CIELO project: building bridges between nuclear data communities around the world

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IAEA, Vienna,
July 11, 2024

LA-UR-24-25743

In memory of Eric Bauge, Our longstanding collaborator and friend

Thanks to Toshihiko Kawano for the photo

Nuclear physics

- microscopic optical model
- uncertainties & covariances

Leadership

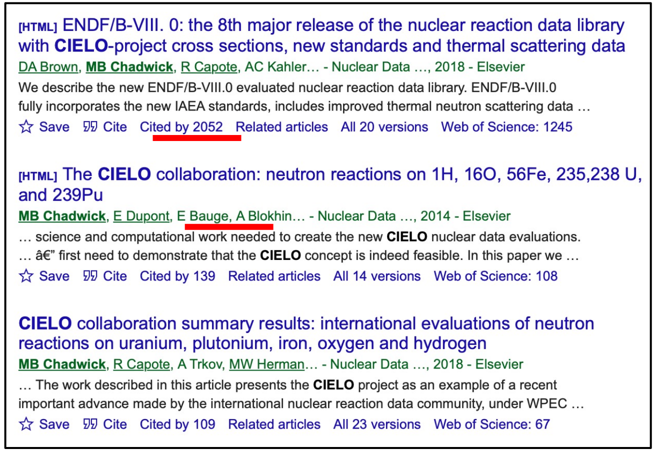
- excellence at Bruyeres
- numerous collab. agreements
- LANSCE exp. with CEA
- IAEA, OECD/WPEC

Varenna conferences, PNDND*2, CNR09

Collaborative International Evaluation Library Organization (CIELO), 2013-2018, led to much-improved ENDF nuclear data

- Initiated in 2013 via the OECD/NEA/WPEC
- Numerous collaboration meetings
- 2 summary papers in ND proceedings
- Led to advances included in ENDF/B-VIII.0 and JEFF
- Transitioned to IAEA/INDEN project

A CIELO collaboration team photo, from the kick-off meeting on 5-8 November 2013 in Geel, Belgium.



[HTML] ENDF/B-VIII. 0: the 8th major release of the nuclear reaction data library with **CIELO**-project cross sections, new standards and thermal scattering data
DA Brown, **MB Chadwick**, R Capote, AC Kahler… - Nuclear Data …, 2018 - Elsevier
We describe the new ENDF/B-VIII.0 evaluated nuclear reaction data library. ENDF/B-VIII.0 fully incorporates the new IAEA standards, includes improved thermal neutron scattering data …
☆ Save 99 Cite Cited by 2052 Related articles All 20 versions Web of Science: 1245

[HTML] The **CIELO** collaboration: neutron reactions on 1H, 16O, 56Fe, 235,238 U, and 239Pu
MB Chadwick, E Dupont, E Bauge, A Blokhin… - Nuclear Data …, 2014 - Elsevier
… science and computational work needed to create the new **CIELO** nuclear data evaluations. … â€" first need to demonstrate that the **CIELO** concept is indeed feasible. In this paper we …
☆ Save 99 Cite Cited by 139 Related articles All 14 versions Web of Science: 108

CIELO collaboration summary results: international evaluations of neutron reactions on uranium, plutonium, iron, oxygen and hydrogen
MB Chadwick, R Capote, A Trkov, MW Herman… - Nuclear Data …, 2018 - Elsevier
… The work described in this article presents the **CIELO** project as an example of a recent important advance made by the international nuclear reaction data community, under WPEC …
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Cielo Collaboration: new measurements & evaluations

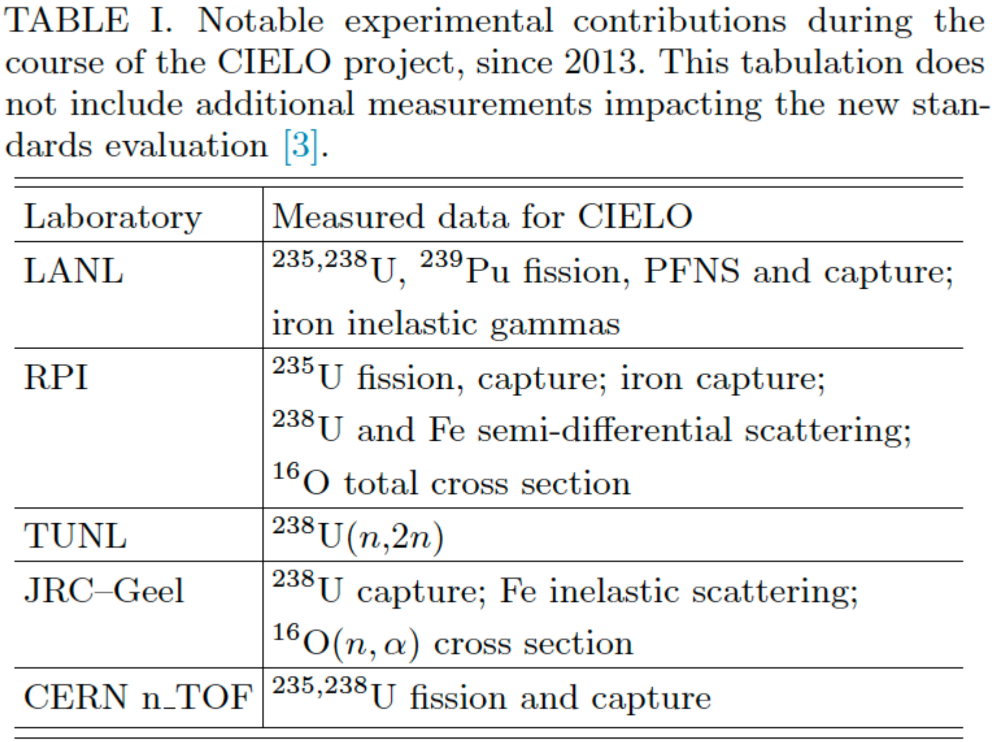


TABLE I. Notable experimental contributions during the course of the CIELO project, since 2013. This tabulation does not include additional measurements impacting the new standards evaluation [3].

Laboratory	Measured data for CIELO
LANL	^{235,238}U, ^{239}Pu fission, PFNS and capture; iron inelastic gammas
RPI	^{235}U fission, capture; iron capture; ^{238}U and Fe semi-differential scattering; ^{16}O total cross section
TUNL	^{238}U$(n,2n)$
JRC–Geel	^{238}U capture; Fe inelastic scattering; ^{16}O(n,α) cross section
CERN n_TOF	^{235,238}U fission and capture

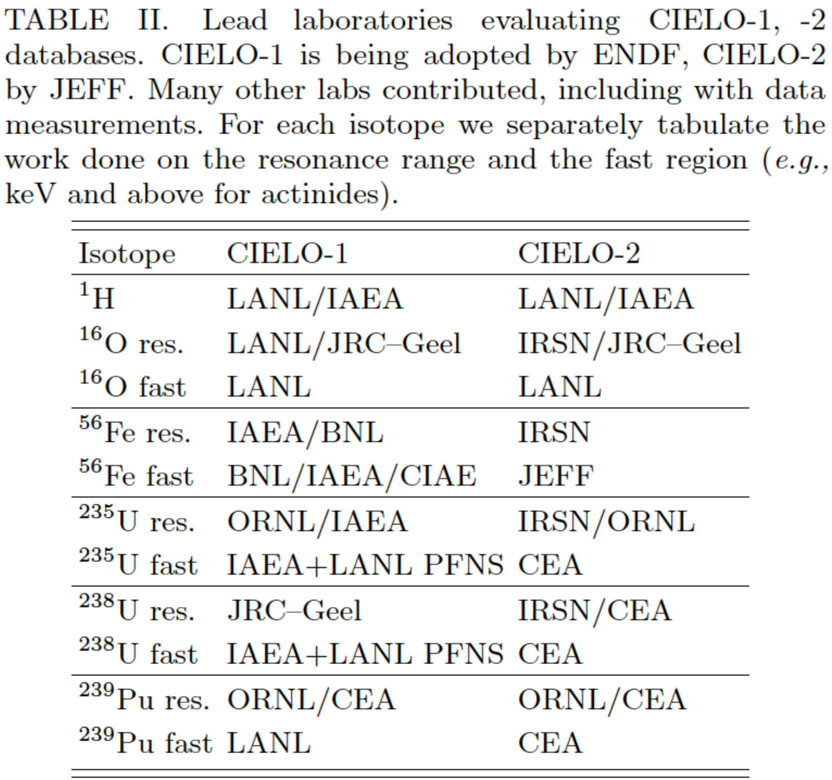
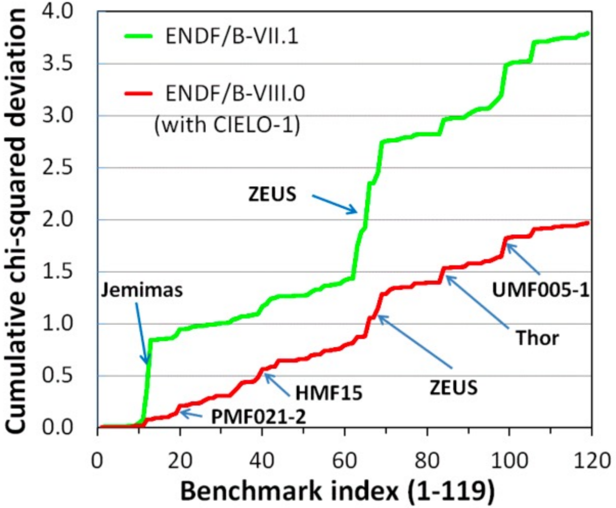


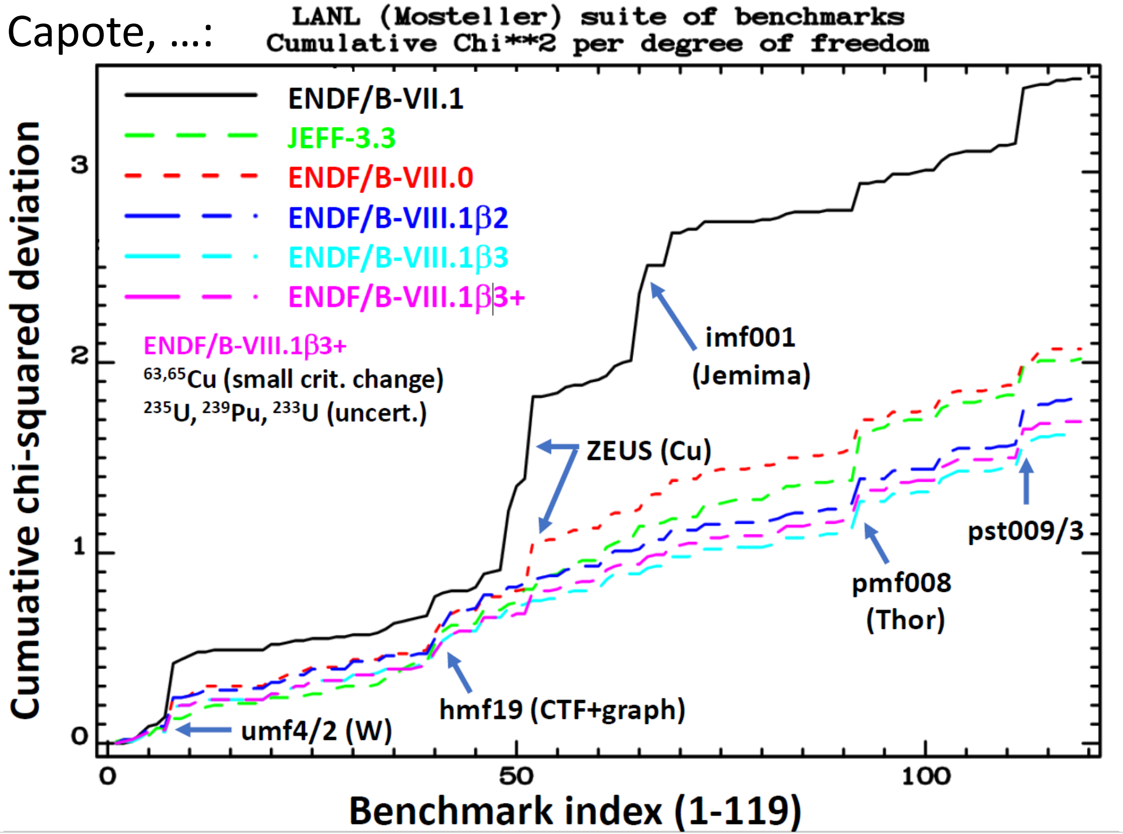
TABLE II. Lead laboratories evaluating CIELO-1, -2 databases. CIELO-1 is being adopted by ENDF, CIELO-2 by JEFF. Many other labs contributed, including with data measurements. For each isotope we separately tabulate the work done on the resonance range and the fast region (*e.g.*, keV and above for actinides).

Isotope	CIELO-1	CIELO-2
^{1}H	LANL/IAEA	LANL/IAEA
^{16}O res.	LANL/JRC–Geel	IRSN/JRC–Geel
^{16}O fast	LANL	LANL
^{56}Fe res.	IAEA/BNL	IRSN
^{56}Fe fast	BNL/IAEA/CIAE	JEFF
^{235}U res.	ORNL/IAEA	IRSN/ORNL
^{235}U fast	IAEA+LANL PFNS	CEA
^{238}U res.	JRC–Geel	IRSN/CEA
^{238}U fast	IAEA+LANL PFNS	CEA
^{239}Pu res.	ORNL/CEA	ORNL/CEA
^{239}Pu fast	LANL	CEA

Integral data criticality modeling improvements with CIELO

Thx to Trkov, Capote, …:





CIELO: much discussion on uncertainties, where many different opinions existed

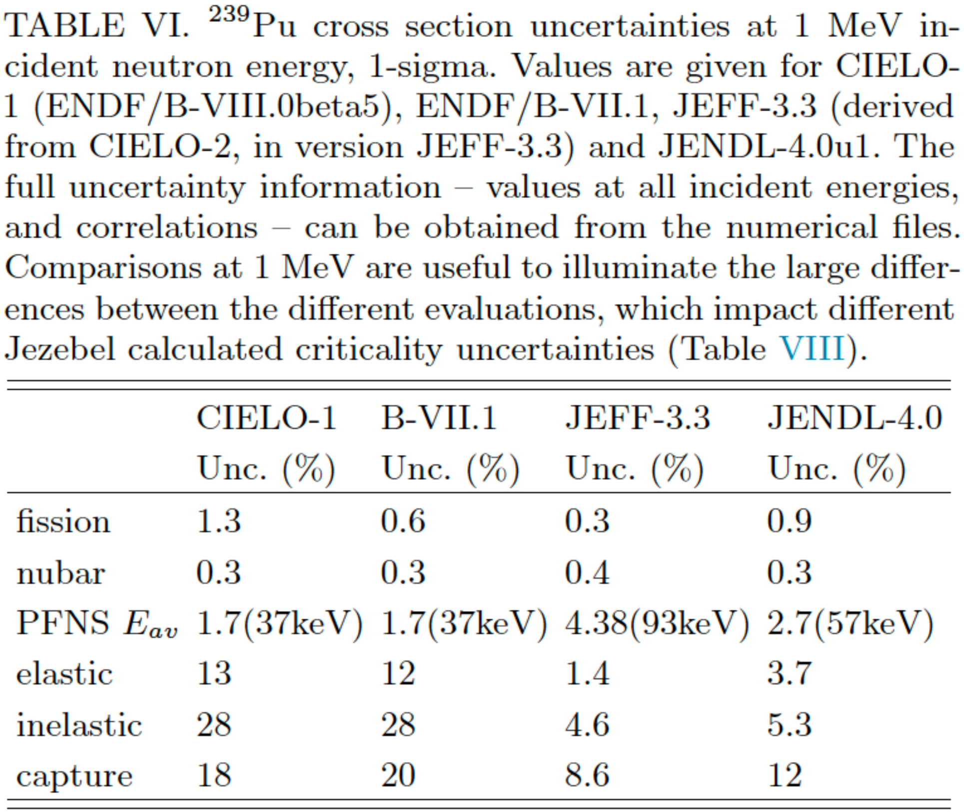
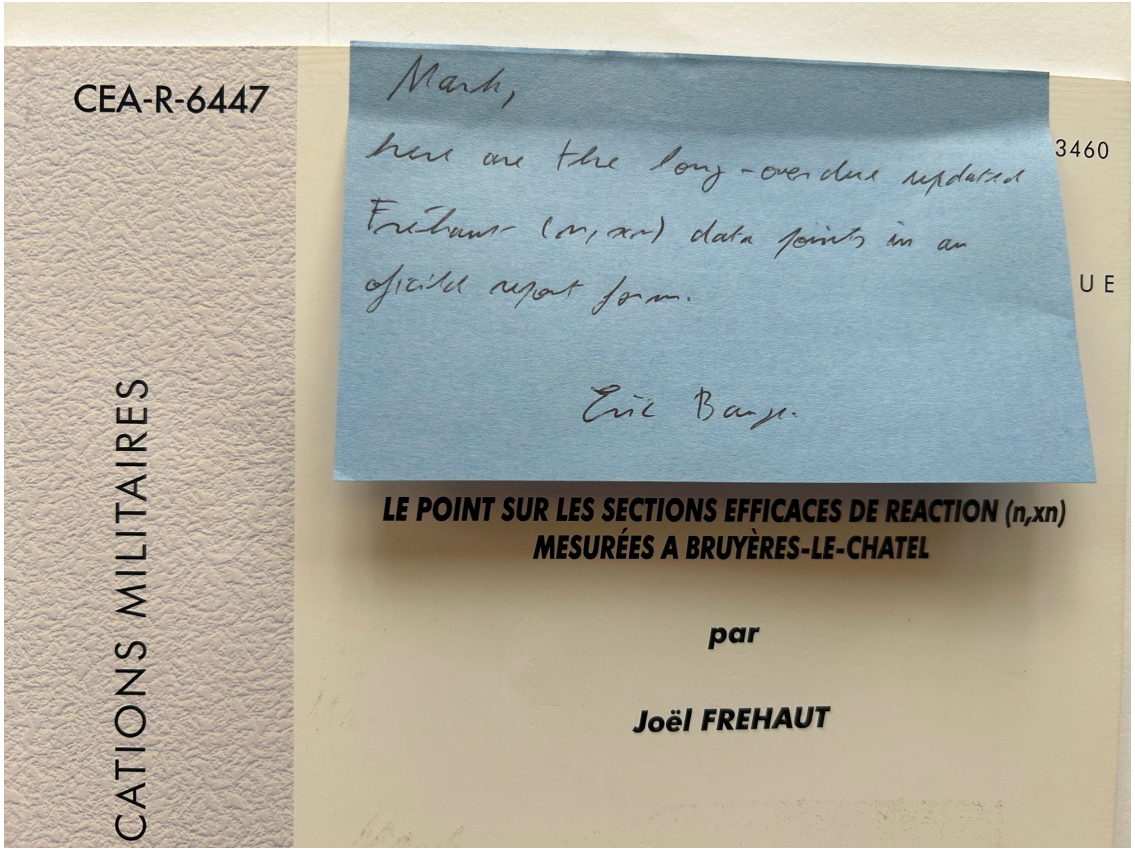


TABLE VI. ^{239}Pu cross section uncertainties at 1 MeV incident neutron energy, 1-sigma. Values are given for CIELO-1 (ENDF/B-VIII.0beta5), ENDF/B-VII.1, JEFF-3.3 (derived from CIELO-2, in version JEFF-3.3) and JENDL-4.0u1. The full uncertainty information – values at all incident energies, and correlations – can be obtained from the numerical files. Comparisons at 1 MeV are useful to illuminate the large differences between the different evaluations, which impact different Jezebel calculated criticality uncertainties (Table VIII).

	CIELO-1 Unc. (%)	B-VII.1 Unc. (%)	JEFF-3.3 Unc. (%)	JENDL-4.0 Unc. (%)
fission	1.3	0.6	0.3	0.9
nubar	0.3	0.3	0.4	0.3
PFNS E_{av}	1.7(37keV)	1.7(37keV)	4.38(93keV)	2.7(57keV)
elastic	13	12	1.4	3.7
inelastic	28	28	4.6	5.3
capture	18	20	8.6	12

One little example that I found when sorting out my docs



CEA-R-6447

3460

U E

CATIONS MILITAIRES

Mark,

here are the long-overdue updated Frehaut (n,xn) data points in an official report form.

Eric Bauge.

LE POINT SUR LES SECTIONS EFFICACES DE REACTION (n,xn) MESURÉES A BRUYÈRES-LE-CHATEL

par

Joël FREHAUT

Compound Nuclear Reactions & Related Topics, CNR*24

Related Topic:

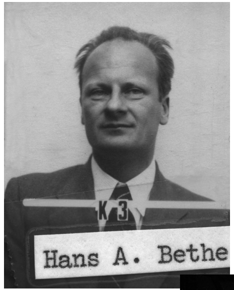
The A=5 ^{5}He compound system created in DT fusion

Some of the first breakthroughs in fusion (1943-1945)

The Lab Director:

The PI, brilliant but difficult:

The team:



Bretscher

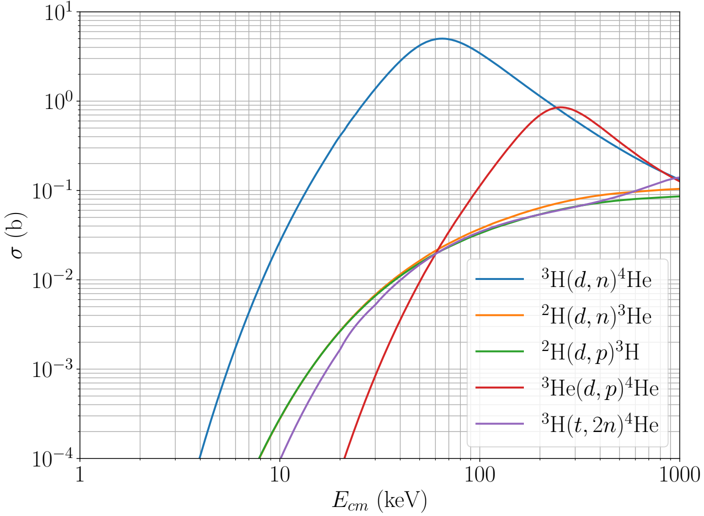
DT has a large 5b resonance at 65 keV (c.m.), but this was not known in 1942.

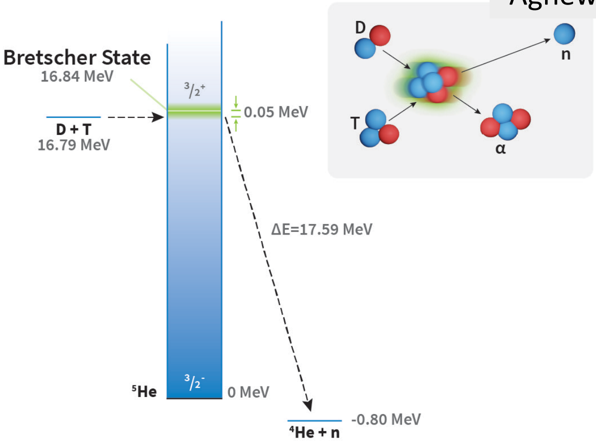
$^4S_{3/2}$ -> $^2D_{3/2}$

$l=0$ $l=2$

(1/2+ early guess proved wrong, since the 5b xs would exceed the unitarity limit. Solved by 1952 (Argo, Agnew, Flowers)

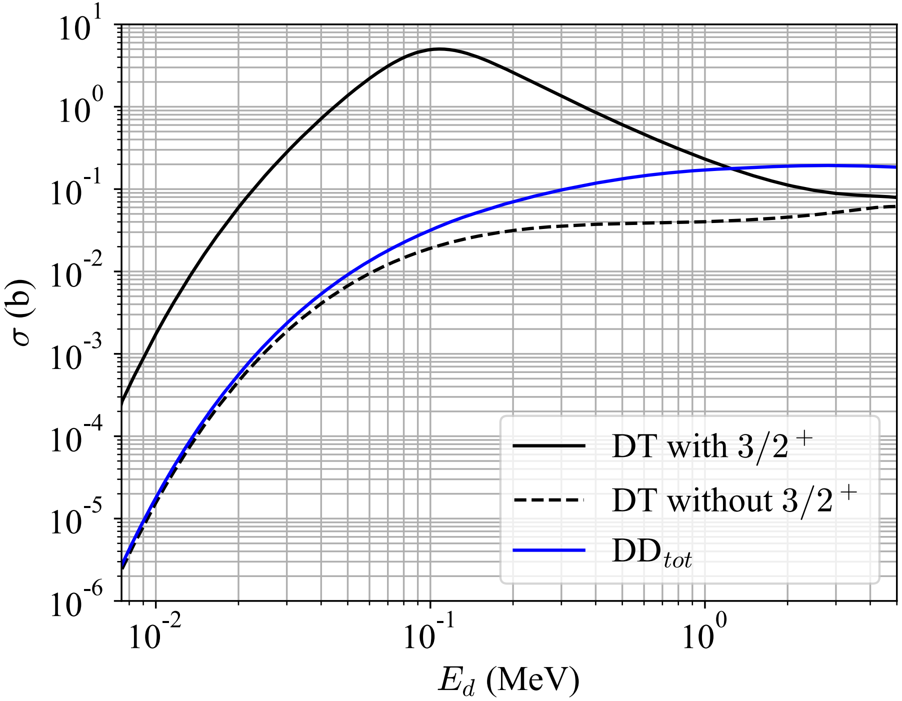
Massive 5 b at 65 keV; for comparison,
^{239}Pu(n,f) is 1.6 b here





A remarkable coincidence of nature is that the 3/2$^+$ A=5 resonance is at 16.84 MeV, close to the 16.79 MeV separation energy, giving a **100x resonant enhancement**

DT would be 100x smaller, like DD, without the resonance



Mark Paris, T-2

Modern analyses of light reactions use R-matrix to combine theory and measurements in all relevant channels (Hale & Paris, ENDF)

Modern R-matrix & ab-initio approaches for DT fusion

Multi-channel R-matrix analysis

LANL, Hale & Paris

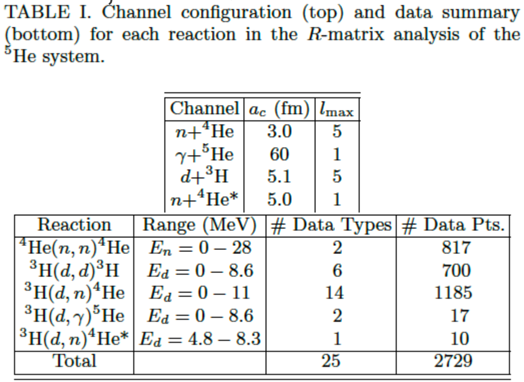


TABLE I. Channel configuration (top) and data summary (bottom) for each reaction in the R-matrix analysis of the ^{5}He system.

Channel	a_c (fm)	$l_{\max}$
$n+{}^4\mathrm{He}$	3.0	5
$\gamma+{}^5\mathrm{He}$	60	1
$d+{}^3\mathrm{H}$	5.1	5
$n+{}^4\mathrm{He}^*$	5.0	1

Reaction	Range (MeV)	# Data Types	# Data Pts.
$^4\mathrm{He}(n,n)^4\mathrm{He}$	$E_n = 0 - 28$	2	817
$^3\mathrm{H}(d,d)^3\mathrm{H}$	$E_d = 0 - 8.6$	6	700
$^3\mathrm{H}(d,n)^4\mathrm{He}$	$E_d = 0 - 11$	14	1185
$^3\mathrm{H}(d,\gamma)^5\mathrm{He}$	$E_d = 0 - 8.6$	2	17
$^3\mathrm{H}(d,n)^4\mathrm{He}^*$	$E_d = 4.8 - 8.3$	1	10
Total		25	2729

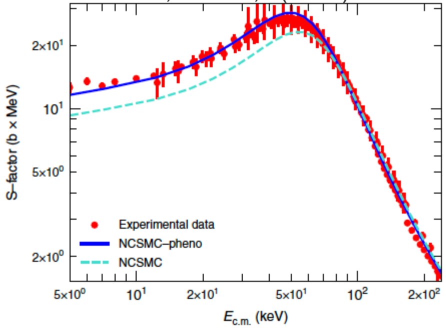
Basis for ENDF data & used world-wide in sim. codes, *e.g.* via parameterizations (incl Bosch & Hale)

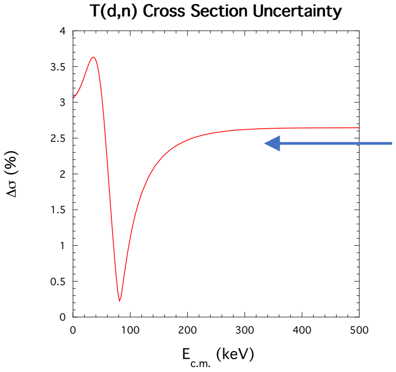
Ab-initio no-core shell model with continuum (potentials from chiral effective field theory)

CEA-LLNL-TRIUMF

Hupin, Quaglioni, Navratil

Nature Communications, 10-351,1 (2019)





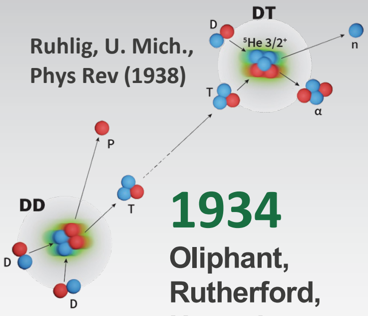
DT known to a few % accuracy

DT fusion first observed at Michigan in 1938 ad inspired Los Alamos 1943-5 fusion breakthroughs

1920
Aston
masses 4p>^{4}He
Eddington
fusion in stars

1928
Gamow
α penerability

1929
Houtermans, Atkinson
p fusion in stars



Ruhlig, U. Mich., Phys Rev (1938)

1934
Oliphant, Rutherford, Harteck
DD fusion & tritium discovered

1937
Rutherford
Triterium

1938
Alvarez
T @ Berkeley
Ruhlig
Observed secondary DT

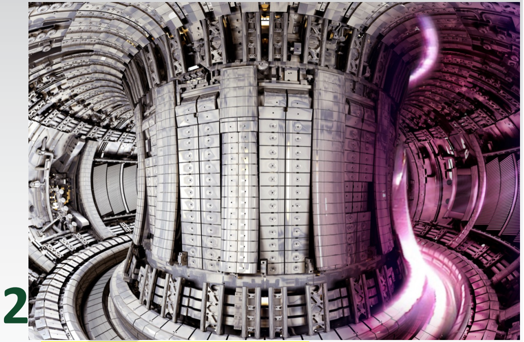
1942
Teller, Bethe, Konopinski, Oppenheimer
Berkeley JRO memo. & S680-X patent

1943-45
Los Alamos
Manhattan Project
DT xs

1951

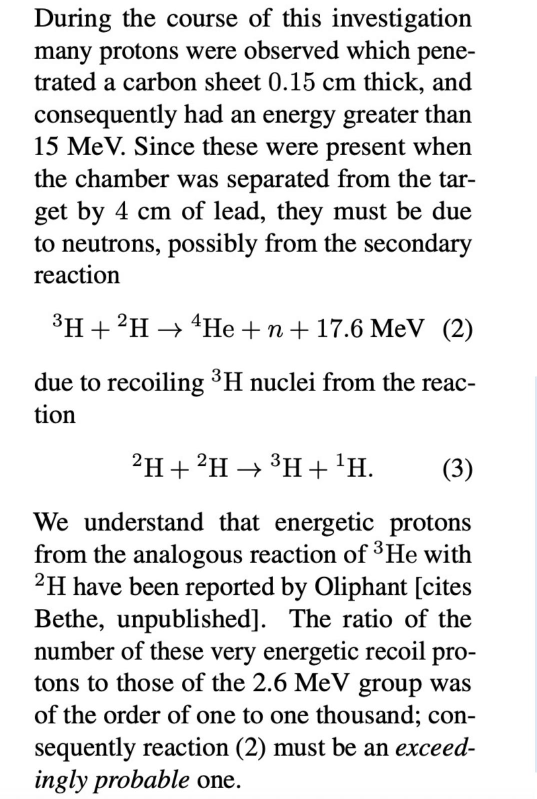

Greenhouse Los Alamos
Ignition of DT
Bretscher: DT resonance

1952
Ivy Mike
Los Alamos
H Bomb



2021-22
JET, ITER, magnetic fusion, & NIF ignition

Ruhlig’s Phys. Rev. 54 (1938) paper contains this minimal comment at the end, on in-flight DT reactions (found by Mark Paris)



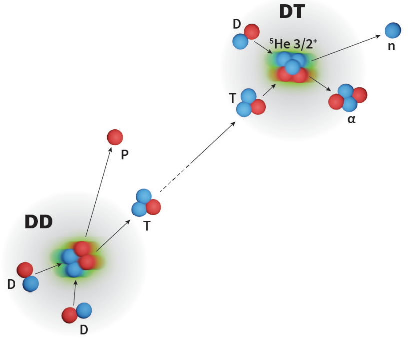
During the course of this investigation many protons were observed which penetrated a carbon sheet 0.15 cm thick, and consequently had an energy greater than 15 MeV. Since these were present when the chamber was separated from the target by 4 cm of lead, they must be due to neutrons, possibly from the secondary reaction

$$^{3}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + n + 17.6\ \mathrm{MeV} \quad (2)$$

due to recoiling ^{3}H nuclei from the reaction

$$^{2}\mathrm{H} + {}^{2}\mathrm{H} \rightarrow {}^{3}\mathrm{H} + {}^{1}\mathrm{H}. \quad (3)$$

We understand that energetic protons from the analogous reaction of ^{3}He with ^{2}H have been reported by Oliphant [cites Bethe, unpublished]. The ratio of the number of these very energetic recoil protons to those of the 2.6 MeV group was of the order of one to one thousand; consequently reaction (2) must be an *exceedingly probable* one.



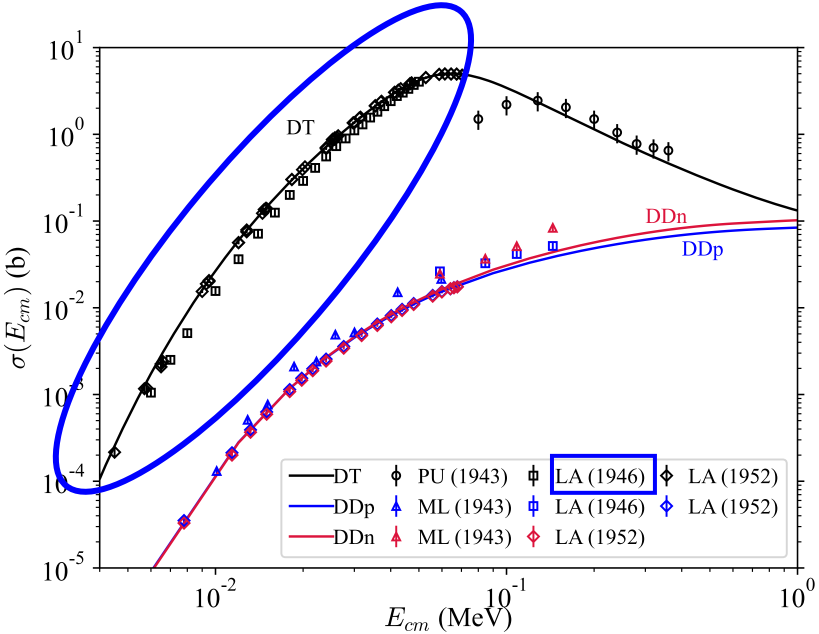
First observation of DT, 1938, U. Michigan

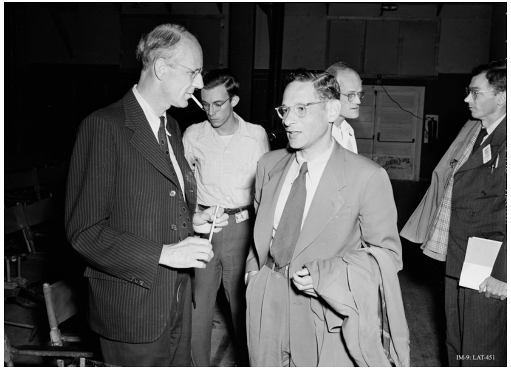
Lestone has simulated this experiment. We don’t quite agree with Ruhlig’s 10^{-3} – we get some orders of magnitude lower. (Lestone &LLNL’s Zimmerman agree)

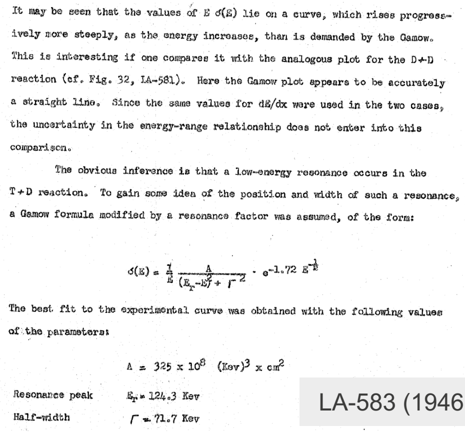
- We (Wilhelmy, Tornow, Lestone et al) have recently repeated the 1938 experiment at TUNL
- Secondary in-flight DT reactions used at NIF to diagnose stopping powers, Sayre, Hayes

Los Alamos 1945 DT measurement extended to low energies relevant for fusion applications & identified the resonance

Bretscher & French, in Fermi's Division with Teller
Los Alamos, 1945







It may be seen that the values of E σ(E) lie on a curve, which rises progressively more steeply, as the energy increases, than is demanded by the Gamow. This is interesting if one compares it with the analogous plot for the D+D reaction (cf. Fig. 32, LA-581). Here the Gamow plot appears to be accurately a straight line. Since the same values for dE/dx were used in the two cases, the uncertainty in the energy-range relationship does not enter into this comparison.

The obvious inference is that a low-energy resonance occurs in the T+D reaction. To gain some idea of the position and width of such a resonance, a Gamow formula modified by a resonance factor was assumed, of the form:

$$\sigma(E) = \frac{1}{E}\,\frac{A}{(E_r - E)^2 + \Gamma^2}\cdot e^{-1.72\,E^{-\frac{1}{2}}}$$

The best fit to the experimental curve was obtained with the following values of the parameters:

$$A = 325 \times 10^8\ (\text{Kev})^3 \times \text{cm}^2$$

Resonance peak $E_r = 124.3$ Kev
Half-width $\Gamma = 71.7$ Kev

LA-583 (1946) & PR (1949)

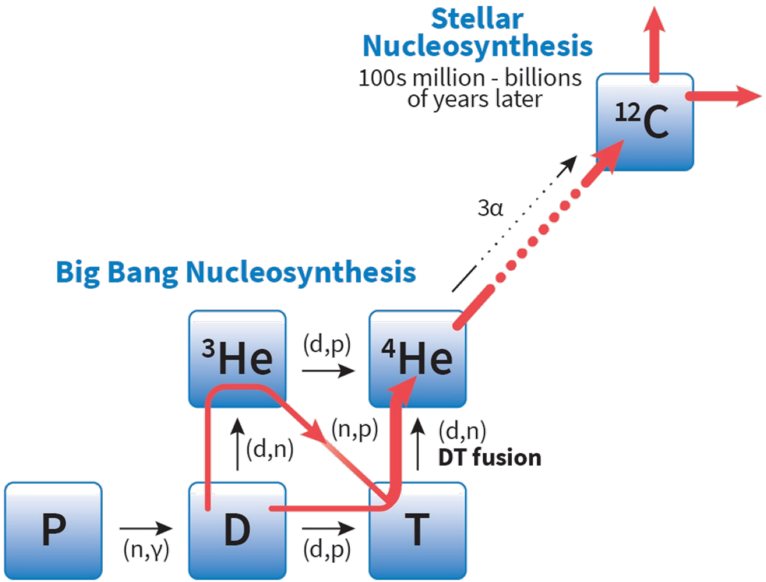
Los Alamos
NATIONAL LABORATORY

By the end of WW-II the project had reached some important conclusions

The DT fusion cross section is resonance-enhanced (100x bigger), making thermonuclear technologies feasible

That led to another invention: the name “fusion” (Bethe, 1950)

Big Bang DT fusion 13.8 billion years ago



BBN: 99% of ^4He was made from DT fusion. (25% of baryonic mass, rest ~^1H)

25% of human mass (excluding 1H) subsequently made from ^4He in stars

12 Unclassified Papers in FST (Fusion Science & Technology) 2024 Journal

T.E. Mason. ``*Thoughts on the H-Bomb Decision, Oppenheimer's Loyalty/Security Hearing, and the Vacation of the AEC Decision''*

M.B. Chadwick, M.W. Paris, G.M. Hale, J.P. Lestone, S. Alhumaidi, J.B. Wilhelmy, and N.A. Gibson, ``*Early Nuclear Fusion Cross Section Advances 1934--1952 & Comparison to Today's ENDF Data''*

J. P. Lestone, C. R. Bates, M. B. Chadwick, and M. W. Paris. ``*Ruhlig's 1938 first-ever observation of the fusion of A=3 ions with deuterium: An analysis of secondary reactions following dd fusion in a heavy phosphoric target''*

J.P. Lestone, S.W. Finch, F. Friesen, E. Mancil, W. Tornow, J. Wilhelmy, and M.B. Chadwick, ``*Observation of t(d,n)a neutrons following d(d,p)t reactions in a deuterium gas cell: An attempt to repeat Ruhlig's 1938 observation of secondary reactions"*

J.P. Lestone, ``*Some of the history surrounding the Oliphant et al discovery of dd fusion and an inference of the d(d,p)t cross section from the 1934 paper.''*

S.A. Becker, ``*The serendipitous discovery of the new elements einsteinium and fermium from the debris of the Mike thermonuclear test''*

M.W. Paris and M.B. Chadwick, ``*Anthropic importance of the ``Bretscher state in DT fusion''*

J. Katz, ``*The first calculation of Comptonization''*

L.G. Margolin and K.L. Van Buren, ``Richtmyer on Shocks. ``*Proposed Numerical Methods for Calculation of Shocks,''*

C. R. Bates and M. B. Chadwick, ``*Lithium neutron cross sections during the Manhattan Project and the quest for the H-bomb''*

K. Schoenberg, ``*A historical perspective of controlled thermonuclear research at Los Alamos (1946 - 1990)"*