process (neutron capture on a slow time scale) in massive stars with $M > 8M_{\odot}$ ($M_{\odot}$ = solar mass) destined to become supernovae [1]. Calculations suggest that this range of stellar masses is responsible for producing most of the nuclides attributed to slow neutron capture for atomic masses $A \sim 60-90$ as well as many lighter than $A = 60$ [2]. The remainder of the *s* process ($A \sim 90-209$) is thought to be produced in asymptotic giant branch (AGB) stars by a combination of the $^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$ reactions during the helium shell flashes that characterize these stars

PHYSICAL REVIEW C **78**, 025803 (2008)

The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process

M. Heil,[1,*] R. Detwiler,[2,†] R. E. Azuma,[2,3] A. Couture,[2,‡] J. Daly,[2,§] J. Görres,[2] F. Käppeler,[1] R. Reifarth,[1,||] P. Tischhauser,[2,¶] C. Ugalde,[2,**] and M. Wiescher[2]

The temperature during the *s* process in the ^{13}C pocket of 90×10^6 K (corresponding to a thermal energy of $kT =$ 8 keV) corresponds to a Gamow window around 190 keV (140–230 keV) for the (α, n) reaction on ^{13}C. Since this energy is far below the Coulomb barrier, the reaction cross section is extremely small and not accessible to direct measurements. For this reason, its value has to be determined by extrapolation of the cross sections measured at higher energies. The extrapolation is complicated by the unknown influence of a broad subthreshold state with $J^\pi = 1/2^+$ at $E_x =$ 6.356 MeV ($E_\alpha^{lab} = -3$ keV), and by two subthreshold resonances with $J^\pi = 1/2^-$ at $E_x = 5.939$ MeV ($E_\alpha^{lab} =$ -547 keV) and $J^\pi = 3/2^+$ at $E_x = 5.869$ MeV ($E_\alpha^{lab} =$ -641 keV).

In the Gamow peak region (140 -230 keV) ~ 1 count/month

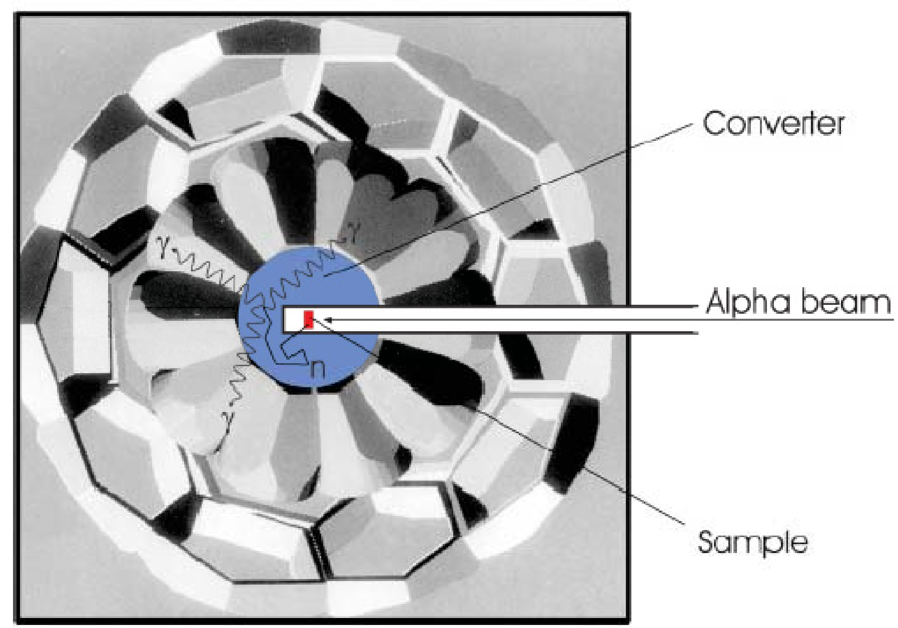
Active shielding techniques;
Pulse shape analysis;
neutron background 0.014 n/s

Karlsruhe 3.7 MV Van De Graaff

α beam ~ 50 μA

n-Detector: 4π Karlsruhe BaF_2 calorimeter (20 cm inner Φ; thickness 15 cm) with n/γ converter (paraffin loaded with Cd at 3%)

Total 41 crystals



PHYSICAL REVIEW C 78, 025803 (2008)

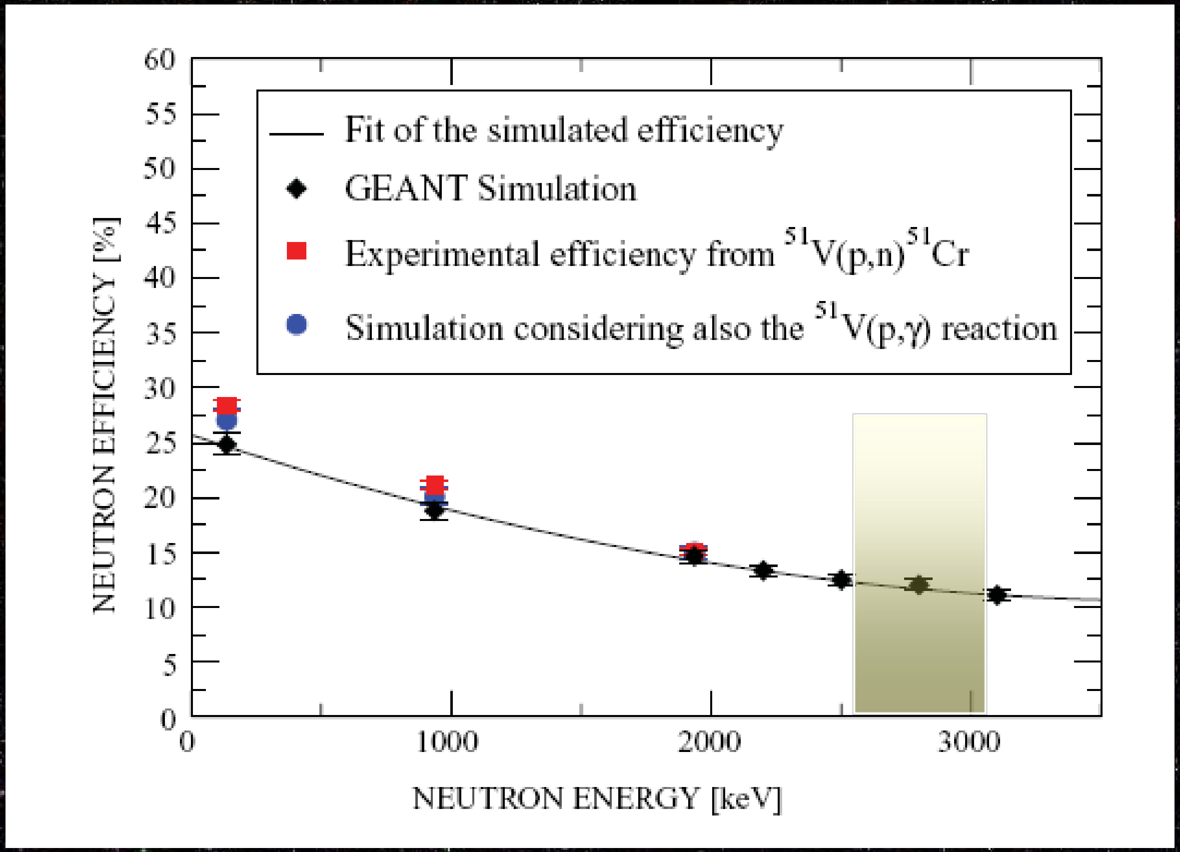
The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process

M. Heil,[1,*] R. Detwiler,[2,†] R. E. Azuma,[2,3] A. Couture,[2,‡] J. Daly,[2,§] J. Görres,[2] F. Käppeler,[1] R. Reifarth,[1,‖] P. Tischhauser,[2,¶]
C. Ugalde,[2,**] and M. Wiescher[2]

$^{13}C(\alpha,n)$: Q-value = 2215.6 MeV

$^{113}Cd(n,\gamma)^{114}Cd$, γ-flash energy: 9.04 MeV → Multiplicity suitable for bck. reduction

BaF_2 efficiency ~ 95%



PHYSICAL REVIEW C 78, 025803 (2008)

The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process

M. Heil,[1,*] R. Detwiler,[2,†] R. E. Azuma,[2,3] A. Couture,[2,‡] J. Daly,[2,§] J. Görres,[2] F. Käppeler,[1] R. Reifarth,[1,∥] P. Tischhauser,[2,¶] C. Ugalde,[2,**] and M. Wiescher[2]

~ 3 times the bck. level

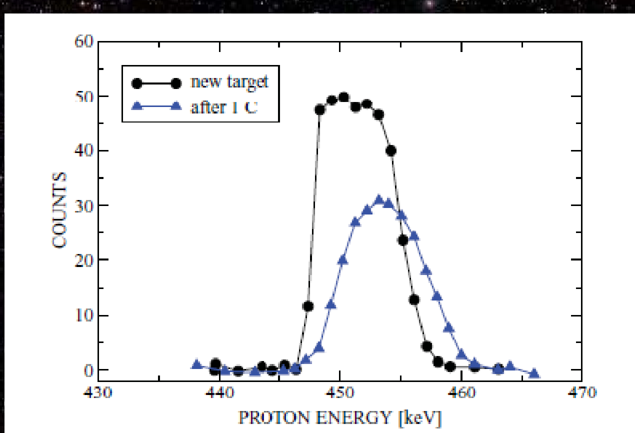
Y ~ 1 mC^{-1} → 5 10^{-2} count/s

Y ~ 20 mC^{-1} → 1 count/s

TABLE III. Experimental *S* factors.

E_{lab} (keV)	$E_{c.m.}$ (keV)	Yield (mC^{-1})	*S* factor (10^6 MeV b)	Uncertainties (%) Stat.	Sys.
416	318	0.97	1.17	92	11
437	334	2.4	1.07	45	30
439	336	2.0	0.80	42	40
449	343	3.4	1.14	23	23
493	377	21.4	1.11	4.3	17
536	403	46.1	1.05	3.4	31
568	435	119	0.92	1.8	11
642	491	1034	1.11	1.8	6.4
695	531	3525	1.19	0.9	9.3
747	571	12169	1.48	0.5	9.0
800	612	32567	1.55	0.8	4.7
849	649	76240	1.70	0.2	5.0
899	687	175813	2.00	0.1	5.0

Systematic: dominated by target deterioration

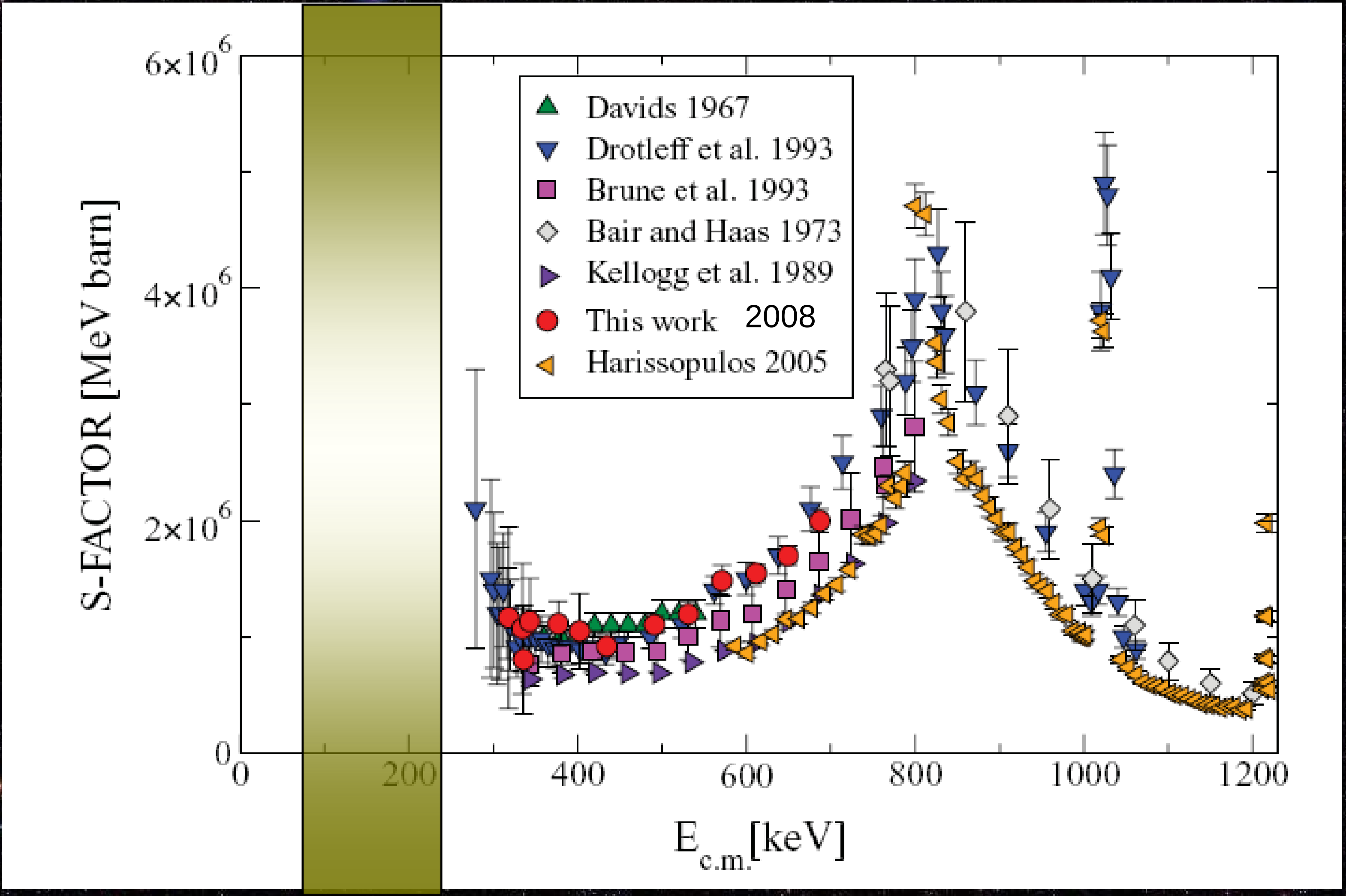


At lowest energies: uncertainty dominated by counting statistics

PHYSICAL REVIEW C **78**, 025803 (2008)

The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process

M. Heil,[1,*] R. Detwiler,[2,†] R. E. Azuma,[2,3] A. Couture,[2,‡] J. Daly,[2,§] J. Görres,[2] F. Käppeler,[1] R. Reifarth,[1,‖] P. Tischhauser,[2,¶] C. Ugalde,[2,**] and M. Wiescher[2]

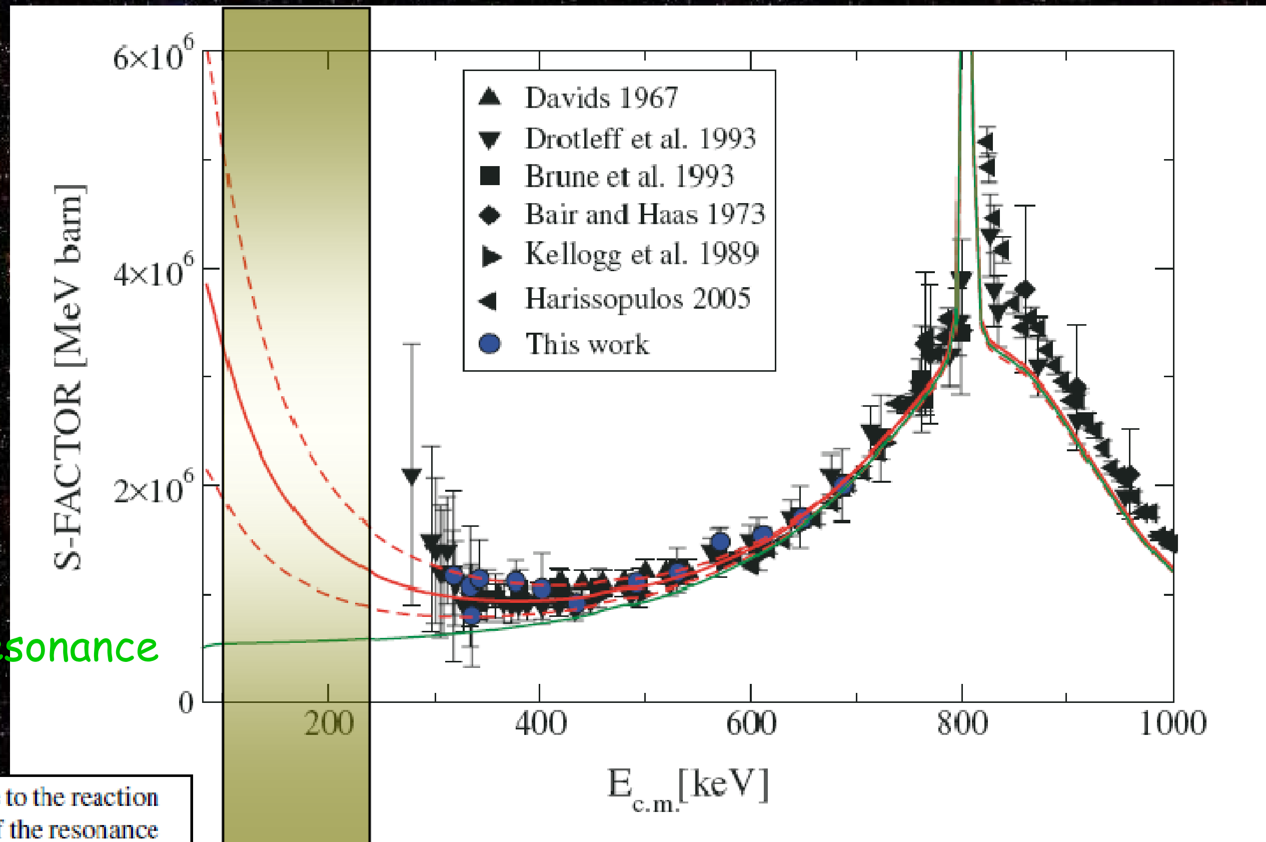


Extrapolation still needed: are we close enough to the Gamow region ?

PHYSICAL REVIEW C 78, 025803 (2008)

The $^{13}C(\alpha, n)$ reaction and its role as a neutron source for the *s* process

M. Heil,[1,*] R. Detwiler,[2,†] R. E. Azuma,[2,3] A. Couture,[2,‡] J. Daly,[2,§] J. Görres,[2] F. Käppeler,[1] R. Reifarth,[1,||] P. Tischhauser,[2,¶] C. Ugalde,[2,**] and M. Wiescher[2]



Without the – 3 keV resonance

Finally, the influence of the $J^\pi = 1/2^+$ close to the reaction threshold needs to be considered. A variation of the resonance parameter Γ_α by factors between 0.17 and 2.5 causes only small changes in the χ^2 value but has significant consequences for the S factor. Hence, the uncertainty in this parameter is responsible for most of the uncertainty in our S-factor extrapolation. Unfortunately, the indirect studies discussed before have not succeeded in reducing this uncertainty by obtaining the reduced α width or ANC for this level. Since the results of these experiments differ substantially, these values may depend significantly on the choice of reaction or reaction model parameters.

TABLE XII. Comparison of stellar rates (in units of 10^{-14} cm^3/mole s) for the $^{13}C(\alpha, n)$ reaction at $T = 0.1 \times 10^9$ K.

Authors	Reaction rate	Ref.
Caughlan and Fowler (1988)	2.58	[11]
Denker and Hammer (1995)	4.32	[12]
NACRE (1999)	$7.24^{+1.25}_{-4.98}$	[13]
This work	4.6±1.0	

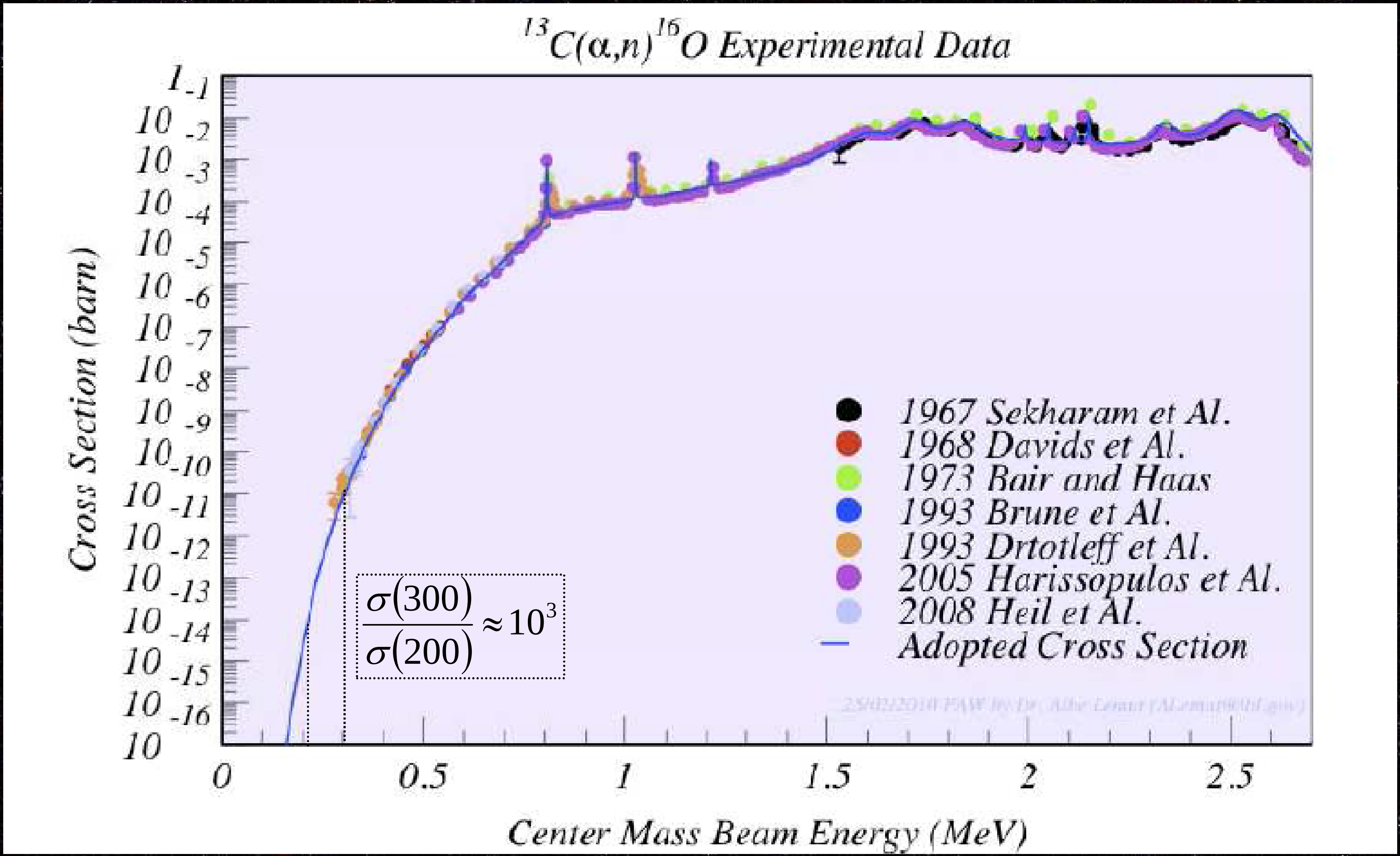
PHYSICAL REVIEW C **78**, 025803 (2008)

The ^{13}C(α, n) reaction and its role as a neutron source for the s process

M. Heil,[1,*] R. Detwiler,[2,†] R. E. Azuma,[2,3] A. Couture,[2,‡] J. Daly,[2,§] J. Görres,[2] F. Käppeler,[1] R. Reifarth,[1,‖] P. Tischhauser,[2,¶] C. Ugalde,[2,**] and M. Wiescher[2]

Any further improvement of the stellar rate requires an extension of the experimental data toward lower energies. Since the present technical possibilities appear to be exhausted, a reduction of the remaining uncertainty can probably only be achieved in an underground laboratory, where the cosmic-ray-induced γ background can be avoided.

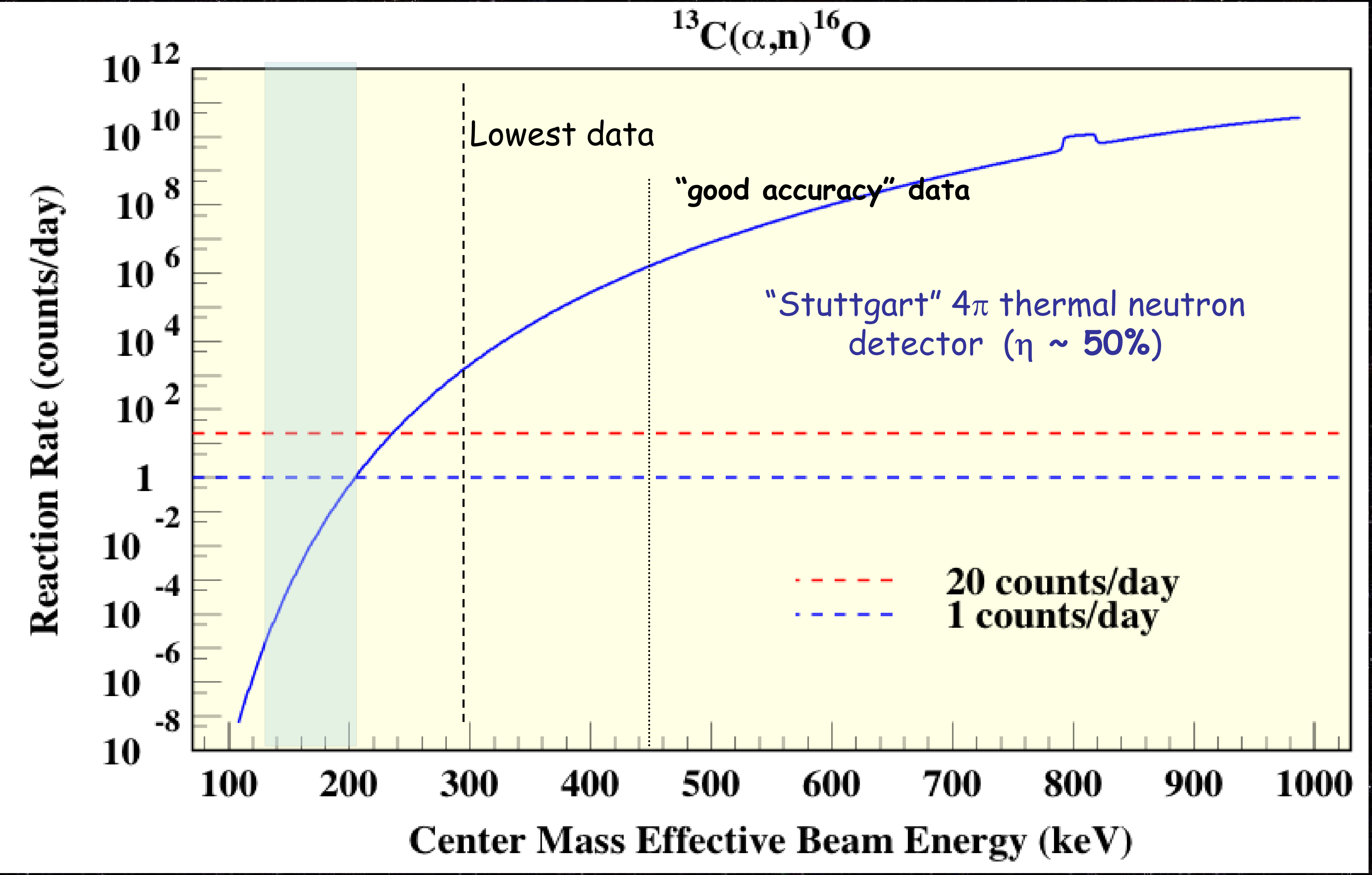
LUNA estimate



Expected rate @ LUNA

$^{13}C(\alpha,n)^{16}O$

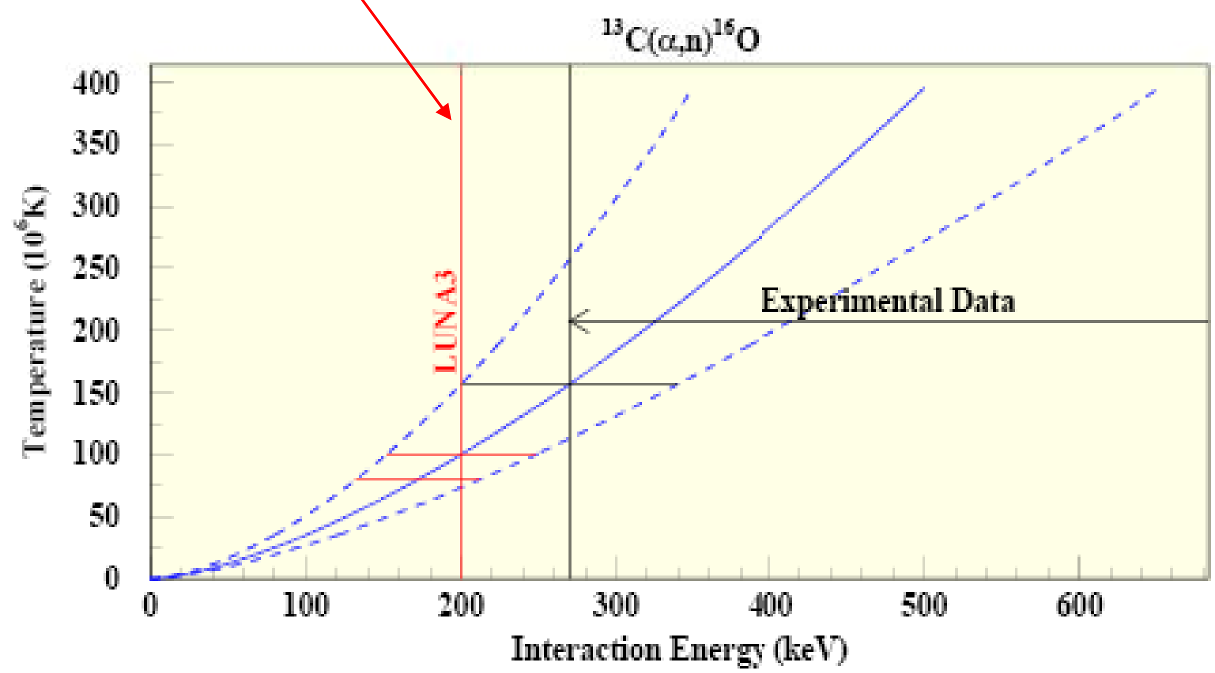
Alpha beam intensity = 200 μA;
Target: ^{13}C, 2 10^{17} at/cm^2 (99% ^{13}C-enriched),
$E_{beam} \leq 0.8$ MeV (lab);



Expected sensitivity @ LUNA

Reaction	Q	Product	T_6	E_{0cm}	ΔE_{0cm}
$^{13}C(\alpha,n)^{16}O$	2215	n	80	172.3	39.8
			100	199.9	47.9
			200	317.5	85.4
			300	415.9	119.7
$^{22}Ne(\alpha,n)^{25}Mg$	-478	n	200	461.5	103.0
			300	604.8	144.4

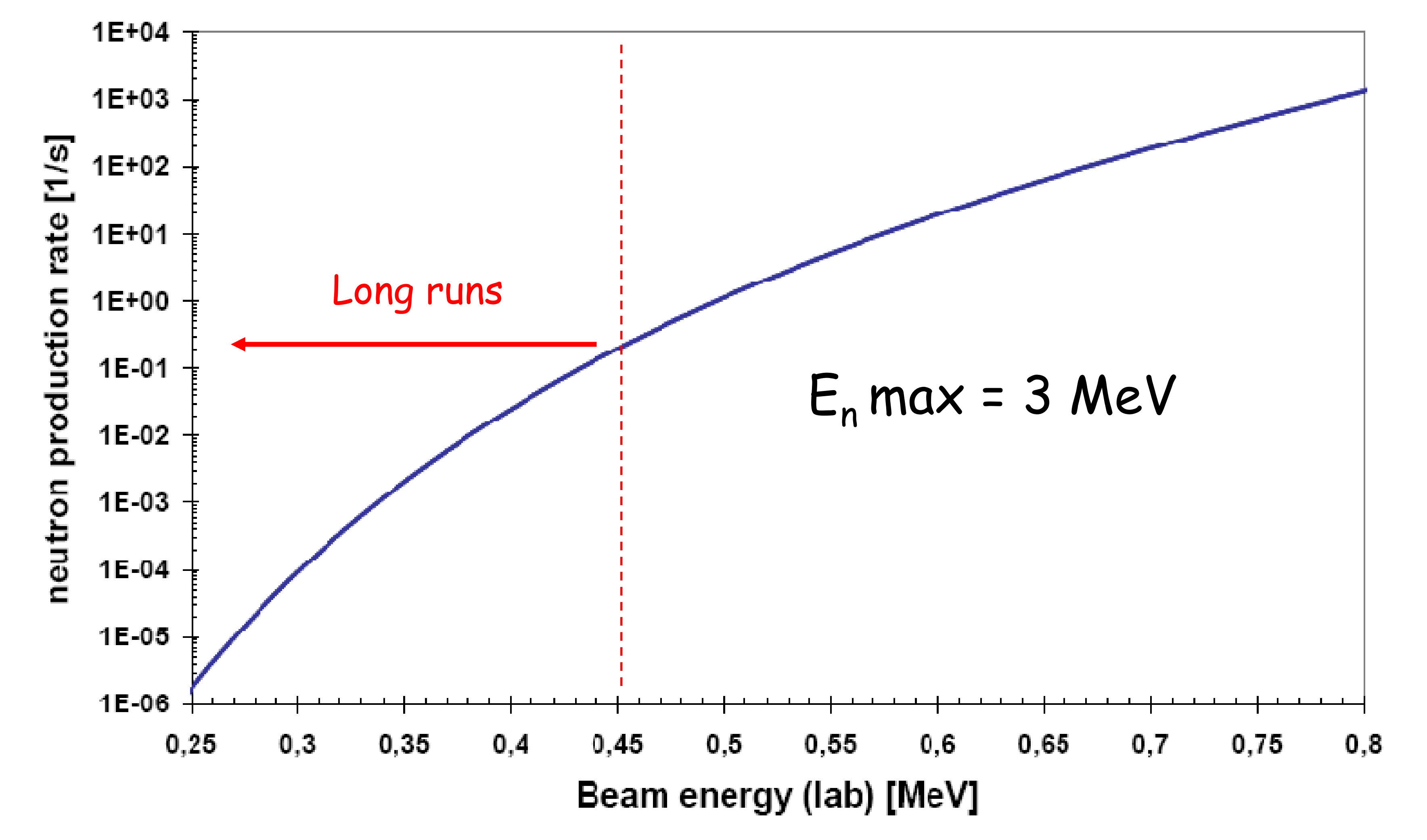
With bck. ~ 1 cnt/day



n production @ LUNA

$^{13}C(\alpha,n)^{16}O$

Alpha beam intensity = 200 μA;
Target: ^{13}C, 2 10^{17} at/cm^2 (99% ^{13}C-enriched),
$E_{beam} \leq$ 0.8 MeV (lab);



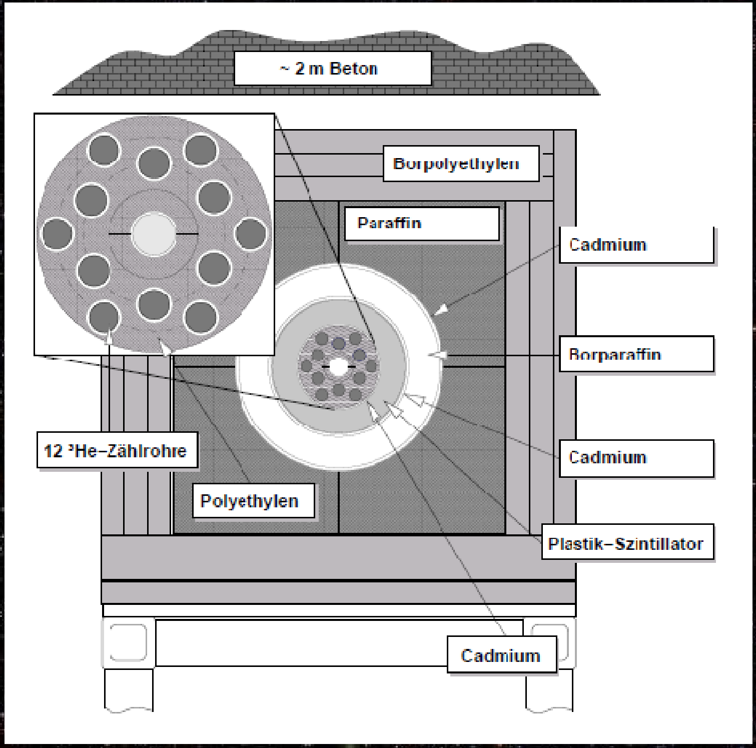
Michael Jaeger, PhD thesis, Stuttgart Univ., 2001

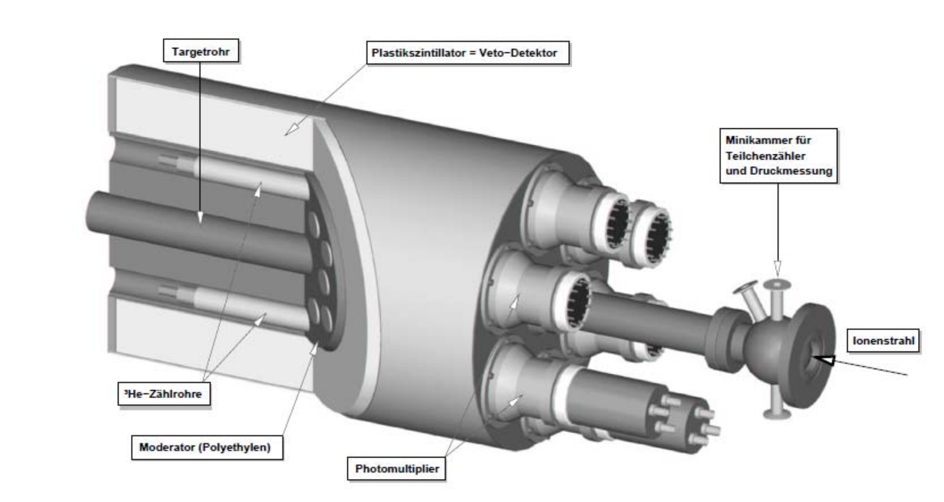
VOLUME 87, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 2001

$^{22}Ne(\alpha,n)^{25}Mg$: The Key Neutron Source in Massive Stars

M. Jaeger,[1] R. Kunz,[1] A. Mayer,[1] J. W. Hammer,[1] G. Staudt,[2] K. L. Kratz,[3] and B. Pfeiffer[3]

A new 4π neutron detector has been designed and tailored to this specific reaction. The reaction neutrons were thermalized in a cylindrical polyethylene moderator and subsequently captured by a setup of 12 proportional counters. The counters were arranged in two rings at radii optimized for the neutron energy of interest for this specific reaction. With this design, an absolute detection efficiency up to 50%, a low sensitivity for background neutrons, as well as some neutron energy information could be obtained simultaneously. The neutron detector assembly was surrounded by a plastic scintillator detector which served as a veto counter to suppress cosmic-ray-induced background. Several layers of passive shielding material (paraffin wax, polyethylene, boron, and cadmium) were arranged around the 4π neutron detector.





Possible development: high efficiency, (moderate) energy resolution, bck. reduction

$\eta \sim 10\%$

A large solid angle multiparameter neutron detector

G. Ricco, M. Anghinolfi, P. Corvisiero, E. Durante, S. Maggiolo, P. Prati, A. Rottura and M. Taiuti

Nuclear Instruments and Methods in Physics Research A307 (1991) 374–379

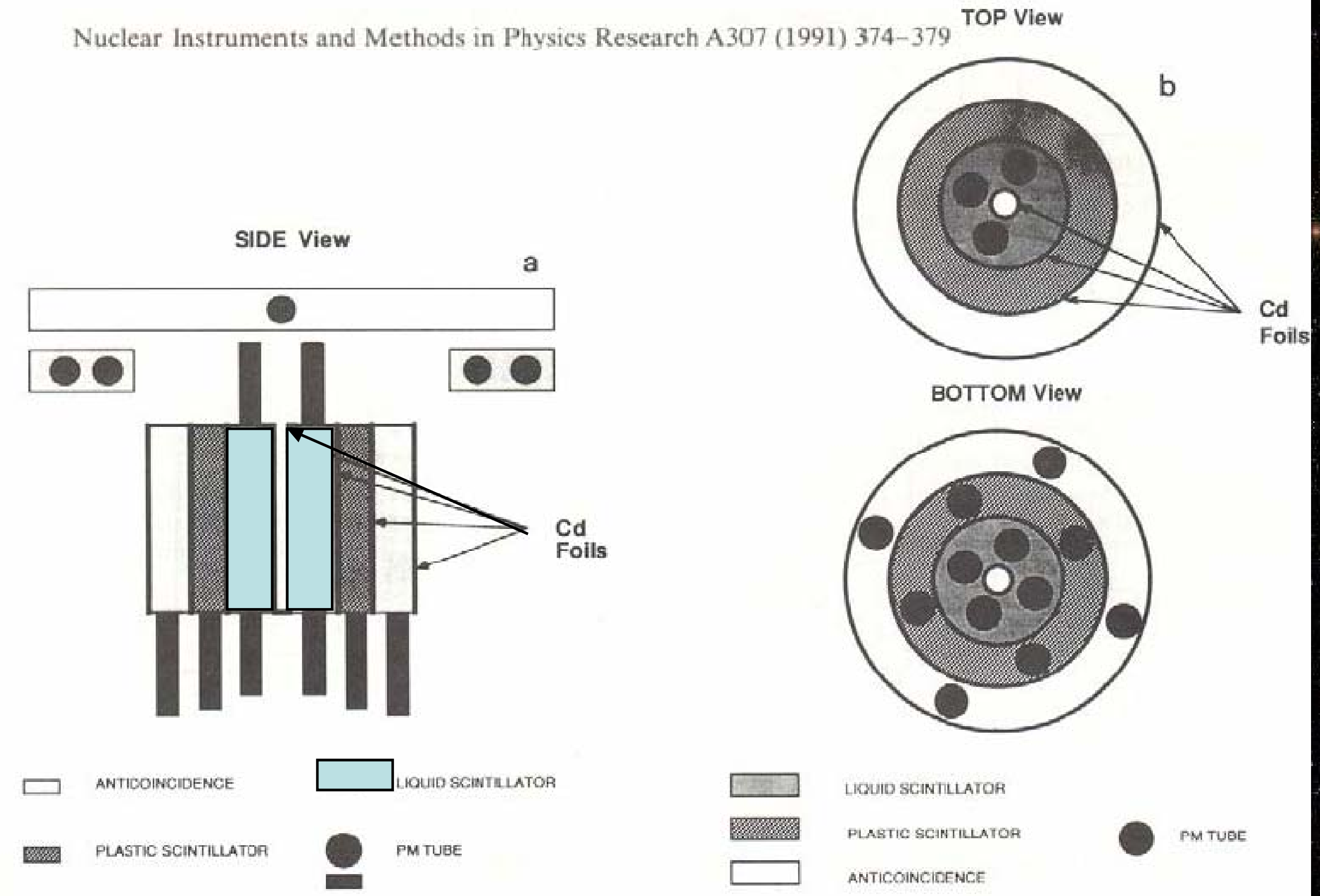
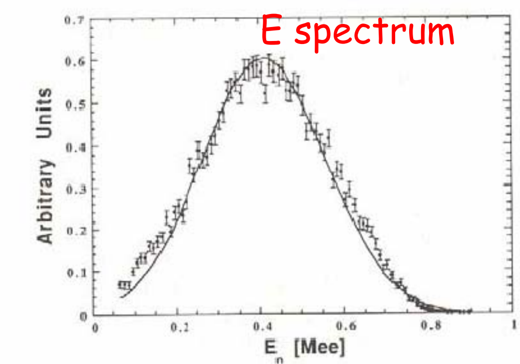
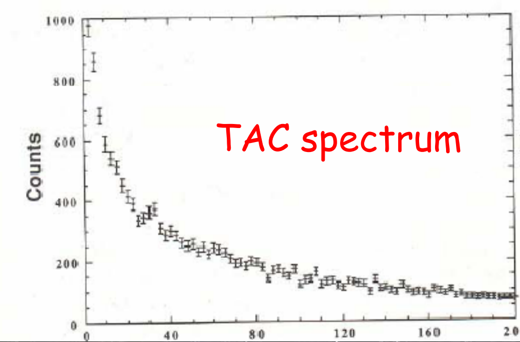
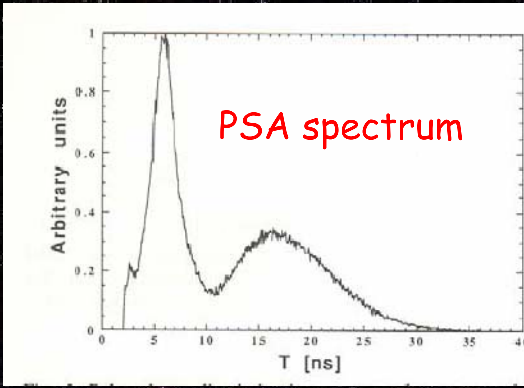


Fig. 1. Spectrometer geometry and composition. (a) Top and bottom view. (b) Side view.





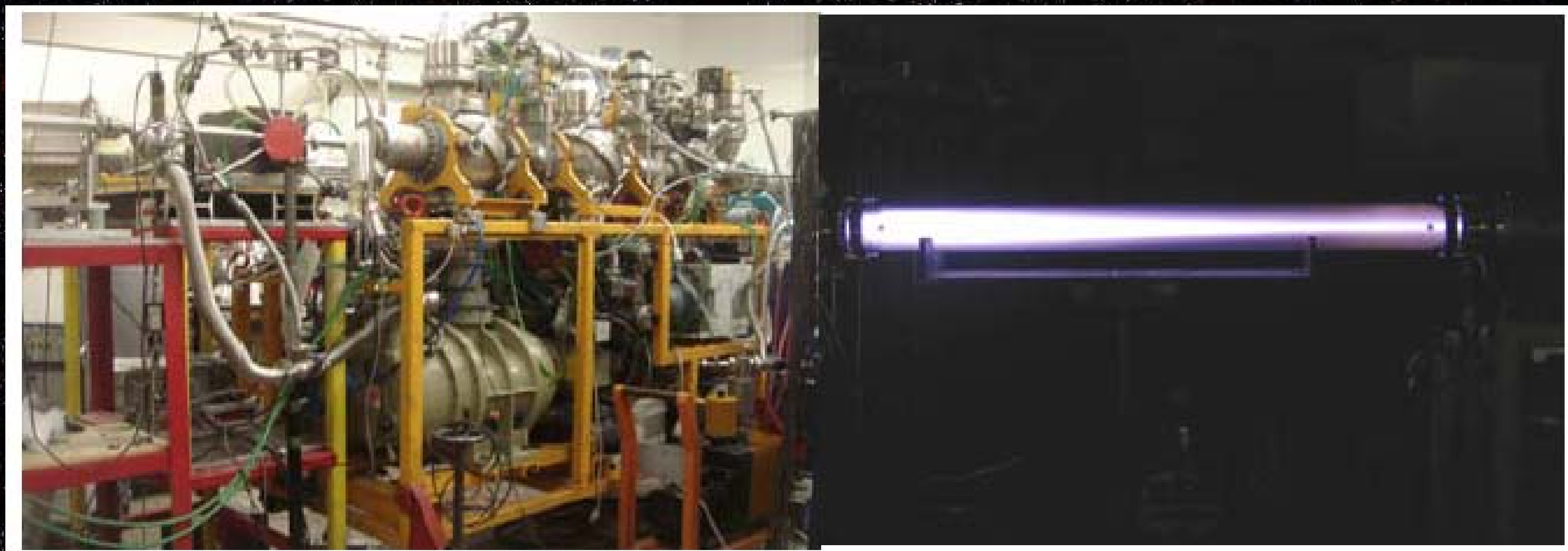


VOLUME 87, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 2001

$^{22}Ne(\alpha,n)^{25}Mg$: The Key Neutron Source in Massive Stars

M. Jaeger,[1] R. Kunz,[1] A. Mayer,[1] J. W. Hammer,[1] G. Staudt,[2] K. L. Kratz,[3] and B. Pfeiffer[3]

The RHINOCEROS windowless gas-target (developed in Stuttgart now in Notre Dame, IN)

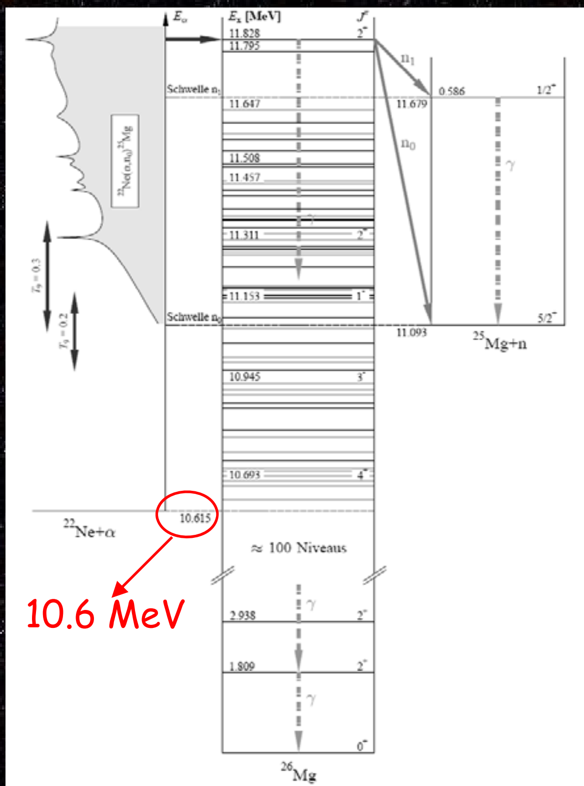


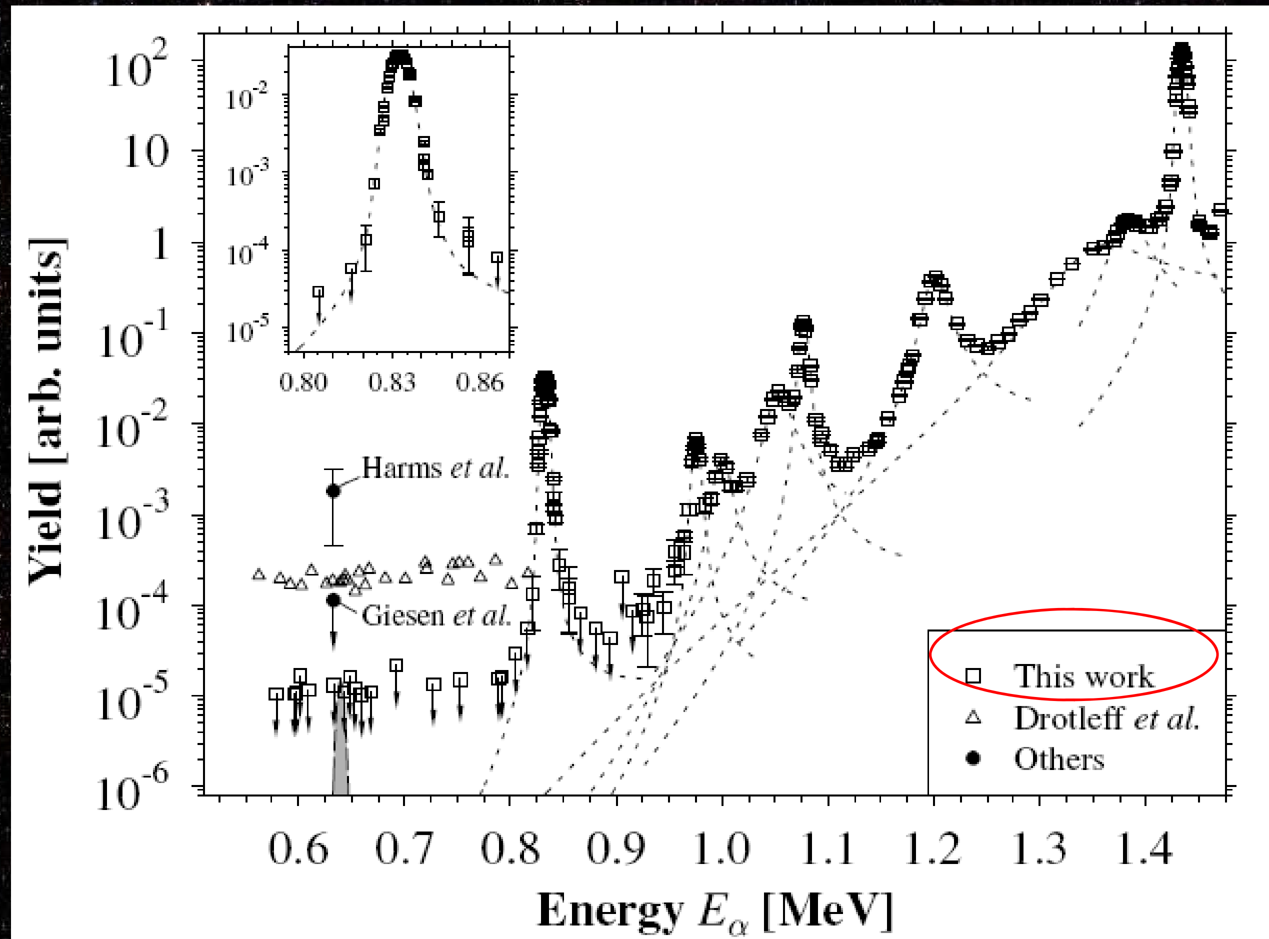
The 99.9% enriched 22Ne target gas was continuously re-circulated to allow long term experiments in a specially designed reaction chamber with highly polished gold-plated walls. The high chemical purity of the gas was sustained by three purification elements: a cryogenic trap at liquid nitrogen temperature, a zeolite trap, and a getter purifier. The pressure was reduced by the differential pumping stages of the RHINOCEROS facility to several times 10^{-8} mbar.

VOLUME 87, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 2001

$^{22}Ne(\alpha,n)^{25}Mg$: The Key Neutron Source in Massive Stars

M. Jaeger,[1] R. Kunz,[1] A. Mayer,[1] J. W. Hammer,[1] G. Staudt,[2] K. L. Kratz,[3] and B. Pfeiffer[3]





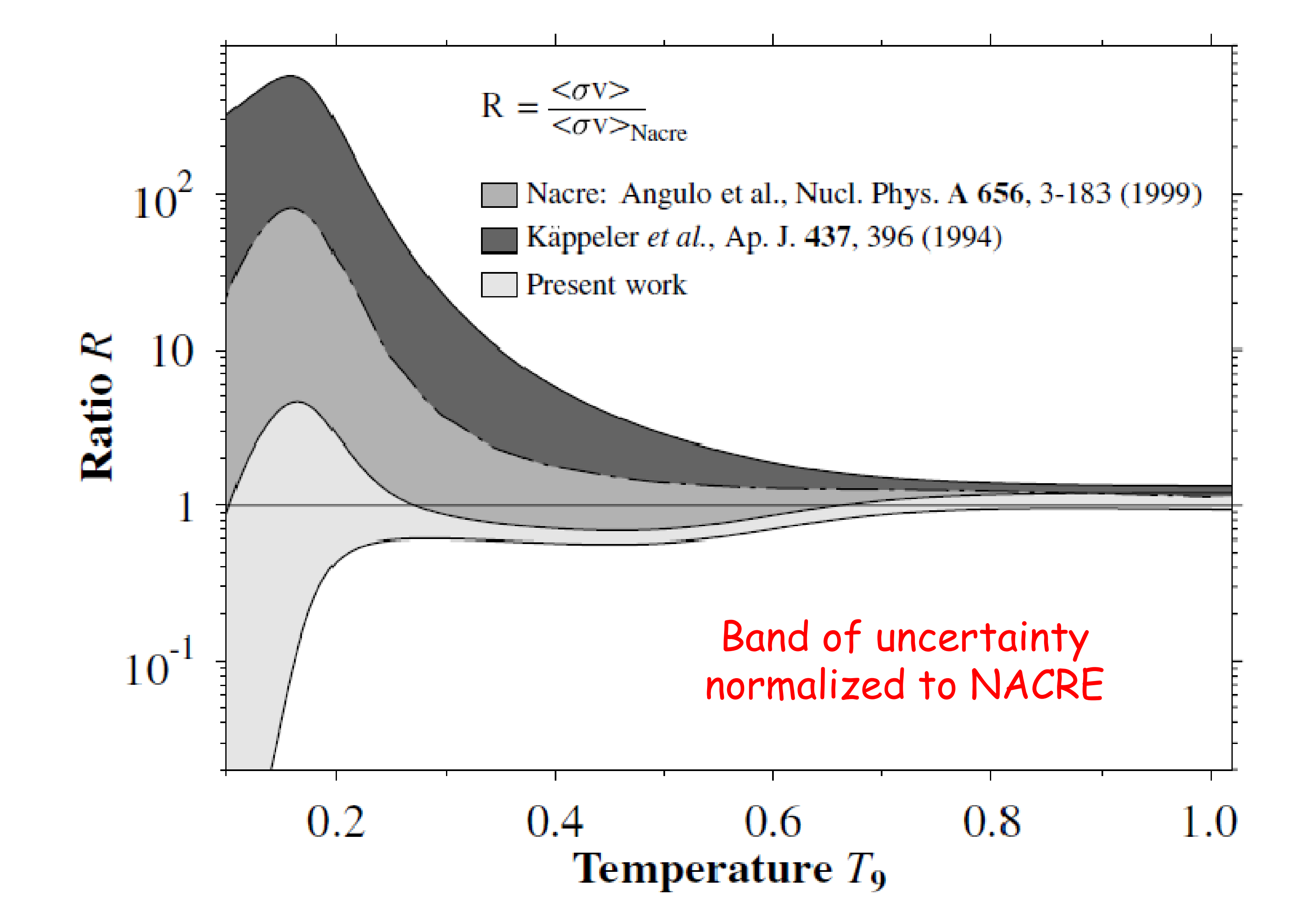
Moreover, $^{22}Ne(\alpha,n)^{25}Mg$ competes with $^{22}Ne(\alpha,\gamma)^{26}Mg$ and therefore the σ of both the reactions is needed

Even with such low-energy neutrons, a coupled n-γ detector could be a step forward

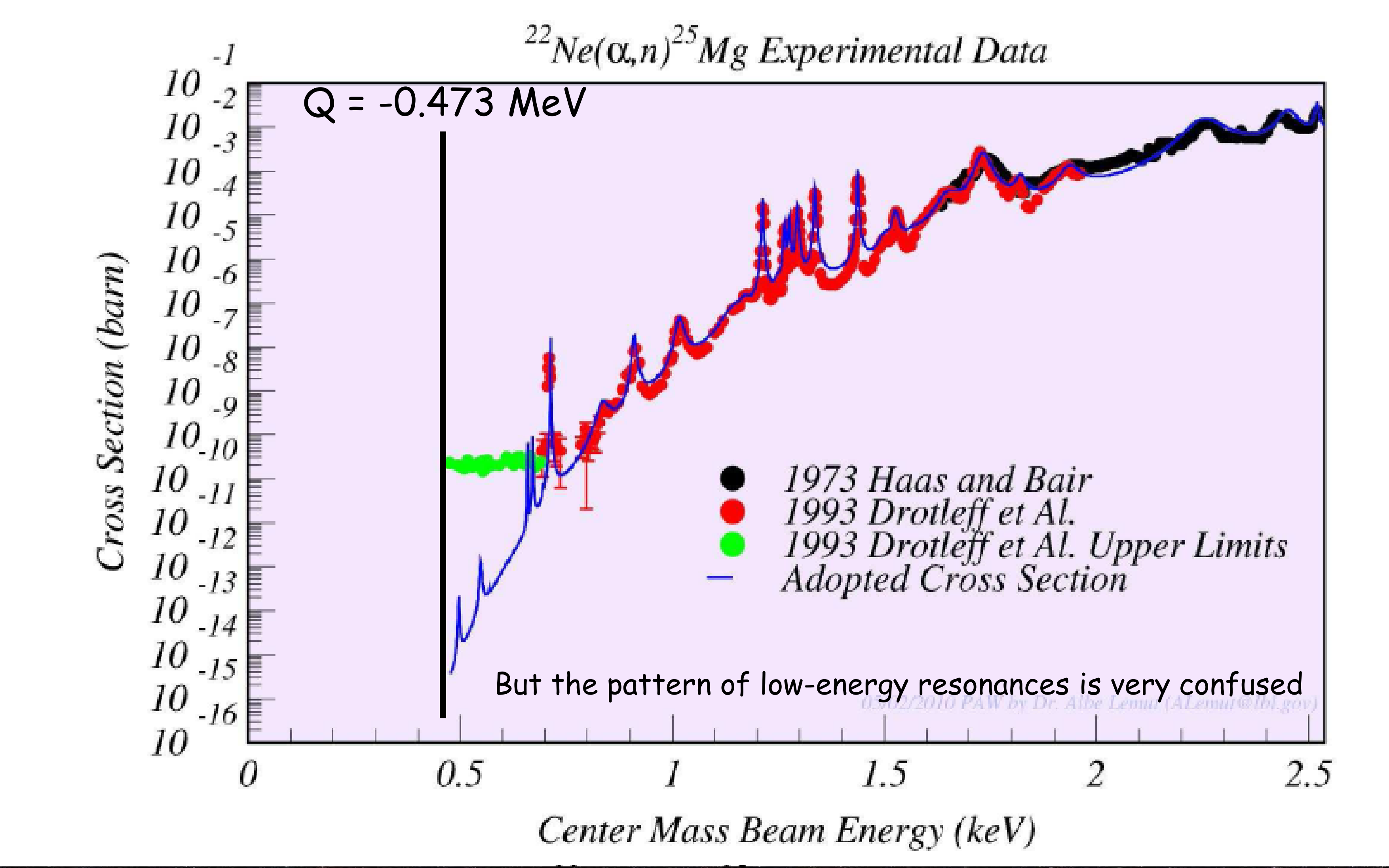
VOLUME 87, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 2001

$^{22}Ne(\alpha,n)^{25}Mg$: The Key Neutron Source in Massive Stars

M. Jaeger,[1] R. Kunz,[1] A. Mayer,[1] J. W. Hammer,[1] G. Staudt,[2] K. L. Kratz,[3] and B. Pfeiffer[3]



LUNA estimate

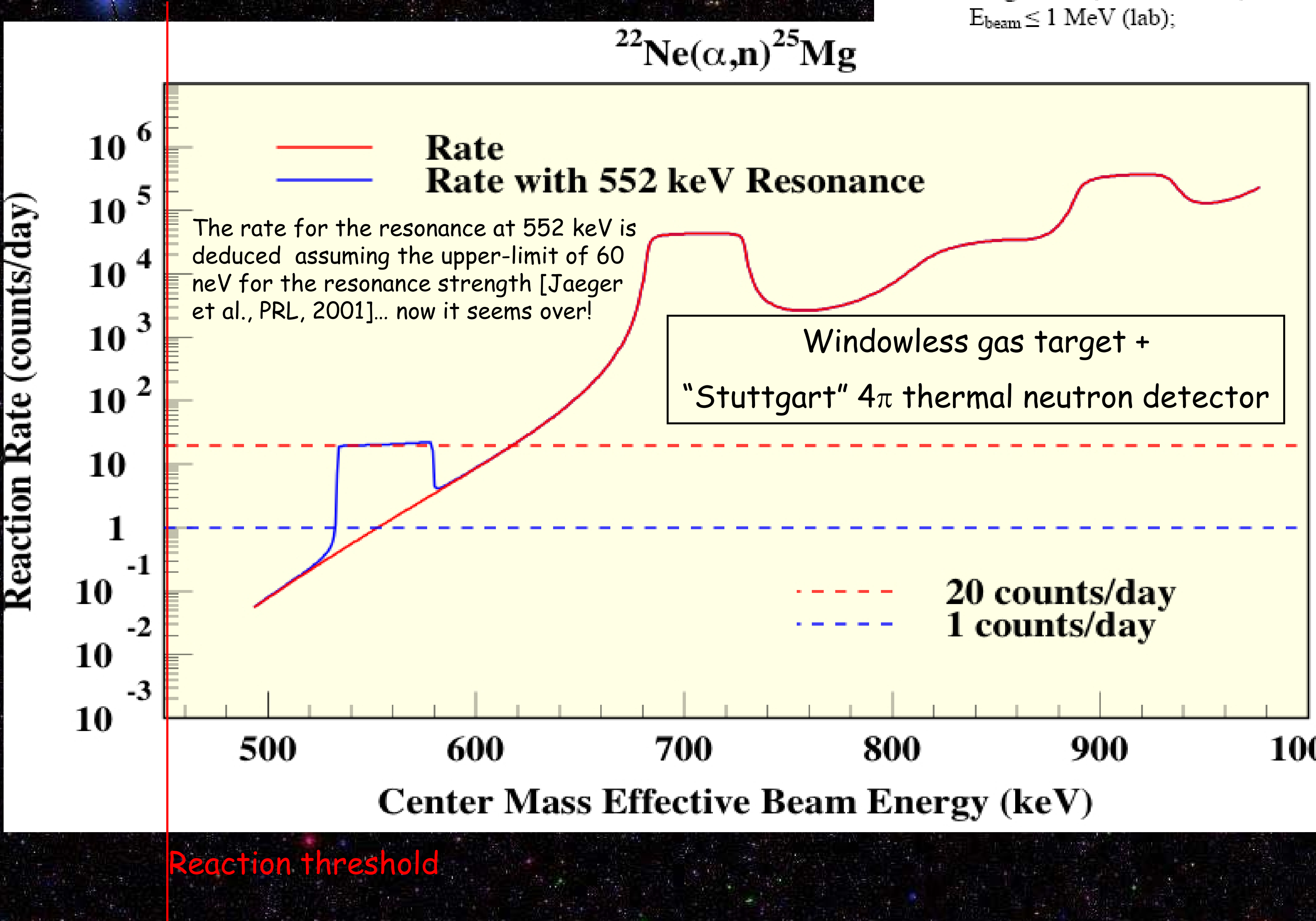


Last estimate by A. Lemut, LBL, Ca

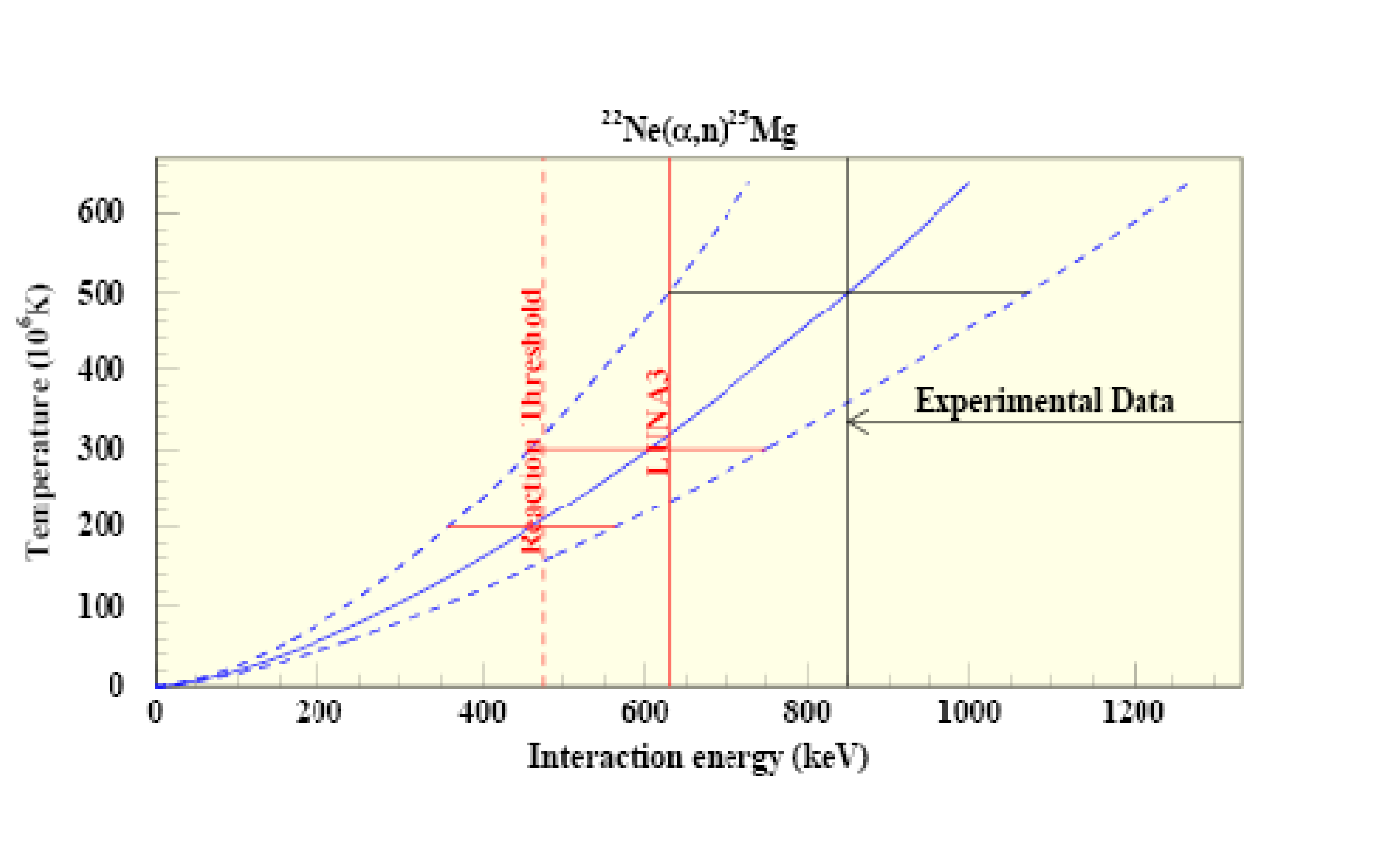
Expected rate @ LUNA

$^{22}Ne(\alpha,n)^{25}Mg$

Alpha beam intensity = 200 μA,
Target: ^{22}Ne, 1 10^{18} at/cm^2,
$E_{beam} \leq 1$ MeV (lab);



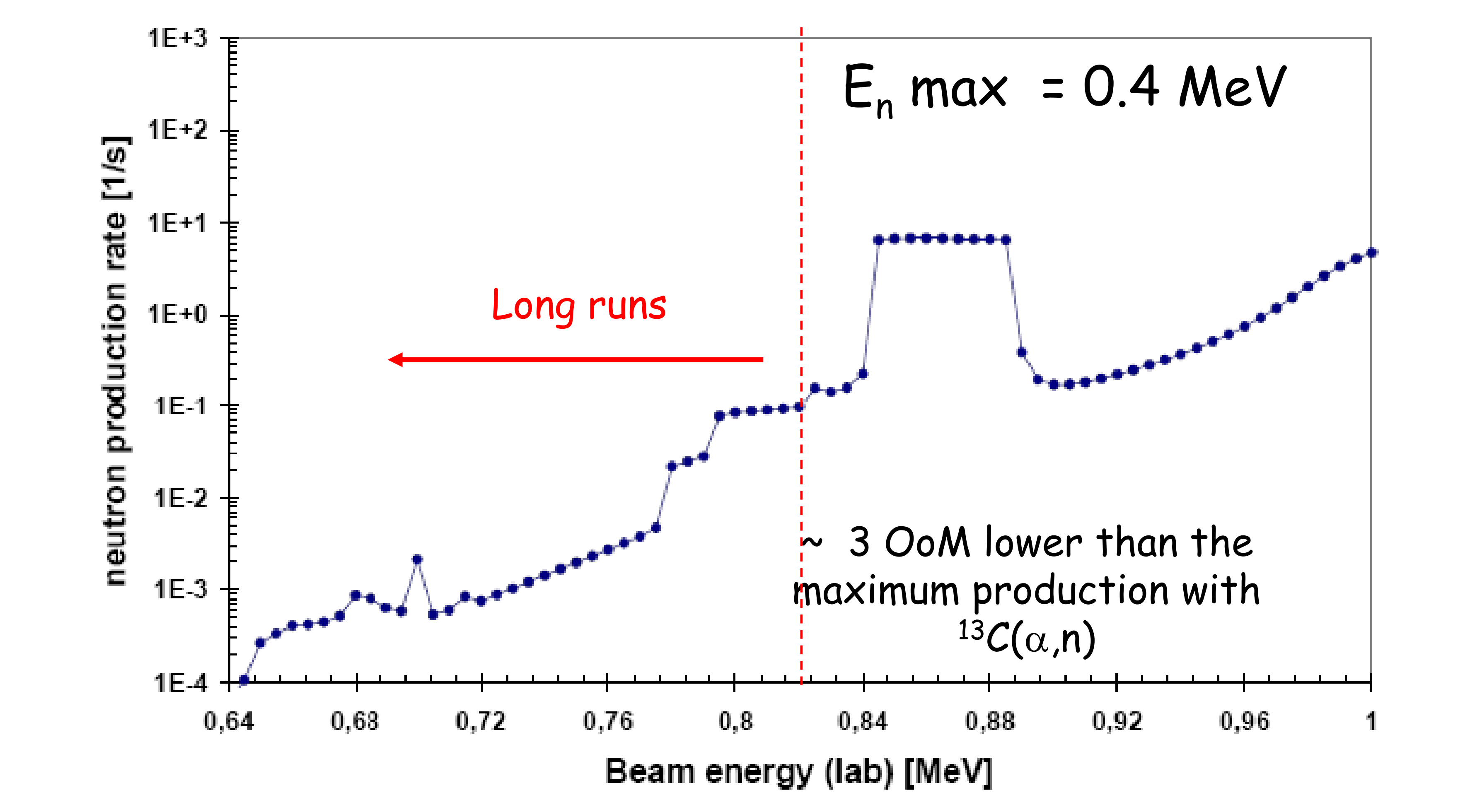
Expected sensitivity @ LUNA



n production @ LUNA

$^{22}Ne(\alpha,n)^{25}Mg$

Alpha beam intensity = 200 µA,
Target: ^{22}Ne, 1 10^{18} at/cm^2,
$E_{beam} \leq$ 1 MeV (lab);



Neutron background @ Gran Sasso

P.Belli et al., Nuovo Cimento 101A n. 6 (1989)

Neutron Energy	Flux ($cm^{-2}\ s^{-1}$)
0.025 eV	$(1.98 \pm 0.05)\ 10^{-6}$
0.05 – 10^3 eV	$(1.08 \pm 0.02)\ 10^{-6}$
1 keV – 2.5 MeV	$(0.54 \pm 0.07)\ 10^{-6}$
> 2.5 MeV	$(0.23 \pm 0.07)\ 10^{-6}$

→ $\sim 2.85\ 10^3\ m^{-2}\ d^{-1}$

(To be compared with $\sim 5.5\ 10^6\ m^{-2}\ d^{-1}$ cosmic neutrons at sea level)

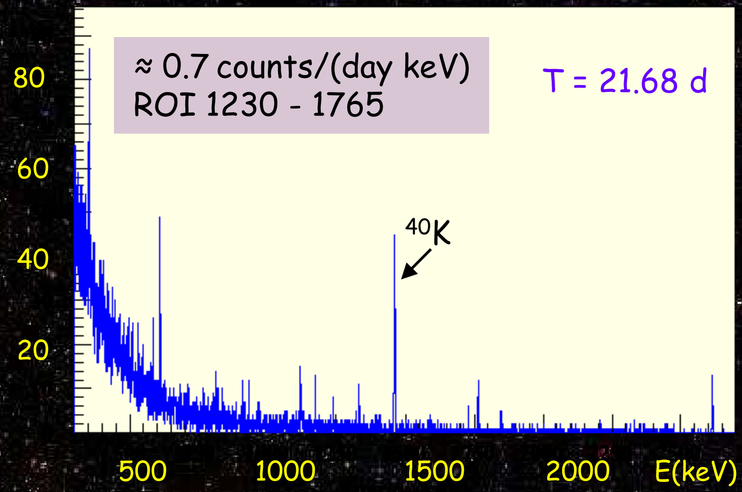
Unless the fast component is resolved (with a neutron spectrometer), a background rate of a few hundreds count/day is expected with a real detector installed at Gran Sasso

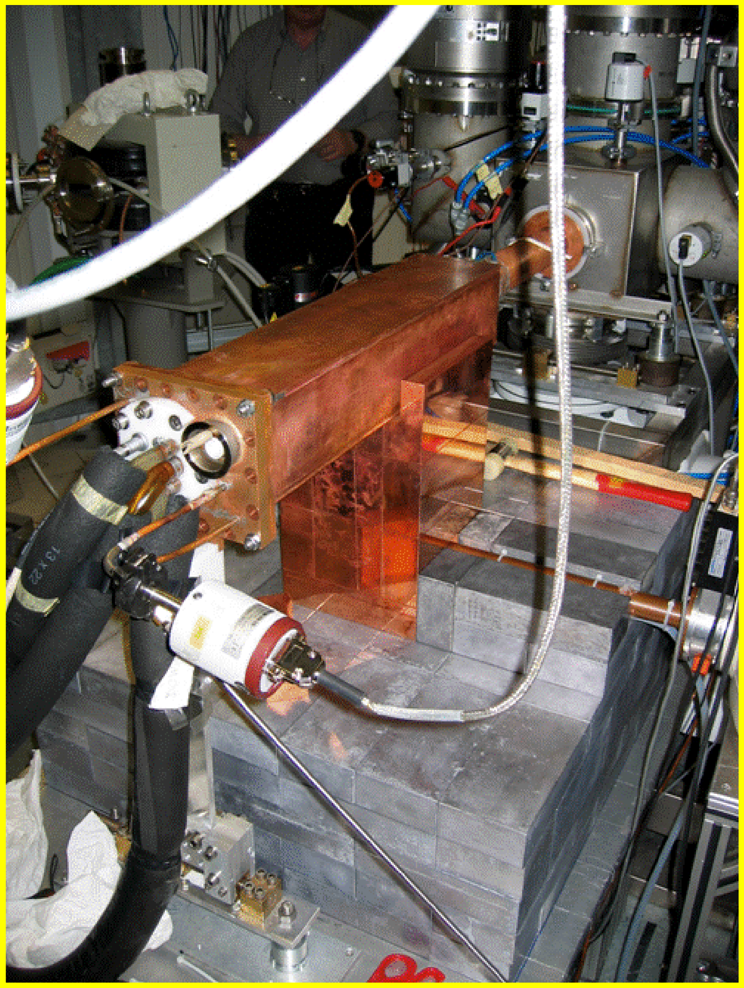
↓

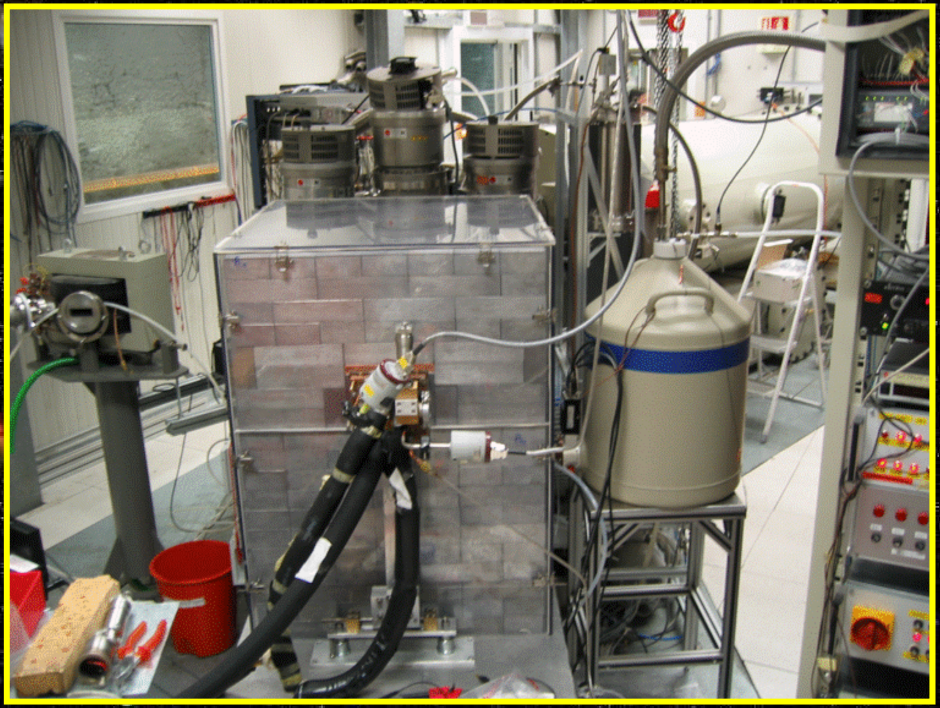
Passive shielding is required to achieve a background rate of ~ 1 count/day

Passive shielding is very effective underground: e.g. the LUNA set-up for $^{3}He(\alpha,\gamma)^{7}Be$

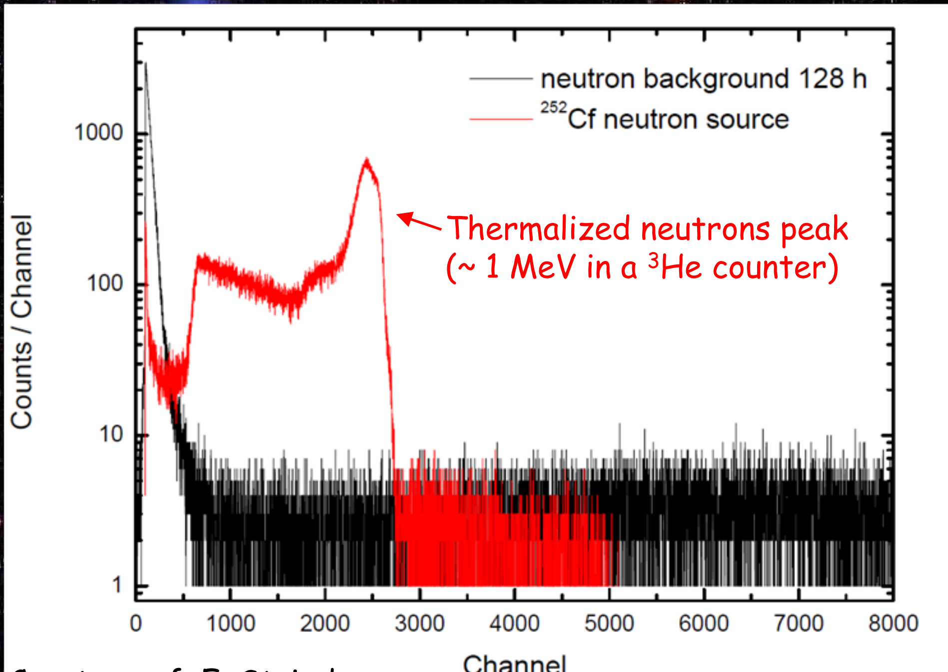
0.4 m^3 Pb and Cu shield → bck reduction: 10^5







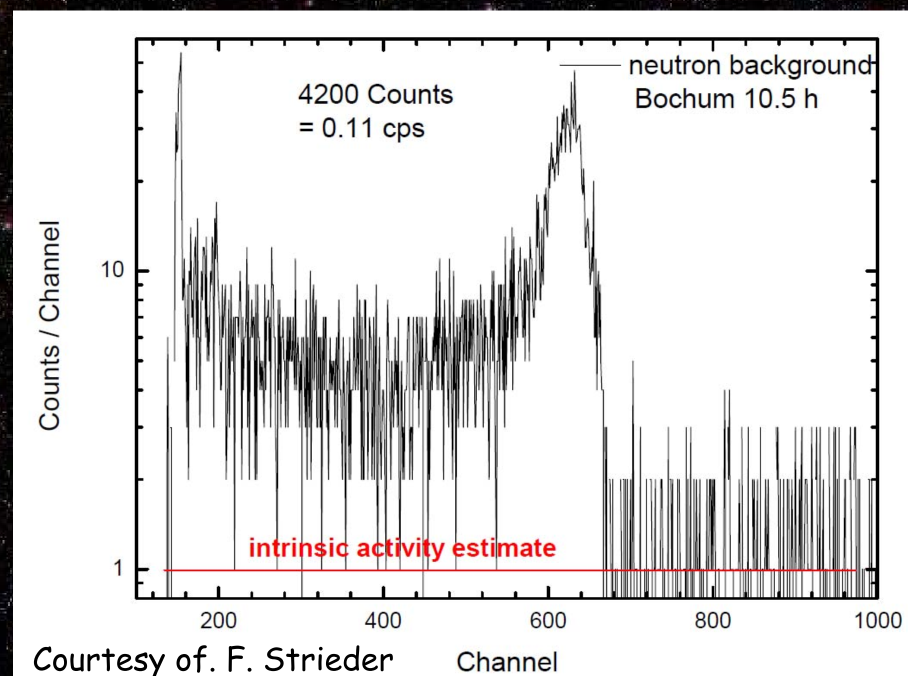
Not only shielding..



Courtesy of. F. Strieder

Spectrum collected at Boulby mine with the 4π Stuttgart detector

Spectrum collected at Bochum with the 4π Stuttgart detector



Courtesy of. F. Strieder

The flat bck. is most likely intrinsic α background in the ^{3}He tubes and extends to about 5 MeV. Similar indications from Notre Dame.

Summary and open issues

• Significative room for improve the study of $^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$: in the first case very likely an underground experiment could definitively solve the problem. $0.1 < E_a < 1$ MeV for both the experiments.

• New neutron detectors: Maybe a combination of previous designs (e.g. an "active" moderator + Cd foils + high resolution γ detectors).

• Proper passive shielding and clean detecting materials must be developed to fully exploit the advantages offered by the underground environment.

• Technical solution for using the same detector for both the experiments.

• ^{13}C target production to enhance purity, stability, etc.

• New gas target with technical solution to prevent beam induced n background and contaminations