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

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In memory of Eric Bauge,
Our longstanding collaborator and friend

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

Thanks to Toshihiko Kawano for the photo
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
**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].

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Measured data for CIELO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LANL</td>
<td>$^{235,238}\text{U}$, $^{239}\text{Pu}$ fission, PFNS and capture; iron inelastic gammas</td>
</tr>
<tr>
<td>RPI</td>
<td>$^{235}\text{U}$ fission, capture; iron capture; $^{238}\text{U}$ and Fe semi-differential scattering; $^{16}\text{O}$ total cross section</td>
</tr>
<tr>
<td>TUNL</td>
<td>$^{238}\text{U}(n,2n)$</td>
</tr>
<tr>
<td>JRC–Geel</td>
<td>$^{238}\text{U}$ capture; Fe inelastic scattering; $^{16}\text{O}(n,\alpha)$ cross section</td>
</tr>
<tr>
<td>CERN n_TOF</td>
<td>$^{235,238}\text{U}$ fission and capture</td>
</tr>
</tbody>
</table>

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).

<table>
<thead>
<tr>
<th>Isotope</th>
<th>CIELO-1</th>
<th>CIELO-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1\text{H}$</td>
<td>LANL/IAEA</td>
<td>LANL/IAEA</td>
</tr>
<tr>
<td>$^{16}\text{O}$ res.</td>
<td>LANL/JRC–Geel</td>
<td>IRSN/JRC–Geel</td>
</tr>
<tr>
<td>$^{16}\text{O}$ fast</td>
<td>LANL</td>
<td>LANL</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$ res.</td>
<td>IAEA/BNL</td>
<td>IRSN</td>
</tr>
<tr>
<td>$^{56}\text{Fe}$ fast</td>
<td>BNL/IAEA/CIAE</td>
<td>JEFF</td>
</tr>
<tr>
<td>$^{235}\text{U}$ res.</td>
<td>ORNL/IAEA</td>
<td>IRSN/ORNL</td>
</tr>
<tr>
<td>$^{235}\text{U}$ fast</td>
<td>IAEA+LANL PFNS CEA</td>
<td></td>
</tr>
<tr>
<td>$^{238}\text{U}$ res.</td>
<td>JRC–Geel</td>
<td>IRSN/CEA</td>
</tr>
<tr>
<td>$^{238}\text{U}$ fast</td>
<td>IAEA+LANL PFNS CEA</td>
<td></td>
</tr>
<tr>
<td>$^{239}\text{Pu}$ res.</td>
<td>ORNL/CEA</td>
<td>ORNL/CEA</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$ fast</td>
<td>LANL</td>
<td>CEA</td>
</tr>
</tbody>
</table>
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).

<table>
<thead>
<tr>
<th></th>
<th>CIELO-1</th>
<th>B-VII.1</th>
<th>JEFF-3.3</th>
<th>JENDL-4.0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unc. (%)</td>
<td>Unc. (%)</td>
<td>Unc. (%)</td>
<td>Unc. (%)</td>
</tr>
<tr>
<td>fission</td>
<td>1.3</td>
<td>0.6</td>
<td>0.3</td>
<td>0.9</td>
</tr>
<tr>
<td>nubar</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>PFNS $E_{av}$</td>
<td>1.7(37keV)</td>
<td>1.7(37keV)</td>
<td>4.38(93keV)</td>
<td>2.7(57keV)</td>
</tr>
<tr>
<td>elastic</td>
<td>13</td>
<td>12</td>
<td>1.4</td>
<td>3.7</td>
</tr>
<tr>
<td>inelastic</td>
<td>28</td>
<td>28</td>
<td>4.6</td>
<td>5.3</td>
</tr>
<tr>
<td>capture</td>
<td>18</td>
<td>20</td>
<td>8.6</td>
<td>12</td>
</tr>
</tbody>
</table>
One little example that I found when sorting out my docs.
Related Topic:

The $A=5\ ^{5}\text{He}$ 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.

A remarkable coincidence of nature is that the $\frac{3}{2}^+$ 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

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

Mark Paris, T-2
Modern R-matrix & ab-initio approaches for DT fusion

Multi-channel R-matrix analysis
LANL, Hale & Paris

<table>
<thead>
<tr>
<th>Channel</th>
<th>$E_n$ (fm)</th>
<th>$t_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>n+$^4$He</td>
<td>3.0</td>
<td>5</td>
</tr>
<tr>
<td>$\gamma$+$^4$He</td>
<td>0.5</td>
<td>1</td>
</tr>
<tr>
<td>d+$^3$H</td>
<td>6.0</td>
<td>1</td>
</tr>
<tr>
<td>n+$^4$He*</td>
<td>5.0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table I. Channel configuration (top) and data summary (bottom) for each reaction in the R-matrix analysis of the $^3$He system.

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)

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

DT known to a few % accuracy
DT fusion first observed at Michigan in 1938 and inspired Los Alamos 1943-5 fusion breakthroughs.

- **1920**: Aston masses $4p\text{He}$
- **1929**: Eddington fusion in stars
- **1934**: Oliphant, Rutherford, Hartee DD fusion & tritium discovered
- **1928**: Gamow $\alpha$ penetrability
- **1937**: Rutherford Triterium
- **1938**: Alvarez T@Berkeley
- **1939**: Ruhlig observed secondary DT
- **1939-45**: Los Alamos Manhattan Project DT xs
- **1942**: Teller, Bethe, Konopinski, Oppenheimer Berkeley JRO memo & S680-X patent
- **1943-5**: Ivy Mike H Bomb
- **2021-22**: JET, ITER, magnetic fusion, & NIF ignition
- **1951**: Greenhouse Los Alamos Ignition of DT
- **1952**: Bretscher DT resonance

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

\[ ^3H + ^2H \rightarrow ^4He + n + 17.6 \text{ MeV} \quad (2) \]

due to recoiling \(^3H\) nuclei from the reaction

\[ ^2H + ^2H \rightarrow ^3H + ^1H. \quad (3) \]

We understand that energetic protons from the analogous reaction of \(^3He\) with \(^2H\) 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

In the graph, the values of $\sigma(E_{cm})$ lie on a curve, which rises progressively more steeply as the energy increases, thus is demanded by the result. This is interesting if one compares it with the analogous plot for the T-D reaction (cf. Fig. 11, LA-583). Now the former plot appears to be accurately a straight line. Since the same value for $0.1$ are 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 Gaussian formula modified by a resonance curve was assumed. Using the form

$$
\sigma(E) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{1}{2} \frac{(E - E_0)^2}{\sigma^2}\right)
$$

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

- $E_0 = 46.3$ MeV
- $\sigma = 2.3$ MeV

LA-583 (1946) & PR (1949)
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 $^4\text{He}$ was made from DT fusion. (25% of baryonic mass, rest ~$^1\text{H}$)

25% of human mass (excluding $^1\text{H}$) subsequently made from $^4\text{He}$ 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’’


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 ‘‘Breitscher 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)’’