**Nuclear Data Section**

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**Memo CP-D/995**

**Date:** 3 June 2020

**To:** Distribution

**From:** N. Otsuka

**Subject: Coding of carbon-12 break up by neutron (Antolković’s experiments)**

**Reference:** Memo CP-D/646

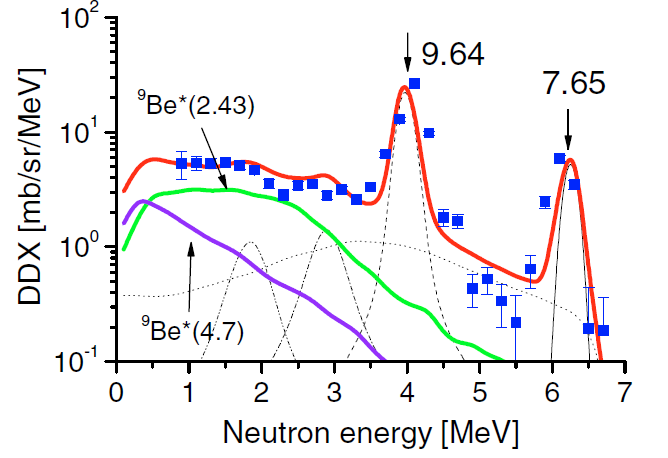
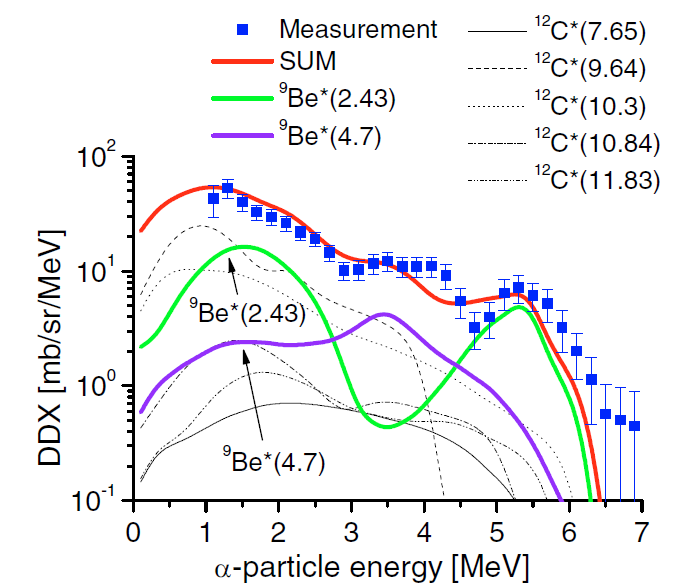
B. Antolković performed “kinematical complete measurements” of 12C(n,n+3α) twice by detection of three alpha particles by emulsions (EXFOR 22231 and 30635). During review of EXFOR 40359 retransmitted in PRELIM.4187, I found their data sets are useful to check whether our REACTION coding rule works well for breakup reactions (c.f. Memo CP-D/646), and I reviewed the REACTION strings of these entries.

Various 12C+n reactions leaving n+3α as the final products

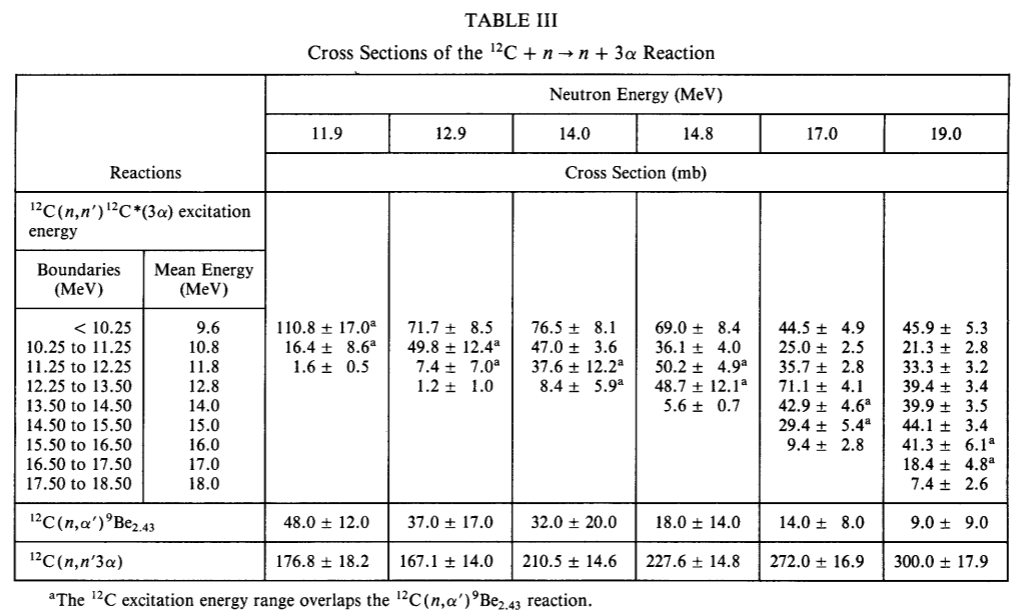
(12C\*: Carbon-12 in an excitation state other than 12C4.4. 9Be\*: Bellyrium-9 in an excitation state. SB: simultaneous breakup.).

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| # | Reaction | Product | 1st decay | 2nd decay | Remark |
| 1 | 12C(n,n’) | 12C\* |  |  |  |
|  |  | 12C\* | →α+8Be |  |  |
|  |  |  | 8Be | →α+α |  |
| 2 | 12C(n,n’) | 12C\* |  |  |  |
|  |  | 12C\* | →α+α+α |  |  |
| 3 | 12C(n,α) | 9Be\* |  |  |  |
|  |  | 9Be\* | →n+8Be |  |  |
|  |  |  | 8Be | →α+α |  |
| 4 | 12C(n,α) | 9Be\* |  |  |  |
|  |  | 9Be\* | →α+5He |  |  |
|  |  |  | 5He | →n+α |  |
| 5 | 12C(n,n+α) | 8Be |  |  | Three-body SB |
|  |  | 8Be | →α+α |  |  |
| 6 | 12C(n,α+α) | 5He |  |  | Three-body SB |
|  |  | 5He | →n+α |  |  |
| 7 | 12C(n,n+α+α+α) |  |  |  | Four-body SB |

Below are the outgoing alpha and neutron spectra for 14 MeV neutrons (K. Kondo et al., ND2007 Conf. Proc. p.407), which show the contribution of various sequential decay channels following the (n,n’) and (n,α) reactions.



**EXFOR 22231** (B. Antolković et al., Nucl. Sci. Eng.**107**(1991)1. PTB D-T neutron source)

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**22231.005** (Last line of Table III – “12C(n,n’3α)”)

It gives the cross section for the ***all*** (#1 to #7) paths resulting n+3α as the final products (but excluding #1+#2 via 12C7.6, which was undetectable due to too low α energies). It is currently compiled with

REACTION (6-C-12(N,N+2A)2-HE-4,,SIG,,MSC)

12C(n,n+3a) cross section excluding 12C(n,n2)12C

contribution

where MSC is needed because of exclusion of #1+#2 via 12C7.6.

This code reminds us the following basic rule for break upcoding in Memo CP-D/646:

When a reaction proceeds through an intermediate nucleus that is unstable and breaks up with the emission of particles (*e.g.* n, p, α), the reaction is coded **with the products of the breakup as the output particles**.

**22231.004** (Second line from the bottom of Table III – “12C(n,α’)9Be2.43”, also in Fig.8)

It gives the cross section for #3+#4 vith 9Be\* = 9Be2.43. It is currently compiled with

REACTION (6-C-12(N,A)4-BE-9,PAR,SIG)

with E-LVL=2.43 MeV, and it is correct.

**22231.002** (Lines with 12C(n,n’)12C\*(3α) excitation energy in Table III and in Fig.8.)

It gives 005 minus 004, namely for the paths #1+#2 (excluding the path via 12C7.6), #3+#4 (excluding paths via 9Be2.43), and #5 to #7. The data set is divided by the 12C excitation energy group, and I proposed

REACTION (6-C-12(N,N+2A)2-HE-4,ISP,SIG)

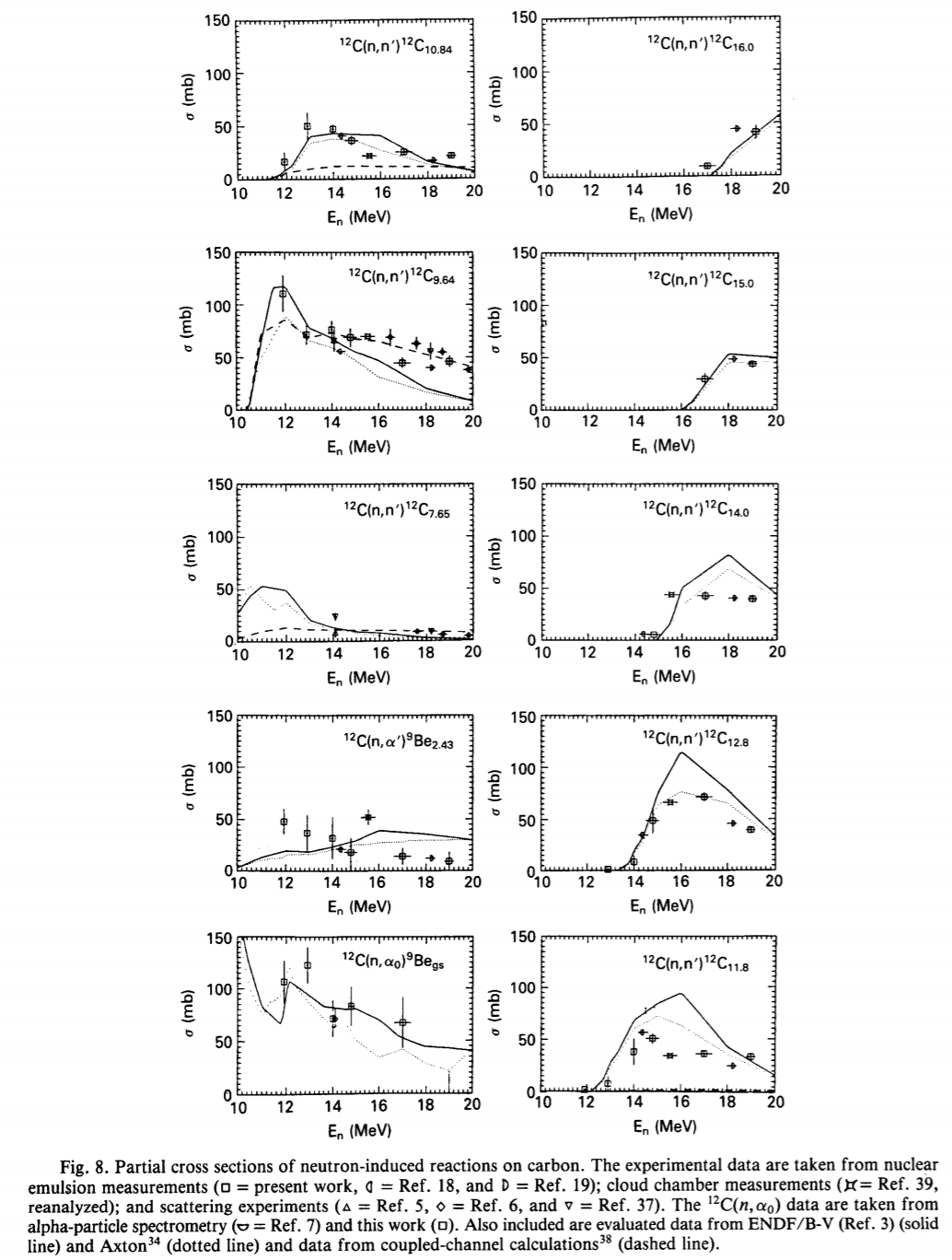
EN-SEC (E-EXC,6-C-12)

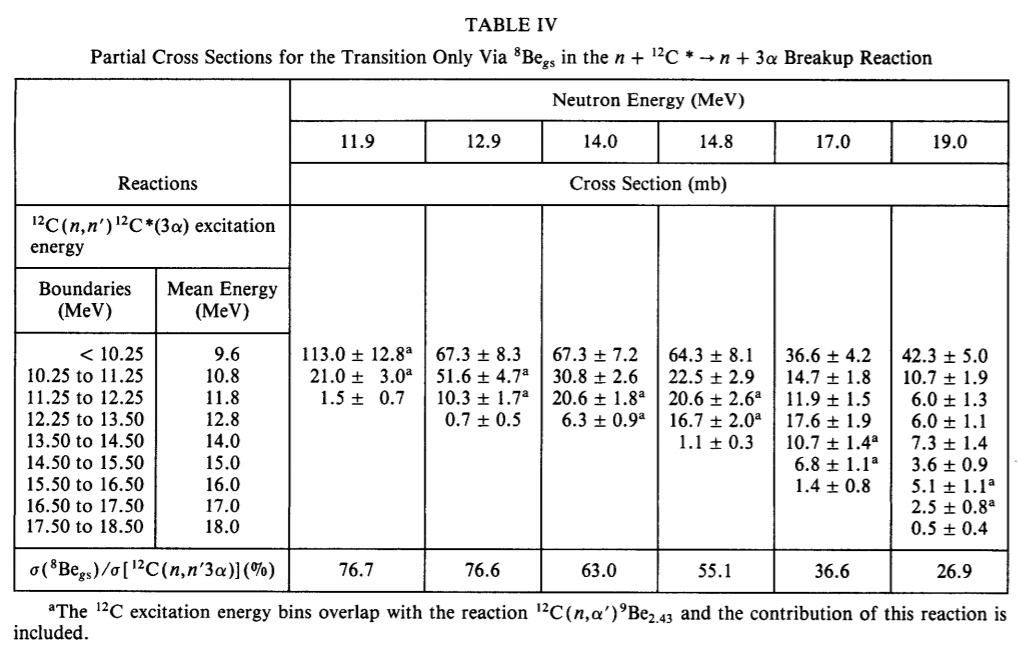
during the last retransmission. This RECTION code is questionable since some paths (#3 to #7) do not go through 12C as an actual intermediate state (N.B. We can define the 12C excitation energy for any 3α system). The article mentions that the simultaneous breakup contribution (#5 to #7) is less than 10% of the 12C9.64 but becomes considerable for higher 12C states, and therefore the paths other than #1+#2 are not negligible. On the other hand the authors plot the 22231.002 data as inelastic scattering cross sections in Fig. 8, and especially assign the three 12C levels 9.64, 10.8 and 11.8 MeV to the first three energy groups in Table III – [.10.25 MeV], [10.25 MeV to 11.25 MeV] and [11.25 to 12.25 MeV]. Under this situation, now I consider

REACTION (6-C-12(N,INL)6-C-12,PAR,SIG,,MSC)

EN-SEC (E-EXC,6-C-12)

with free text explanation like “cross section for all (n,n3a) reactions characterized by the three-alpha energy excluding (n,n2) and (n,a1)” could reflect author’s intention better than the current REACTION code.



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**22231.006** (Table IV with 12C(n,n’)12C\*(3α) excitation energy)

It gives the cross section for the path #1+#3+#5 with 8Beg.s. characterized by the 3α energies but excluding #1 via 12C7.6 (undetectable in this experiment). I proposed

REACTION (6-C-12(N,N+A)4-BE-8,ISP/PAR,SIG)

EN-SEC (E-EXC,6-C-12)

(E-LVL,4-BE-8)

with E-LVL=0 MeV in the last retransmission. However, #3 and #5 do not go through 12C as an intermediate state, and now I consider

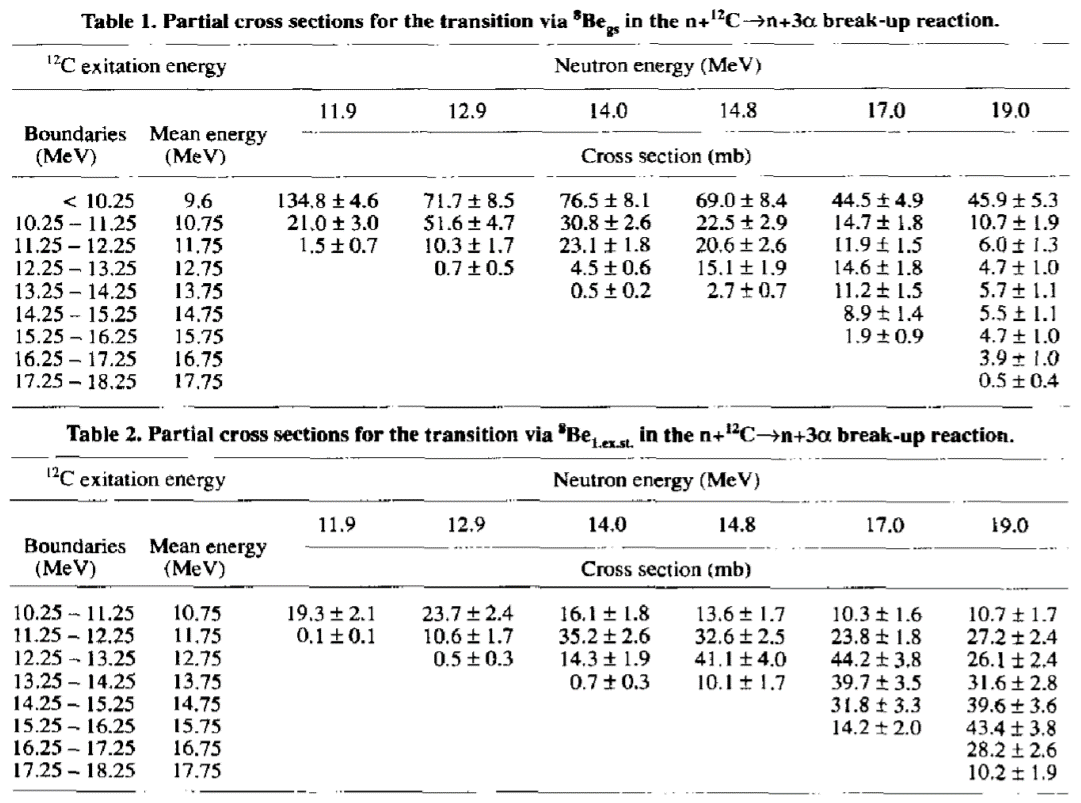
REACTION (6-C-12(N,N+A)4-BE-8,ISP/PAR,SIG,,MSC)

EN-SEC (E-EXC,6-C-12)

(E-LVL,4-BE-8)

with free text explanation like “cross section for all (n,n3a) reactions via 8Be(g.s.) and characterized by the three-alpha energy” could be better.

The authors superseded this data set by **22231.009** (=Table 1 of B. Antolković et al., Radiat. Prot. Dosim.**44**(1992)31). The Table 2 of this 1992 article gives the same quantity for 8Be3.03, and it is compiled in **22231.010** by the same manner.



**22231.008** (Table V)

This is *not* from the emulsion experiment but from another measurement with a NE213 liquid scintillator as the target material. The pulse-height spectrum in the smooth line in Fig.4 is calculated with n-p scattering and 12C(n,n0+n1)12C as the first interaction in the scintillator. Then its difference from the measured pulse-height spectrum (histogram in Fig.4) was attributed to the “neutron-induced reaction cross section” by the authors. The cross section in Table V is for the paths #1 to #7 (but excluding #1+#2 via 12C7.6 due to the detection limit.), 12C(n,α0)9Beg.s., 12C(n,p)12N (Ethr=13.6 MeV) and 12C(n,d)11C (Ethr=14.9 MeV). It is currently coded by

REACTION (6-C-12(N,N+2A)2-HE-4,,SIG,,MSC)

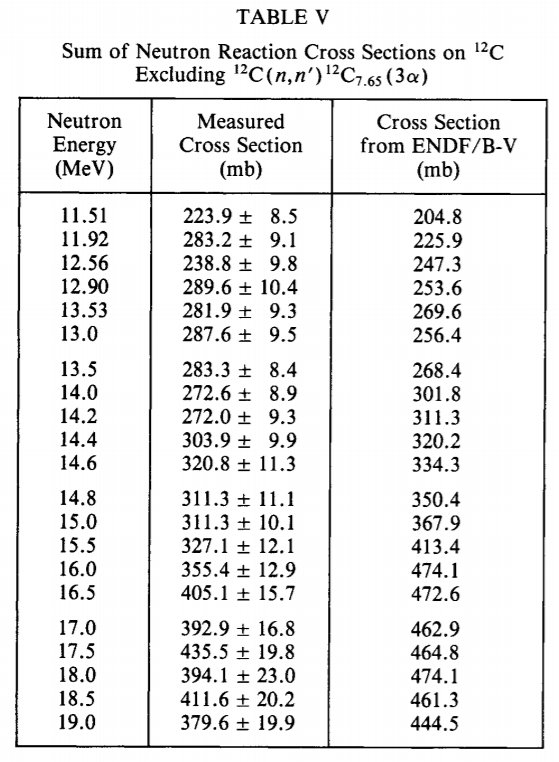
Three-alpha break up cross section (excluding

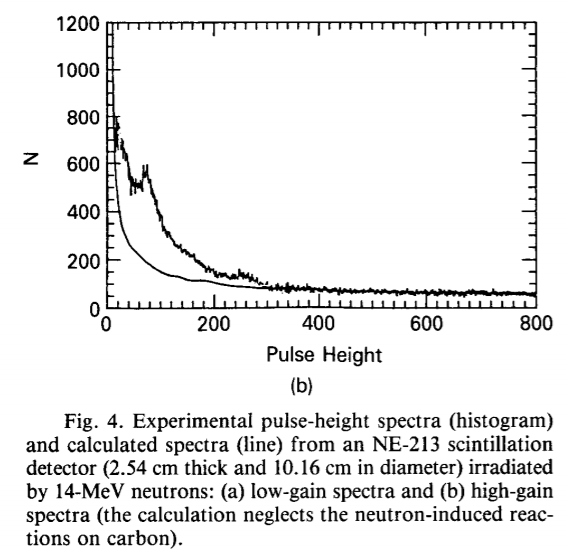
12C(n,n'2)12C(7.65MeV)(3alpha) contribution) plus

12C(n,alpha0)9Be cross section.

and it looks fine.

As the free text explains, this approximates the cross section for the all (n,3a) breakup paths observed in the emulsion measurement plus 12C(n,α0)9Beg.s.,, but also includes the (n,p) and (n,d) contribution above En~14.0 MeV. (Indeed the authors derive the 12C(n,α0)9Beg.s. cross section by subtraction of 22231.005 plus evaluated (n,p) and (n,d) cross sections from this data set. The derived (n,α0) cross section is in Fig.8 but not tabulated and not in the EXFOR entry.

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**EXFOR 30635** (B. Antolković et al., Nucl. Phys.**A394**(1983)87. Louvain Be(d,n) source)

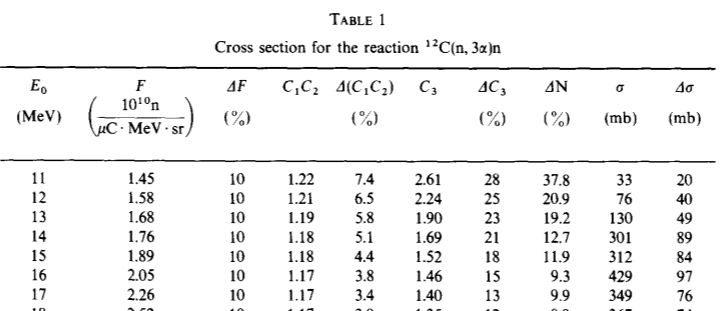
This is a similar kinematically complete emulsion experiment performed by the same author but published 8 years before. The breakup via 12C7.65 was not detectable in this experiment, too.

**30635.002** (Table 1)

This gives the quantity compiled in 22231.005. It is coded by

REACTION (6-C-12(N,N+2A)2-HE-4,,SIG)

Currently exclusion of the breakup via 12C7.65 is mentioned in free text under COMMENT. But it would be better to be mentioned under REACTION with addition of SF8=MSC to be consistent with 22231.005.

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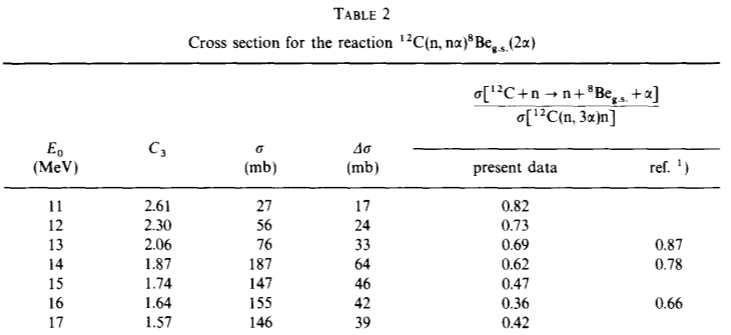
**30653.003** (Table 2)

It gives the cross section is for the paths #1, #3 and #5 with 8Beg.s. but excluding #1 via 12C7.6 (undetectable in this experiment). It is very similar to 22231.006 but the cross section is not divided to the 3α energy groups. It is coded by

REACTION (6-C-12(N,N+A)4-BE-8,PAR,SIG)

EN-SEC (E-LVL,4-BE-8)

and it looks fine.



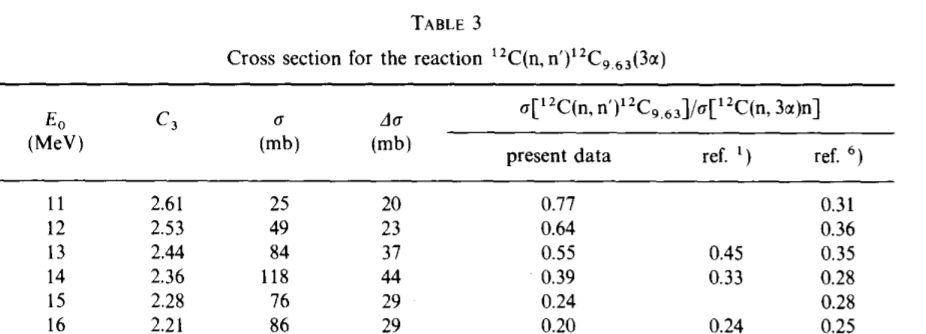
**30653.004** (Table 3)

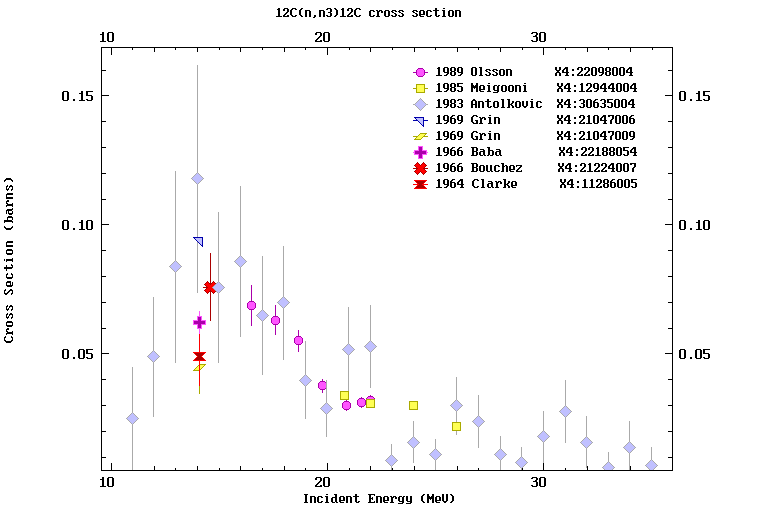
It gives the cross section for the paths #1 and #2 via 12C9.63. It is just the 12C(n,n3)12C cross section, and compiled by

REACTION (6-C-12(N,INL)6-12-C,PAR,SIG)

EN-SEC (E-LVL,6-C-12)

with E-LVL=9.63 MeV. This data set agrees very well with other data sets from the standard technique (neutron detection with TOF).





**Additional remarks:**

* I found the rules formulated in Memo CP-D/646 (=WP2011-29), are very practical for breakup compilation, and all important statements of this Memo should be kept in our manuals.
* I discussed EXFOR 40359.002 and 003 with Stanislav Simakov further after their retransmission in TRANS.4186, and we concluded that the cross sections are for any reaction leaving a neutron slower than the (n,n3) neutron. The upper boundary energies at four outgoing angles in the laboratory system are in Table 1 of the source article, and the corresponding energy in the centre-of-mass system was estimated to 3.37 MeV by Stanislav. This is similar to 22231.002, and I propose addition of SF8=MSC to the REACTION codes of these subentries to indicate that the channels other than the inelastic scattering also contribute.

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