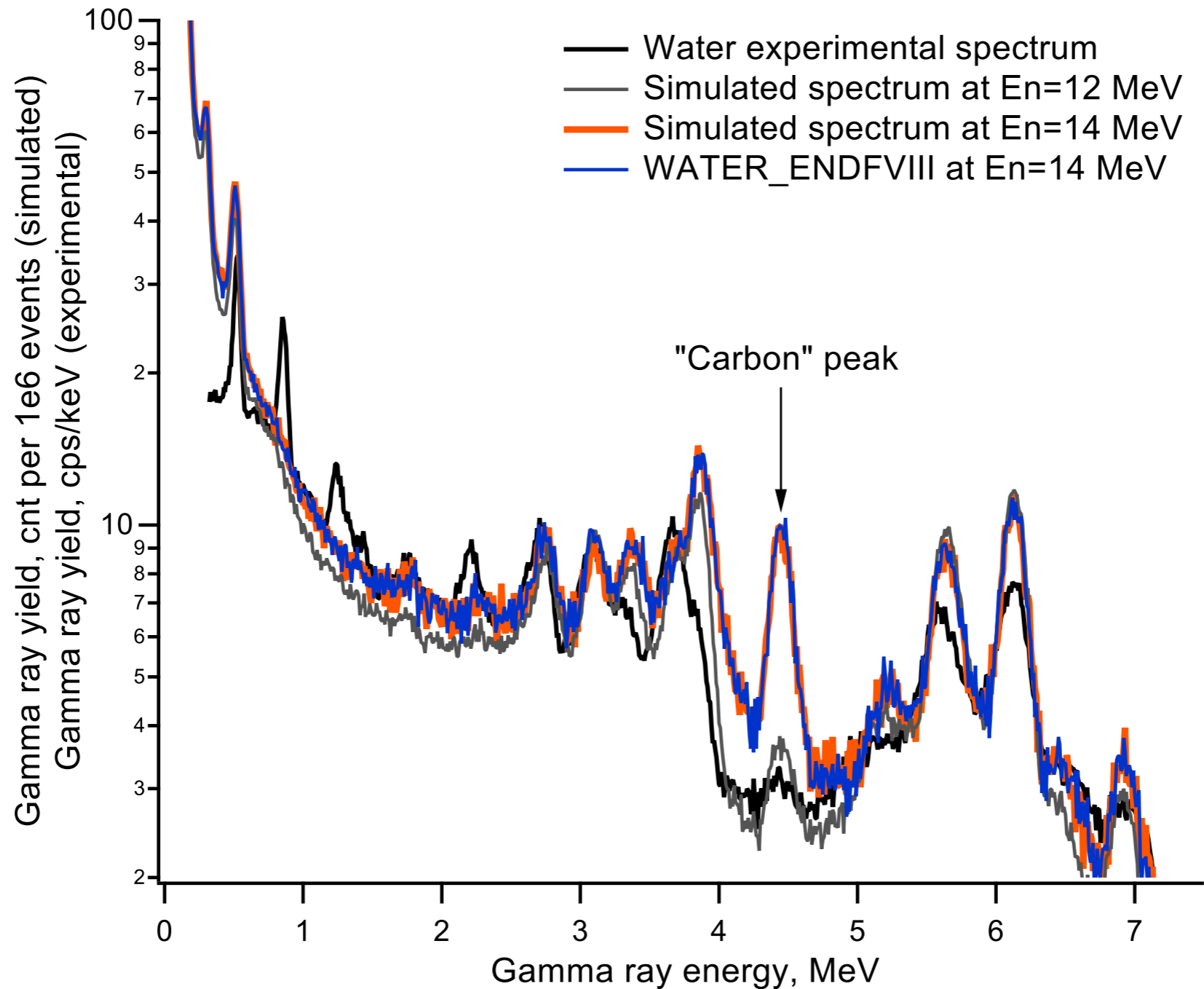# The Carbon Conundrum

D. Brown, NNDC, 27 Nov. 2018

G. Yakubova and collaborators observe a gamma line in the $^{16}O(n,n\alpha)^{12}C$ reaction that is much larger than it should be

Details

- Their simulations were performed with GEANT4, using ENDF/B-VII.1

- The "Carbon" peak gamma line is a product of the reaction
  $^{16}O(n, n'\alpha)^{12}C^* \rightarrow {}^{12}C + \gamma$ (4.44 MeV)

- This line and cross section was unchanged going from ENDF/B-VII.1 to ENDF/B-VIII.0 (see next slide)

- In ENDF/B-VIII.0, this line is given in MT-22

  - The line is given as a discrete line (MF-13,14)

  - The MT-22 cross section (MF-3) also given

- Additionally, the line at 3.854 MeV is from $^{16}O(n, \alpha)^{13}C^* \rightarrow {}^{13}C + \gamma$ (3.854 MeV), and indicates that the MT-803 cross section is too large

- See the attached report

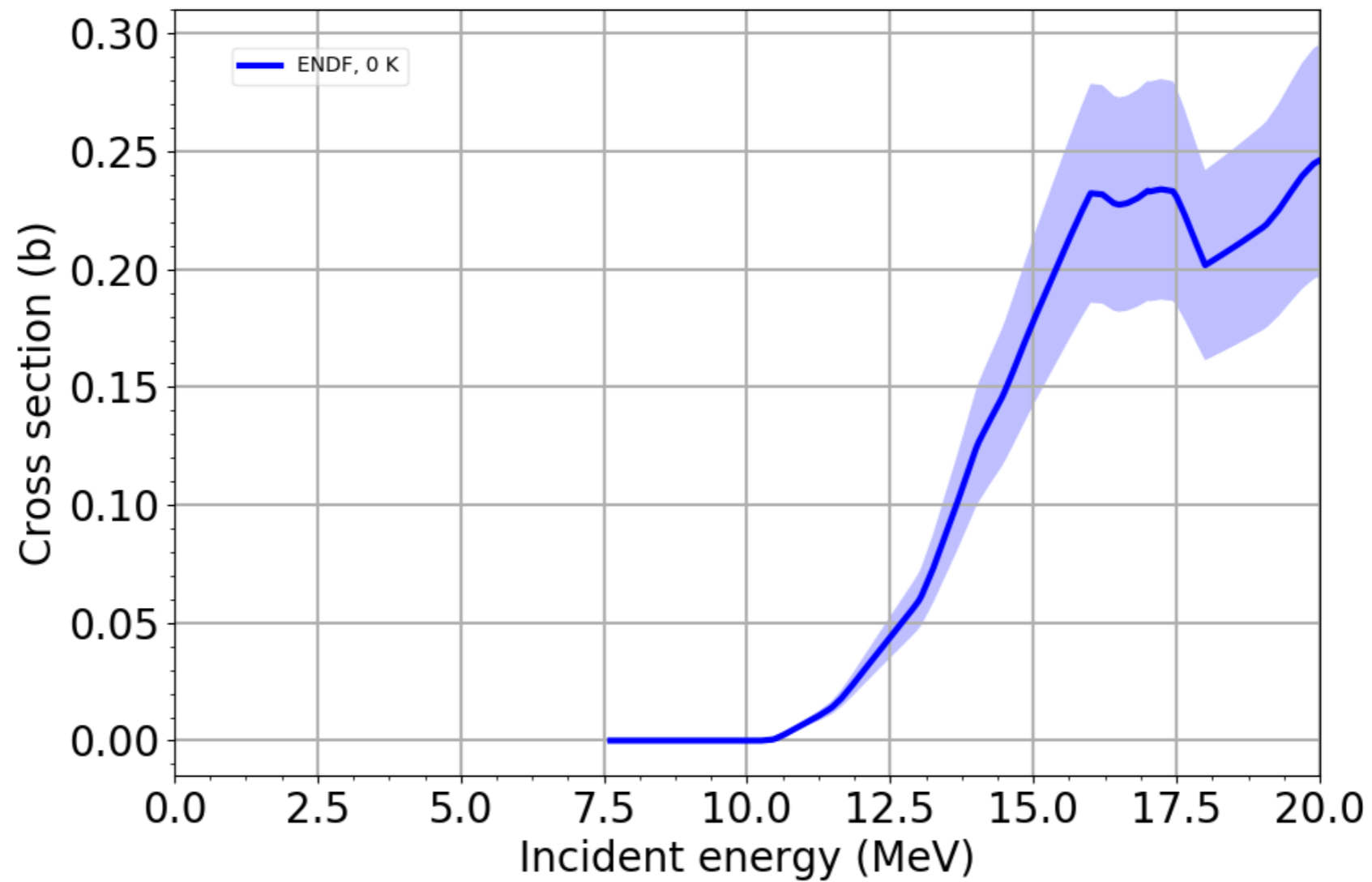# MT-22: $^{16}O(n, n'\alpha\gamma)$

The "Carbon" peak remains in ENDF/B-VIII.0
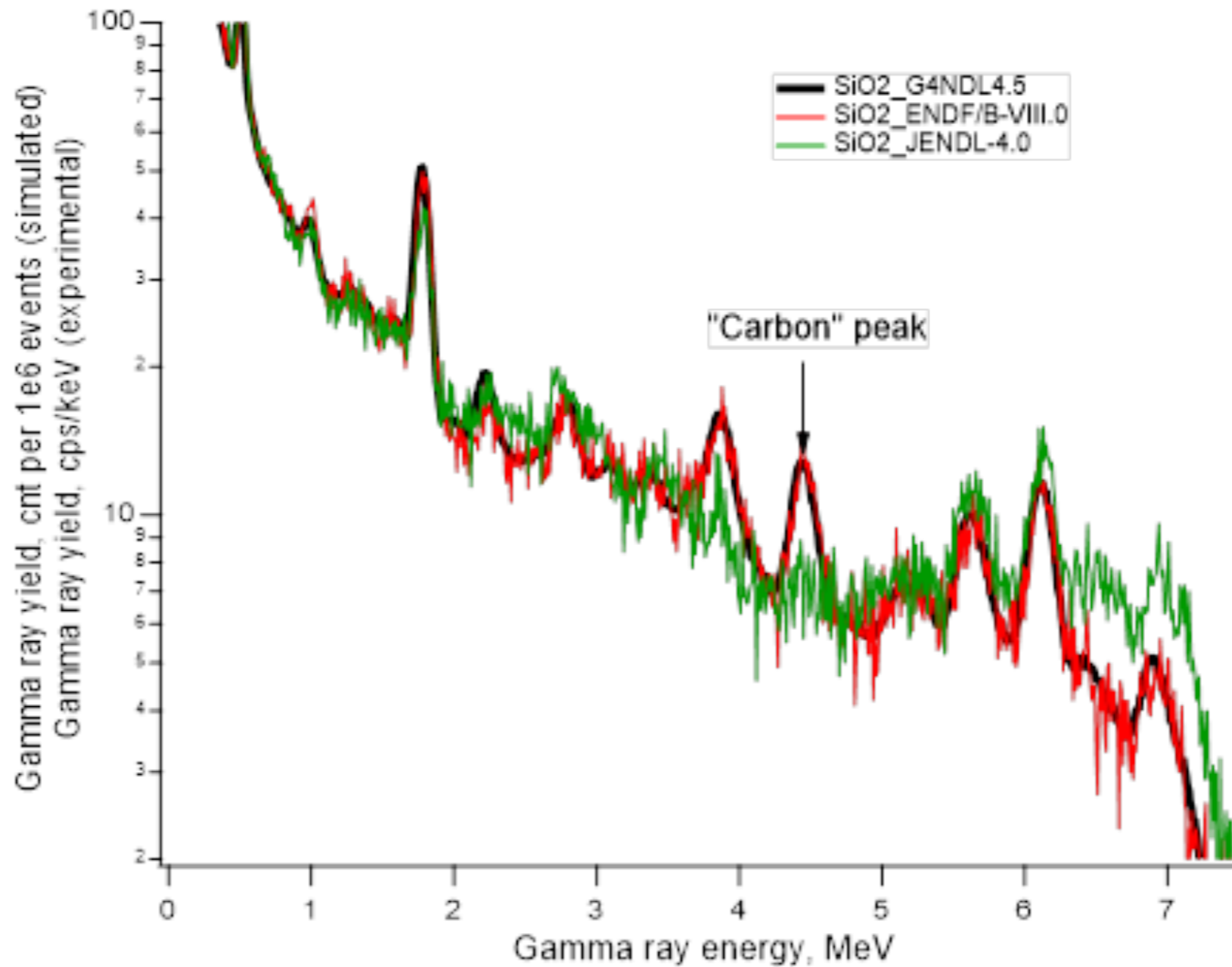
ENDF/B-VIII.0 MT-22 (n,nα)
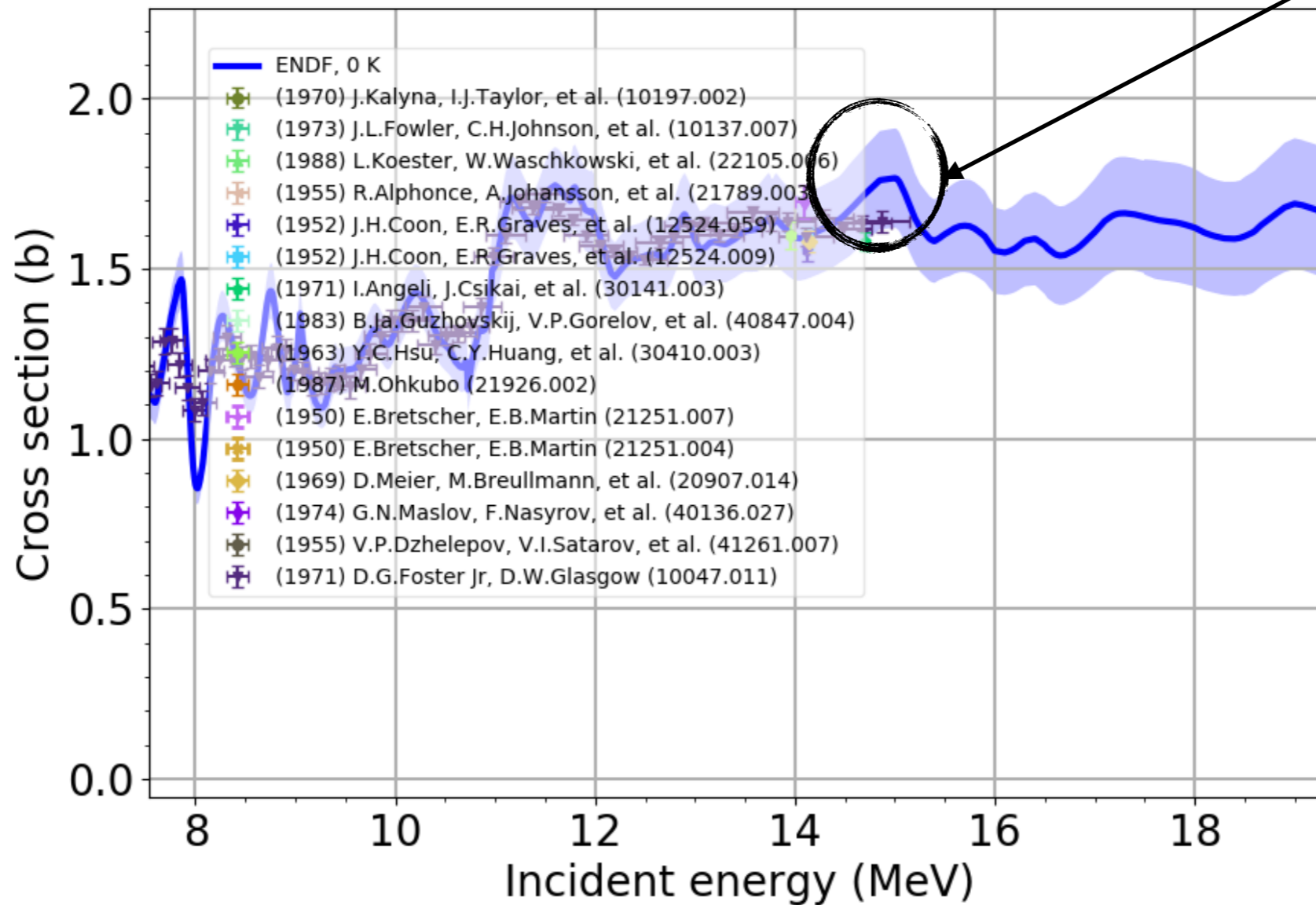
O16(n,n+a)

ENDF/B-VIII.0 MT-1 (total)

O16(n,tot)

Bump caused by MT-22, not supported by data

Relevant text from the ENDF/B-VIII.0 ¹⁶O documentation

```
****************************************************************  825 1451
                                                                825 1451
ENDF/B-VI MOD 3 Evaluation, April 2001, P.G. Young, G.M. Hale  825 1451
 M.B. Chadwick (LANL), E.Caro, C.R. Lubitz (KAPL)              825 1451
ENDF/B-VII modifications by P.R. Page (LANL) described right here 825 1451
                                                                825 1451
                                                                825 1451
MODIFICATIONS MADE FOR ENDF/B-VII:                              825 1451
 .                                                              825 1451
 .                                                              825 1451
 .                                                              825 1451
 MT=51-57     INELASTIC CROSS SECTION TO DISCRETE STATES        825 1451
    Threshold to 30 MeV, the (n,n') cross sections corresponding 825 1451
to gamma-emitting excited levels of 16O are included in MT=51-57 825 1451
as follows:                                                     825 1451
               MT=51  Ex= 6.0494    MeV                         825 1451
               MT=52  Ex= 6.129893 MeV                          825 1451
               MT=53  Ex= 6.9171    MeV                         825 1451
               MT=54  Ex= 7.11685   MeV                         825 1451
               MT=55  Ex= 8.8719    MeV                         825 1451
               MT=56  Ex=10.957     MeV                         825 1451
               MT=57  Ex=11.080     MeV                         825 1451
                                                                825 1451
Note that the 16O levels at 9.585, 9.8445, and 10.356 are      825 1451
omitted because they decay primarily by alpha particle emission 825 1451
and those data are included in MT=22.                           825 1451
 .                                                              825 1451
 .                                                              825 1451
 MT=22 (N,NALPHA) CROSS SECTION                                 825 1451
 Threshold to 30 MeV, based on GNASH calculation, with         825 1451
 adjustments made to improve agreement with experimental data, 825 1451
 especially data of Bormann et al. [Bo63].                     825 1451
 .                                                              825 1451
 .                                                              825 1451
 MT=22  (N,NALPHA) CONTINUUM ENERGY-ANGLE EMISSION DATA         825 1451
 Threshold to 30 MeV, energy-angle correlated energy spectra   825 1451
 are given for neutrons and alpha particles, and isotropic energy 825 1451
 spectra are given for recoiling 12C nuclei.  The neutron and  825 1451
 alpha data were obtained from the GNASH calculations; the recoil 825 1451
 12C distributions were calculated with the RECOIL code [Ma83]. 825 1451
 The discrete gamma rays from (n,nalpha gamma) reactions are   825 1451
 given in MF=13 and 14.                                        825 1451
```

```
 .                                                              825 1451
 .                                                              825 1451
 .                                                              825 1451
 MT=22  (N,NALPHA GAMMA) PHOTON PRODUCTION CROSS SECTIONS       825 1451
  Threshold to 30 MeV:  Only the 4.438-MeV discrete gamma ray   825 1451
  is given and it is based on the Nelson et al. [Ne99] data.    825 1451
 .                                                              825 1451
 .                                                              825 1451
****************************************************************  825 1451
                                                                825 1451
REFERENCES                                                      825 1451
                                                                825 1451
[Bo63]  M. Bormann et al., Zeits.Physik 174, 1 (1963)          825 1451
[Ne99]  R.O. Nelson and A. Michaudon, Los Alamos report LA-UR-99- 825 1451
        4170 (1999).                                           825 1451
```
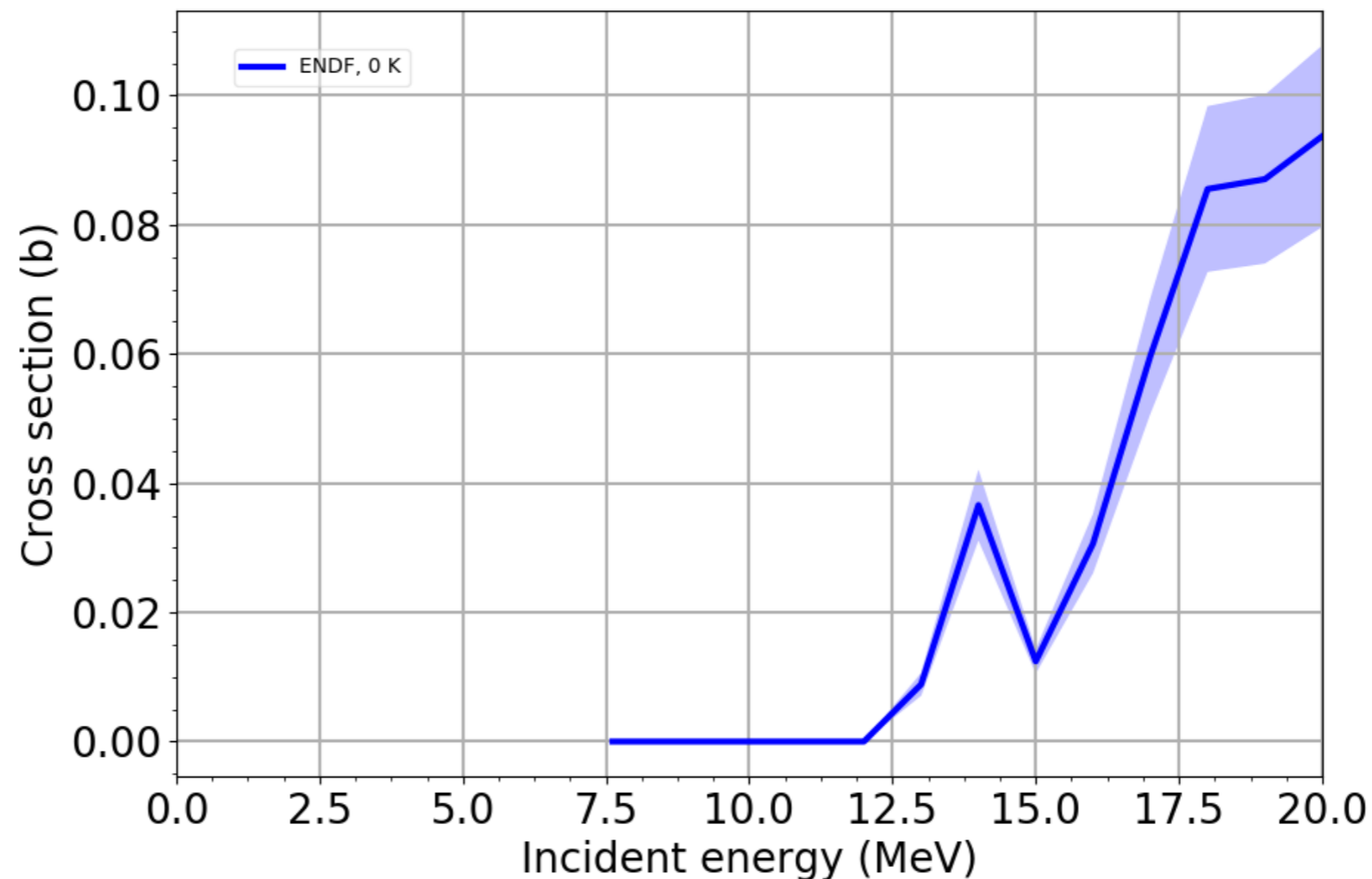
This reference is incorrect, the Bormann paper only contains data for ¹⁶O(n,α)

The Nelson paper, on the other hand, is very useful…

JENDL-4.0 MT-22 (n,nα)

O16(n,n+a)

This reaction was last modified in 1983 as part of JENDL-3.
From the JENDL-4.0 ¹⁶O file documentation, "mt=22 Based on systematics."

Data from Nelson & Michaudon clearly show both are wrong
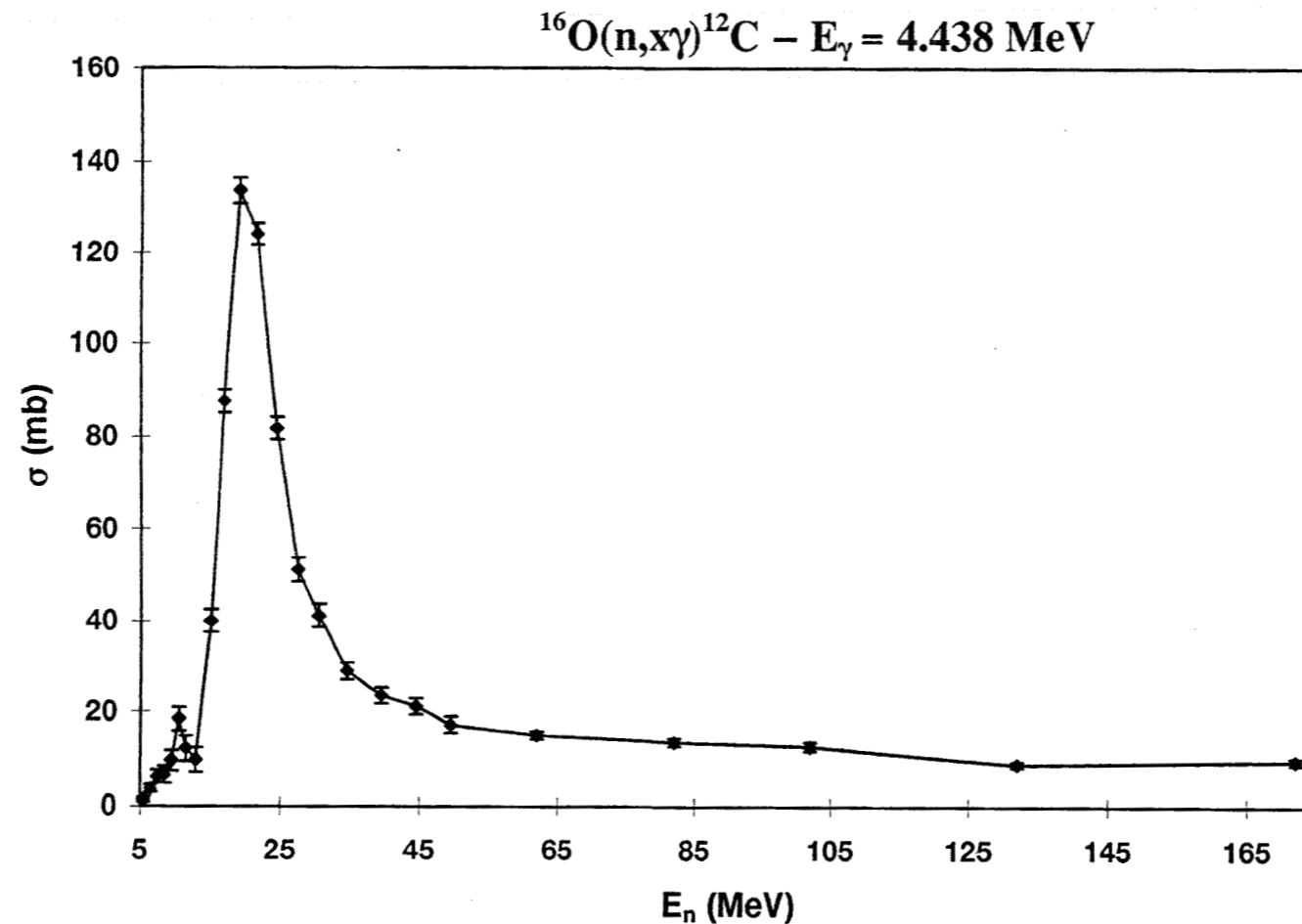

$^{16}O(n,x\gamma)^{12}C - E_\gamma = 4.438$ MeV

Fig. 36. Angle-integrated cross section versus neutron energy from threshold (12.32 MeV) to 172 MeV for the production of the 4.438-MeV γ ray emitted in the $^{16}O(n,x\gamma)^{12}C$ reaction, where x stands for $(n\alpha+dt+npt+2n^3He+n2d+2npd+ 3n2p)$.
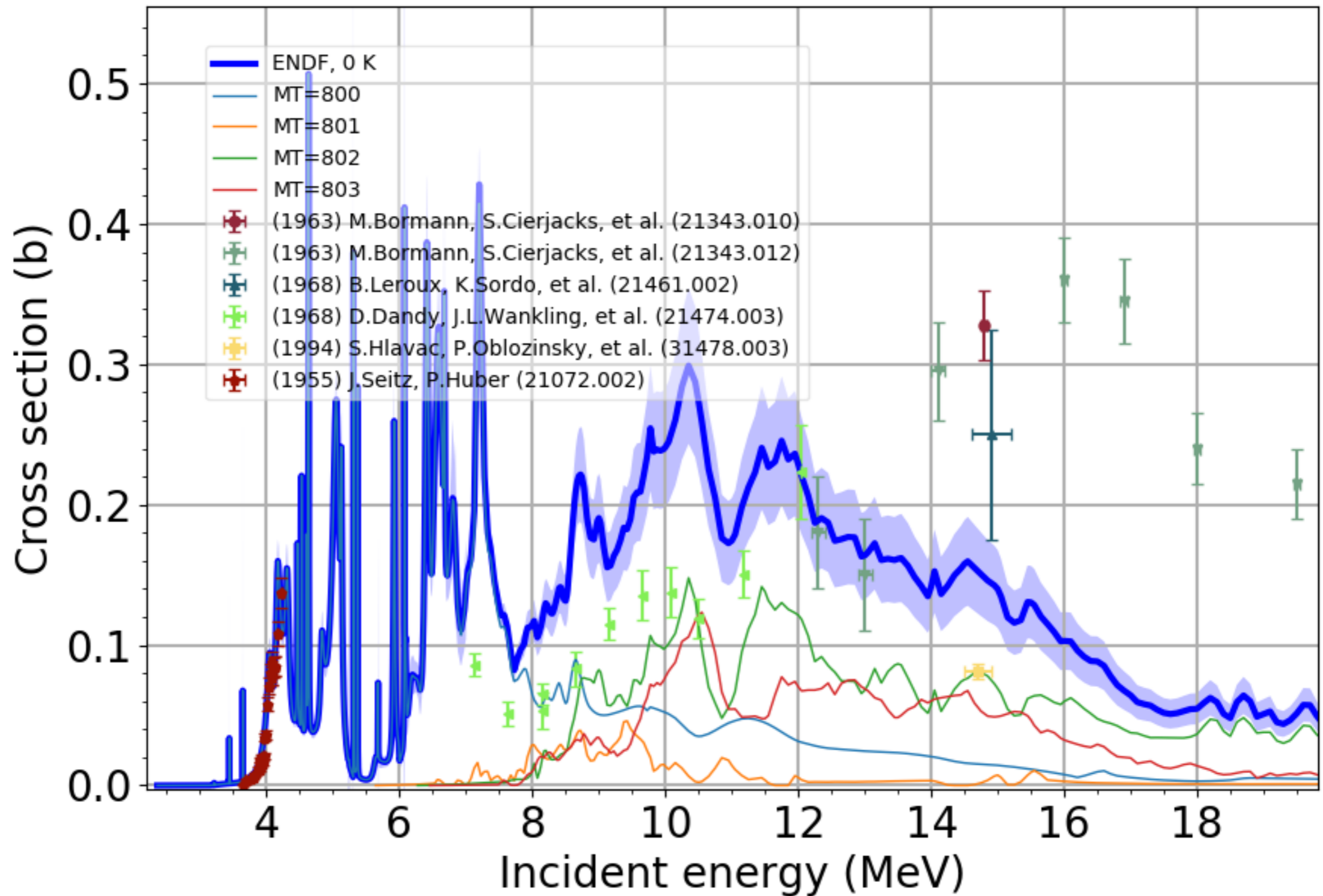
R. O. Nelson and A. Michaudon. High-Resolution Cross Section Measurements of Photon Production from 16O(n, xy) Reactions for Neutron Energies between 4 and 200 MeV, - 1999. LA-UR-99-4170, Los Alamos National Laboratory.
p.83

MT-22 ACTIONS

- ACTION: Request G. Hale and M. Paris to revise downward the (n,nα) cross section, to bring it in accord with Nelson & Michaudon

  - Because this is a two-step reaction, it is outside of the scope of the 2-body R-matrix fits currently done

  - This reaction is small and competes with many other small reactions that end in ^{12}C, producing the same gamma

- ACTION: RequestNelson & Michaudon's experimental data should be available, but I don't find it in EXFOR

  - ACTION: Contact Nelson directly for data

  - ACTION: Boris to compile the reference

- QUESTIONS: Is a new experiment needed? If so, what sponsor?

- QUESTION: Or can USDA experiment be used to provide a direct measurement of this reaction?

MT-803: $^{16}O(n,\alpha)$ to 3rd excited state of ^{12}C

O16(n,a)

Legend:
- ENDF, 0 K
- MT=800
- MT=801
- MT=802
- MT=803
- (1963) M.Bormann, S.Cierjacks, et al. (21343.010)
- (1963) M.Bormann, S.Cierjacks, et al. (21343.012)
- (1968) B.Leroux, K.Sordo, et al. (21461.002)
- (1968) D.Dandy, J.L.Wankling, et al. (21474.003)
- (1994) S.Hlavac, P.Oblozinsky, et al. (31478.003)
- (1955) J.Seitz, P.Huber (21072.002)

Cross section (b) vs. Incident energy (MeV)

The ENDF/B-VIII.0 documentation for the MT-80x indicates not much has happened in a while for MT≠800

```
MT=800    (N,ALPHA0) CROSS SECTION TO 13C GROUND STATE
   0.0 to 6.2 MeV, based on R-matrix analysis described above
under MT=1. Data of Ba72 were used in the original (alpha,n)
direction, with no changes in energy scale or normalization.
Also included were the low-energy (alpha,n) data of [Ke91] and
[Dr93].
   6.2 to 20 MeV, based on data of [Da63],[Da68],[Si68],[Ba73],
and composite of [Mc66b],[Ma68],[Le68] at 14 MeV. Note that the
[Da63] data were renormalized by factor of 1.5 to bring them
into rough agreement with the R-matrix analysis of the [Ba73]
(n,a0) data, together with the total and elastic data in the
analysis. Because the [Da68] experimental data were normalized
to [Da63], the former were also renormalized by the factor of
1.5.

MT=801-803    (N,ALPHA) CROSS SECTION TO EXCITED LEVELS OF 13C
   Threshold to 30 MeV, the cross sections of the 3.0894-,
3.6845-, and 3.8538-MeV levels are inferred from the (n,alpha
gamma) data of Nelson et al. [Ne99], using the level structure
diagram of 13C by Ajzenberg-Selove [Aj91].

MT=107    (N,ALPHA GAMMA) PHOTON PRODUCTION CROSS SECTIONS
   Threshold to 30 MeV:  The cross sections for the 3.0894-,
3.6845-  and 3.8538-MeV gamma rays are based on the Nelson et
al. [Ne99] data.  The 0.1693-, 0.5951- and 0.7644-MeV gamma-ray
cross sections are inferred from the above data through the
Ajzenberg-Selove level scheme [Aj91].  Note that the 0.1693-MeV
gamma from decay of the 3.8538-MeV level also was measured, but
the 3.8538-MeV gamma is more intense and was used to determine
the level excitation cross section.
```

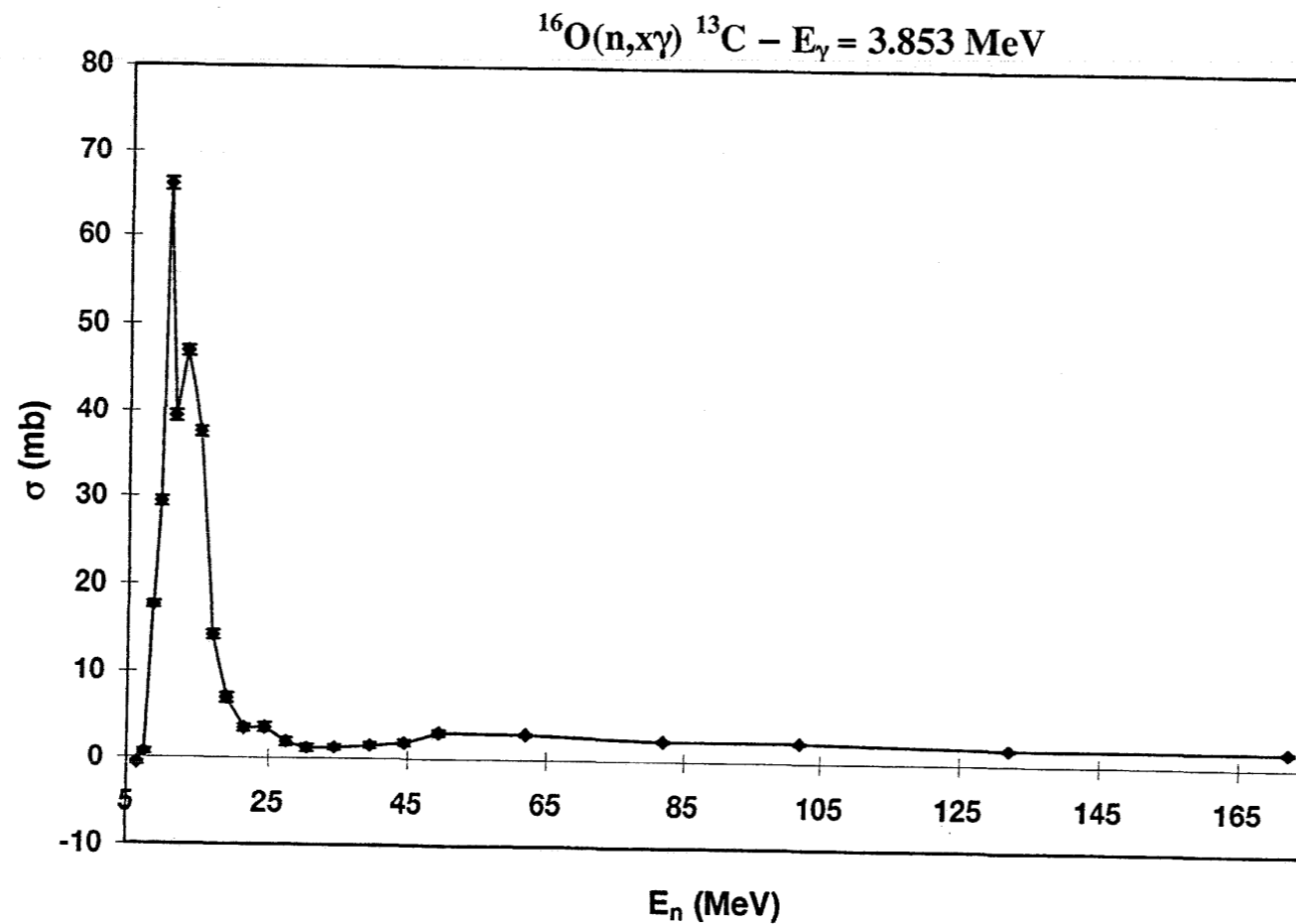# Data from Nelson & Michaudon clearly show MT-803 is wrong

Fig. 35. Angle-integrated cross section versus neutron energy from threshold (6.45 MeV) to 172 MeV for the production of the 3.853-MeV γ ray emitted in the $^{16}O(n,x\gamma)^{13}C$ reaction, where x stands for (α+pt+n³He+2d+npd+2n2p).

R. O. Nelson and A. Michaudon. High-Resolution Cross Section Measurements of Photon Production from 16O(n, xy) Reactions for Neutron Energies between 4 and 200 MeV, - 1999. LA-UR-99-4170, Los Alamos National Laboratory.
p.83

MT-80x ACTIONS

- ACTION: Request G. Hale and M. Paris to revise the (n,α_1), (n,α_2), (n,α_3) cross sections, to bring into accord with Nelson & Michaudon

  - Can these be included in the R-matrix fit with EDA?

- ACTION: RequestNelson & Michaudon's experimental data should be available, but I don't find it in EXFOR

  - ACTION: Contact Nelson directly for data

  - ACTION: Boris to compile the reference

- QUESTIONS: Is a new experiment needed? If so, what sponsor?

- QUESTION: Or can USDA experiment be used to provide a direct measurement of this reaction?