New reaction rates for BBN

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Work in progress....... (January 9, 2019) **This is only a private working document; see § V and the appendix for ^{7}Be(n,p)^{7}Li.**

I. INTRODUCTION

Here are the reaction rates that have significantly changed since our Phys. Rep.. That does not mean that they must, right now, replace the former ones, because the theoretical one [D(p,γ)^{3}He] need to be confirmed, while the three that originate from new experimental data would probably need to be evaluated. Nevertheless, it would be worth while to evaluate their impact on D and ^{7}Li.

II. THE ^{2}H(p,γ)^{3}He RATE

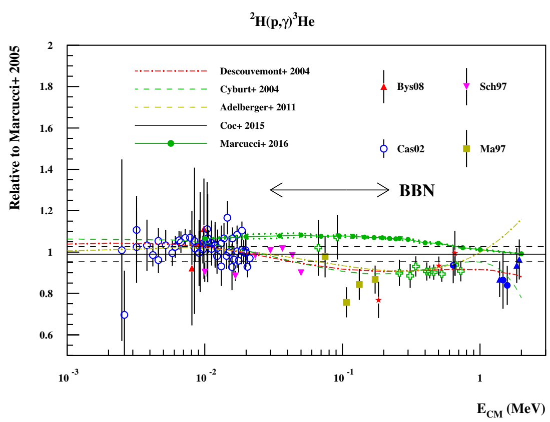

FIG. 1 Ratios of D(p,γ)^{3}He S–factors (Casella et al. , 2002; Bystritsky et al. , 2008; Schulte et al. , 1972; Ma et al. , 1997) (relative to the theoretical one (Marcucci et al. , 2005)) as in Figure 23 in (Pitrou et al. , 2018) but with (Bailey et al. , 1970; Griffiths et al. , 1962) data added. Previous evaluations (Descouvemont et al. , 2004; Adelberger et al. , 2011; Cyburt et al. , 2004) were strongly influenced by the scarce, but low, data (Ma et al. , 1997; Bailey et al. , 1970; Griffiths et al. , 1962) at BBN energies.

The latest evaluations of the D(p,γ)^{3}He rate (Coc et al., 2015; Iliadis et al. , 2016) relied on the theoretical S–factor calculated by Marcucci et al. (2005) normalized to selected experimental data. Figure 1 shows experimental S–factor data normalized to the theoretical one (Marcucci et al. , 2005). It is the same as Fig. 23 in Pitrou et al. (2018), but supplemented by two additional datasets (Bailey et al. , 1970; Griffiths et al. , 1962) for completeness. (They are not used in the evaluations because they lack estimations of systematic errors.) If one neglect the systematic uncertainties (overall normalization factors), it seems that the theoretical S–factor significantly overestimates the experimental data, so that previous evaluations (Descouvemont et al. , 2004; Adelberger et al. , 2011; Cyburt et al. , 2004) proposed smaller S–factors at BBN energies.

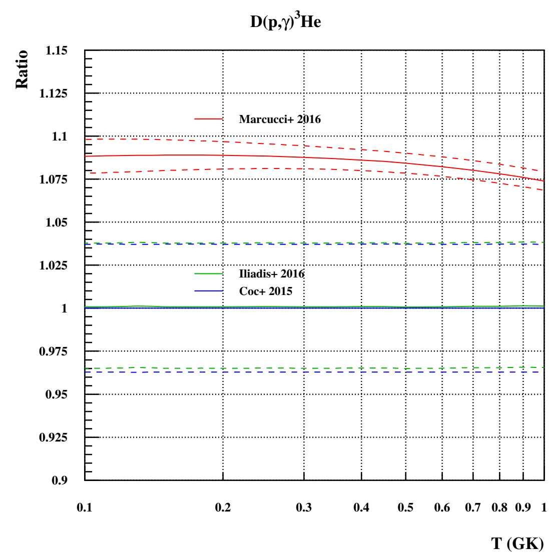

FIG. 2 Ratios of D(p,γ)^{3}He rates (relative to Coc et al. (2015) recommended rate), restricted to the domain of BBN temperatures. (As in subsequent figures, green or blue curves correspond to the rates used in recent papers (Coc et al., 2015; Pitrou et al. , 2018) while red ones are new rates to be evaluated.)

Pitrou et al. (2018) used the most recent (Iliadis et al. , 2016) rate, almost identical (Fig. 2) to Coc et al. (2015), but obviously higher than those earlier evaluations (Descouvemont et al. , 2004; Adelberger et al. , 2011; Cyburt et al. , 2004). Recently, Marcucci et al. improved their theoretical model resulting in an increase

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of the S–factor by about 8%–10% (Martín-Hernández et al., 2016), mostly “ due to the new solutions of the $A = 3$ (scattering) problem”. Using this new S–factor (Table I in Martín-Hernández et al. (2016)), supplemented above 2 MeV by Descouvemont et al. (2004), one obtains the reaction rate[1] that is higher than the previously adopted one (Coc et al., 2015; Iliadis et al. , 2016) by ≈8%. According to e.g. Eq. (2.1) in Coc et al. (2015), one can thus expect a reduction of the predicted D/H by ≈2.6%, ie. Δ(D/H) ≈ -0.06×10^{-5} or D/H ≈ 2.40×10^{-5}. (Martín-Hernández et al., 2016) is a purely theoretical S–factor that requires confirmation that may come from the new, yet unpublished, experimental data obtained at LUNA (Zavatarellia et al. , 2018).

Note that, an additional Δ(D/H)) ≈ -0.03×10^{-5} is expected between BBN and the redshift at which lie the observed cosmological clouds, increasing the tension between predictions and observations.

III. THE ^{3}H(d,n)^{4}He RATE

See de Souza et al. (2019a)...

IV. THE ^{3}HE(d,p)^{4}He RATE

See de Souza et al. (2019b)...

V. THE ^{7}Be(n,p)^{7}Li RATE

Since the evaluations of Descouvemont et al. (2004); Adelberger et al. (2011); Cyburt et al. (2004) no new experimental data have been obtained for this reaction until the n_ToF experiment by Damone et al. (2018). They provide their calculated rate and uncertainties in tabular format[2]. Figure 3 shows that It is 10%–30% higher than the Descouvemont et al. (2004) one, that we previously adopted. That would result (Table 1 of Coc & Vangioni (2010)) in an ≈15% reduction of the ^{7}Li/H prediction.

Figure 4 shows the discrepancy between the n_ToF and the Koehler et al. (1988) data; the latter being normalized to a measurement at thermal energy[3] for which there is some dispersion of experimental values (labelled ”T”). In the region of interest (≈1–100 keV), the data from the reverse reaction, ^{7}Li(p,n)^{7}Be, (Sekharan et al. , 1976; Gibbons & Macklin, 1959) are also inconsistent with each other.

It is interesting to see on Fig. 5, that Damone et al. (2018) and (Koehler et al., 1988) data sets fully agree if

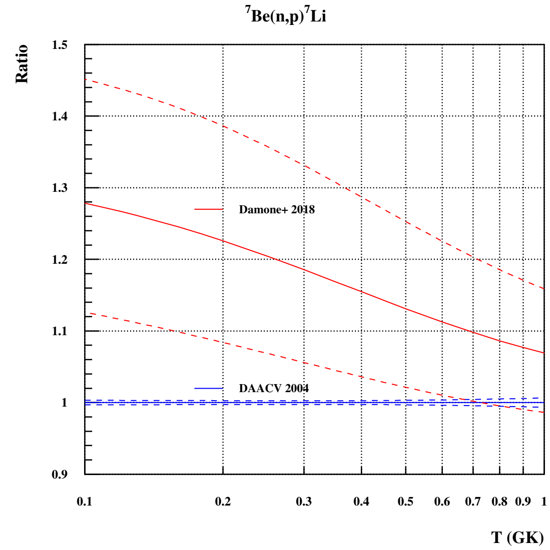

FIG. 3 Ratios of ^{7}Be(n,p)^{7}Li from n_ToF (Damone et al. , 2018) (relative to Descouvemont et al. (2004) recommended rate).

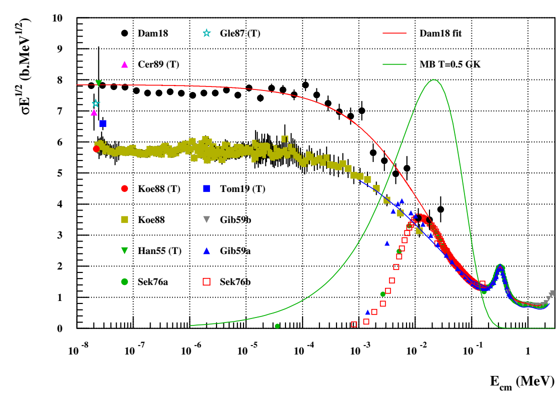

FIG. 4 Data for ^{7}Be(n,p)^{7}Li from n_ToF (Damone et al. , 2018), etc (work in progress). The green curve is the $\sqrt{E}\exp(-E/k_{\rm B}T)$ factor for T = 0.5 GK. (Measurements at thermal energy are plotted, slightly shifted in energy, to avoid overlap of error bars.)

the latter is scaled by a factor of 1.35. It suggest that a precise measurement, either at thermal energy, or at least, well below 1 keV could settle the discrepancy.

In order to evaluate this rate, one hast to consider ^{7}Be(n,p)^{7}Li data, but also data from the reverse reaction ^{7}Li(p,n)^{7}Be. The relation between these two cross sections is given in the Appendix. The global analysis can hence be done after transforming the ^{7}Li(p,n)^{7}Be cross section to the ^{7}Be(n,p)^{7}Li one as depicted on Fig. 4, or

[1] `dpg_Mar16.tsv`
[2] `https://twiki.cern.ch/twiki/bin/view/NTOFPublic/Be7npPaperDraftRatet` converted to `be7np_dam18.tsv`.
[3] p. 920 of Koehler et al. (1988)

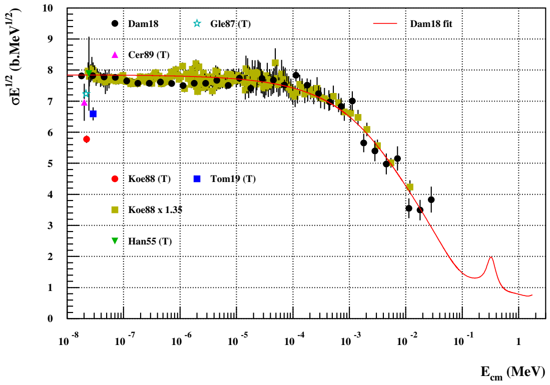

FIG. 5 Same as Fig. 4 but with Koehler et al. (1988) data scaled by a factor of 1.35.

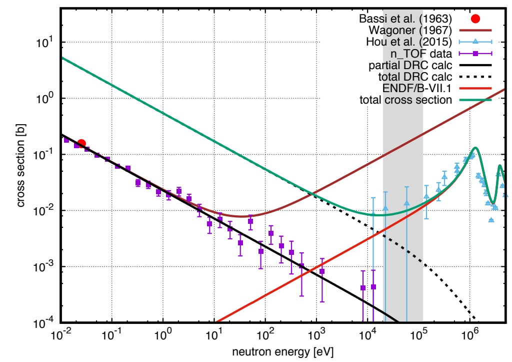

FIG. 6 ^{7}Be(n,α)^{4}He cross–section (Fig. 3 in Barbagallo et al. (2016)).

by including the transformation inside the model, keeping the data from the reverse reaction in its original form.

VI. THE ^{7}Be(n,α)^{4}He RATE

Because of the identical nature of the two outgoing α–particles and parity conservation, this rate is much lower than the ^{7}Be(n,p))^{7}Li one. The p–wave component has been derived from the (inverse–)mirror reactions ^{4}He(α,p)^{7}Li and ^{7}Li(p,(α)^{4}He by Hou et al. (2015). These results are consistent with the, yet unpublished, experimental data for the ^{4}He(α,n)^{7}Be inverse reaction (Hayakawa , 2018). The p–wave component has been partially measured at CERN n_ToF, supplemented by Shell–Model calculations to account for the unmeasured contribution from the lowest ^{8}Be levels (Barbagallo et al. , 2016). The various contributions to the cross section are shown in Fig. 6 from Barbagallo et al. (2016)[4]. The reaction rate is parametrized by:

$$\mathrm{N_A}\langle\sigma v\rangle = 4.81\times10^{5}+1.84\times10^{6}T_9+3.03\times10^{6}T_9^{3/2}, \quad (1)$$

according to Barbagallo et al. (2016), to which we associate an estimated conservative uncertainty factor of 3. As shown in Fig. 7 it includes the Hou et al. (2015) estimate but is an order of magnitude lower than the Wagoner's rate (Wagoner, , 1967). Hence, this reaction can be neglected.

[4] see also `https://twiki.cern.ch/twiki/bin/view/NTOFPublic/Be7na`

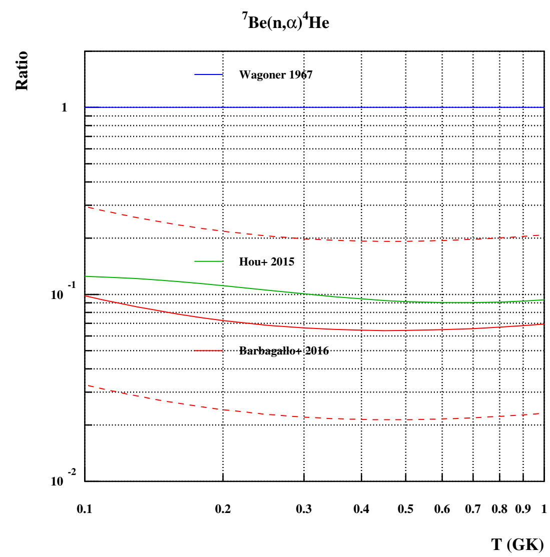

FIG. 7 Ratios of ^{7}Be(n,α)^{4}He rate (relative to Wagoner, (1967) rate).

VII. THE ^{7}Be(d,pα)^{4}He RATE

This was recognized (Coc et al., 2004) as the most promising reaction to solve the lithium problem (low Coulomb barrier), but it required a factor of ≈100 increase in the Caughlan & Fowler (1988) reaction rate to be achieved (Fig. 4 in Coc et al. (2004) and Table I in Coc et al. (2012)). The Caughlan & Fowler (1988) rate comes from Parker (1972), who assumed a constant S–factor of 100 MeV.b, based on the Kavanagh (1960) experimental data: "Experimental measurements of the differential cross-section for this reaction were made by

Kavanagh (1960) for deuteron energies from 700 to 1700 keV. Lacking complete angular distributions, these data can be approximately converted to total cross- sections by multiplying by 4π and (2) by multiplying by a factor of 3 to take into account contributions from higher excited states in ^{8}Be." Unknown resonances that could sufficiently increase the cross section have been proposed (Chakraborty et al. , 2011; Broggini et al. , 2012). However, until very recently, measurements of its average cross section (Angulo et al. , 2005) or properties of candidate resonances (Kirsebom et al. , 2011; O'Malley et al. , 2011; Scholl et al. , 2011) ruled out this possibility. However, the Angulo et al. (2005) experiment, was only sensitive to the ^{7}Be(d,p)^{8}Be(2α) channel. In a recent experiment, Rijal et al. (2018) found a new resonance, but in the, previously unexplored ^{7}Be(d,α)^{5}Li(pα) channel. Their experimental S–factor is much higher than the Kavanagh (1960) and Angulo et al. (2005) other experimental ones, but, because of the overestimation resulting from the multiplicative factors introduced by Parker (1972), by pure chance, the recommended rate and uncertainty[5] is close to the Caughlan & Fowler (1988) rate and factor of three uncertainty factor that we have been using so far.

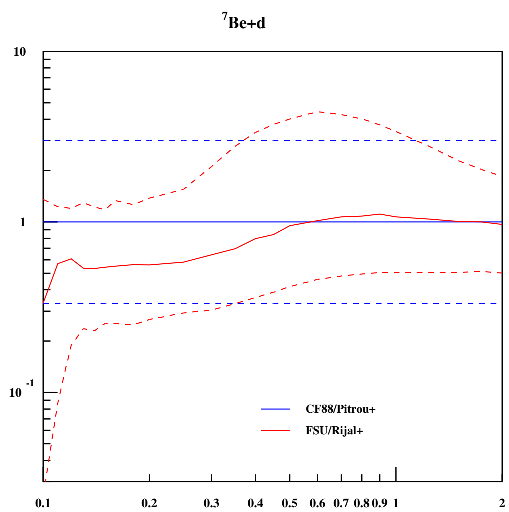

FIG. 8 Ratios of ^{7}Be(d,p)2α rates (relative to Caughlan & Fowler (1988) recommended rate). Red curves are from digitalized data in Fig. 5 of Rijal et al. (2018); blue dashed curves shows our adopted uncertainty factor on Caughlan & Fowler (1988).

Hence, we do not confirm the claimed (Rijal et al. , 2018) reduction of the Li/H prediction.

[5] be7da_rij18.tsv

Appendix A: The ^{7}Be(n,p)^{7}Li data

As data come also from the reverse reaction, ^{7}Li(p,n)^{7}Be, we use the transformation given by:

$$\sigma_{^7\mathrm{Be+n}} = \frac{\mu_{^7\mathrm{Be+n}}}{\mu_{^7\mathrm{Li+p}}} \frac{E_{\mathrm{cm}}^{^7\mathrm{Be+n}}}{E_{\mathrm{cm}}^{^7\mathrm{Li+p}}} \sigma_{^7\mathrm{Li+p}} \tag{A1}$$

or, using Q=1.644242 MeV and masses from Wang et al. (2012),

$$\sigma_{^7\mathrm{Be+n}}\left(E_{\mathrm{cm}}^{^7\mathrm{Be+n}}\right) = \frac{0.99879}{1 - Q \times 1.1436/E_{\mathrm{p}}} \sigma_{^7\mathrm{Li+p}}. \tag{A2}$$

$E_{\mathrm{cm}}^{^7\mathrm{Be+n}}$ is the center of mass energy in the final state:

$$E_{\mathrm{cm}}^{^7\mathrm{Be+n}} = 0.87443 \times E_{\mathrm{p}} - Q. \tag{A3}$$

Note that because of the difference in Eq. A3, it is important to use the correct factor to transform laboratory to center of mass energies. Here we use the nuclear masses (Wang et al. , 2012) ratio instead of the 7/8=0.875 approximation. We have also $E_{\mathrm{cm}}^{^7\mathrm{Be+n}} = 0.87428 \times E_{\mathrm{n}}$.

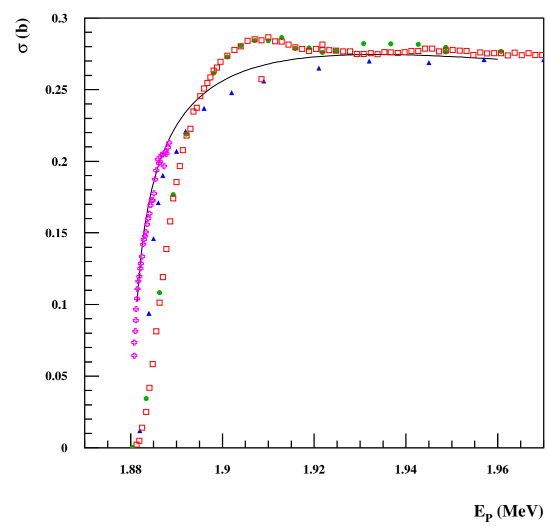

FIG. 9 The ^{7}Li(p,n)^{7}Be data. See Fig. 4 for references and Martín-Hernández et al. (2016, 2018) for pink crosses and black curve.

1. The data from Gibbons & Macklin (1959)

Gibbons & Macklin (1959) measured the reverse reaction ^{7}Li(p,n)^{7}Be, among others. Hence little information is provided on this peculiar reaction in the paper. The data are taken from EXFOR, corresponding to their Fig. 4 ("Author's tabulated data compiled in p225 of Nucl.Data Sheets 1(1966)203." but I did'nt find it). There are two sets of data one from 1.882$\leq E_{\rm p}\leq$2.450 MeV, or 1.44 keV$\leq E_{\rm cm}^{\rm ^7Be+n}\leq$0.498 MeV, with a LiF target, and another one in the range of 2.387$\leq E_{\rm p}\leq$5.418 MeV, or 0.443$\leq E_{\rm cm}^{\rm ^7Be+n}\leq$3.09 MeV with a metalic lithium target. A 5% error is quoted in their Fig. 4 corresponding to the thick LiF target calibration measurement at 2.0 MeV.

2. The data from Sekharan et al. (1976)

Sekharan et al. (1976) measured the reverse reaction ^{7}Li(p,n)^{7}Be with a 4π counter. There are two sets of data in EXFOR, corresponding to their Fig. 3 and Fig. 4. The first set corresponds to 1.8804$\leq E_{\rm p}\leq$4.2037 MeV or 0.036 keV$\leq E_{\rm cm}^{\rm ^7Be+n}\leq$2.0316 MeV. The second set corresponds to 1.8813$\leq E_{\rm p}\leq$2.0673 MeV or 0.823 keV$\leq E_{\rm cm}^{\rm ^7Be+n}\leq$0.16347 MeV.

Descouvemont et al. (2004) used the dataset of Fig. 3 (Sekharan et al. , 1976) from $E_{\rm p}$ = 1.8893 MeV to 2.4438 MeV, i.e. $E_{\rm cm}^{\rm ^7Be+n}$ = 7.8184 keV to 0.49269 MeV, while Damone et al. (2018) plotted the subset from 1.8834 to 4.2037 MeV, $E_{\rm cm}^{\rm ^7Be+n}$ = 26.593 keV to 2.0316 MeV. Indeed, below ≈20 keV other contributions (Damone et al. , 2018; Koehler et al., 1988) dominate.

There is a quoted (absolute) error of ±4% on the figures.

3. The data from Koehler et al. (1988)

Koehler et al. (1988) measured, at the Omega West Reactor, the thermal cross section to be 38820±809 barns, or $\sigma\sqrt{E}$=5.4029±0.1126 b.MeV$^{1/2}$. The error (2%) comes from the determination of the neutron flux (1%), the number of ^{7}Be nuclei (1%), the solid angle (1%), and the counting statistics (p. 919).

They measured the total cross section at the Los Alamos Neutron Scattering Center from 25 meV to 13.5 keV, normalized to their thermal cross section (p. 920). Data are available on EXFOR (3000). The uncertainties come from the ^{6}Li(n,α)^{3}H thermal (1%) and non-thermal (2%) cross section, and anisotropy of the ^{6}Li(n,α)^{3}H (1.5%) and the ^{7}Be(n,p)^{7}Li (≈1.5%) reactions. In total the uncertainty varies from 2% to 8% as the energy increases, as tabulated in the EXFOR file.

4. The data from Damone et al. (2018)

The data from Damone et al. (2018), that they used for the fit (i.e. below 35 keV), can be found, tabulated, on their wiki. Their table include the statistical errors but not the systematic uncertainties "mainly related to the sample inhomogeneity, is 10% from thermal to 50 keV, and could reach 15% above it, due to the estimated effect of the angular distribution assumption." (p. 4).

5. The data from Martín-Hernández et al. (2016)

The data for the reverse reaction ^{7}Li(p,n)^{7}Be measured by Martín-Hernández et al. (2016) is available on EXFOR but they "are normilized to Macklin and Gibbons and Newson data. Absolute determination of $\sigma_{\rm pn}$ was not possible due to the lack of reliable proton beam current indication." See Fig. 9 for comparison with their Fig. 11.

6. Data at thermal energy

Gledenov et al. (1987) data (EXFOR) show a large scatter with large error bars (see Fig. 1 in Damone et al. (2018)), hence they are not used, but their measurement at thermal energy ($E_{\rm n}$ = 0.024657 eV) gives $\sigma_{\rm th}$=49269 b without error bars. Other cross sections at thermal energy ($E_{\rm n}$ = 0.0253 eV or $E_{\rm cm}^{\rm ^7Be+n}$ = 0.0221 eV) are given in Table I.

A new measurement at thermal energy is reported by Tomandi et al. (2019). "The ^{7}Be(n,p) cross section was measured with an ion-implanted ^{7}Be target at a thermal neutron beam of the research reactor LVR-15 iine. The cross section to the ground state of ^{7}Li is σ(n,p$_0$) = 43800±1400 b and the cross section to the first excited state of ^{7}Li σ(n,p$_1$) = 520±260 b" is the only information available. It confirms that the absolute value of the cross section (e.g. Koehler et al. (1988) versus Damone et al. (2018)) is still uncertain.

7. Other data

Adahchour & Descouvemont (2003) also considered Borchers & Poppe (1963) and Poppe et al. (1976) in their calculations, but they corresponds to $E_{\rm cm}^{\rm ^7Be+n}$ above ≈1 MeV and ≈2 MeV, respectively.

References

A. Coc, P. Petitjean, J.-Ph. Uzan, E. Vangioni, P. Descouvemont, C. Iliadis and R. Longland, Phys. Rev. **D92** (2015) 123526 (20 pages), `arXiv:1511.03843 [astro-ph.CO]`.

C. Iliadis, K.S. Anderson, A. Coc, F.X. Timmes and S. Starrfield, Astrophys. J. **831** (2016) 107 (*19 pages*), `arXiv:1608.05853 [astro-ph.SR]`.

C. Pitrou, Coc, J.-Ph. Uzan, and E. Vangioni, *Phys. Rep.*, **754** (2018) 1–66, `arXiv:1801.08023 [astro-ph.CO]`.

L.E. Marcucci, M. Viviani, R. Schiavilla, A. Kievsky, and S. Rosati, Phys. Rev. C **72**, 014001 (2005).

L. E. Marcucci, G. Mangano, A. Kievsky, and M. Viviani, Phys. Rev. Lett. **116**, 102501 (2016)

S. Zavatarellia et al. (The LUNA Collaboration), proceedings of the *15th International Symposium on Nuclei in the Cosmos (NIC2018)*, Laboratori Nazionali del Gran Sasso, L'Aquila - Assergi, Italy June 24–29 2018

C. Angulo, M. Arnould, M. Rayet, P. Descouvemont, D. Baye *et al.*, Nucl. Phys. A **656**, 3 (1999) and `http: pntpm.ulb.ac.be/Nacre/nacre.htm`.

TABLE I Data files for he ^{7}Be(d,pα)^{4}He reaction.

Reference	$E_{\rm cm}^{^7\rm Be+n}$	File/ $\sigma_{\rm T}$	Comments	uncertainty
Gibbons & Macklin (1959)	1.44 keV–0.498 MeV	li7pn_gib59c	reverse	5%
	0.443 MeV–3.09 MeV	li7pn_gib59d	reverse	5%
Sekharan et al. (1976)	0.036 keV–2.0316 MeV	li7pn_sek76c	reverse	4%
	0.823 keV–0.16347 MeV	li7pn_sek76d	reverse	4%
Koehler et al. (1988)	2.3538×10^{-8}–1.1813×10^{-2} MeV	be7np-koe88b	direct	tabulated
Damone et al. (2018)	2.049×10^{-8}–3.247×10^{-2} MeV	be7np-dam18b	direct	tabulated+10–15%
Gledenov et al. (1987)*	0.53 eV–0.364 keV	be7np-gle86b	discarded	
Borchers & Poppe (1963)	0.979–7.06 MeV		discarded	
Poppe et al. (1976)	2.03–7.07 MeV		discarded	
Martín-Hernández et al. (2016)	0.34–7.04 keV	li7pn_mar16b	reverse&relative	
Hanna (1955)*	Thermal	$(5.3\pm0.8)\times10^{4}$ b		
Gledenov et al. (1987)*	Thermal	49269 b		n.a.
Koehler et al. (1988)	Thermal	38820±809 b	normalisation	
Červená et al. (1989)	Thermal	46800±4000 b		
Tomandi et al. (2019)	Thermal	44320±1424 b		

*Missing, data only from EXFOR.

P. Descouvemont, A. Adahchour, C. Angulo, A. Coc, and E. Vangioni-Flam, At. Data Nucl. Data Tables **88**, 203 (2004) and `http://pntpm.ulb.ac.be/bigbang/`.

E. G. Adelberger, A. García, R. G. Hamish Robertson, *et al.*, Rev. Mod. Phys. **83**, 195 (2011).

R.H. Cyburt, Phys. Rev. D **70**, 023505 (2004).

C. Casella, H. Costantini, A. Lemut, B. Limata, R. Bonetti, *et al.*, Nucl. Phys. A **706**, 203 (2002).

V.M. Bystritsky, V.V. Gerasimov, A.R. Krylov, S.S. Parzhitskii, G.N. Dudkin, *et al.*, Nucl. Inst. and Meth. A **595**, 543 (2008).

R.L. Schulte, M. Cosack, A.W. Obst, and J.L. Weil, Nucl. Phys. A **192**, 609 (1972).

L. Ma, H.J. Karwowski, C.R. Brune, Z. Ayer, T.C. Black, *et al.*, Phys. Rev. C **55**, 588 (1997).

G.M. Bailey, G.M. Griffiths, M.A. Olivio, and R.L. Helmer, Can. J. Phys. **48**, 3059 (1970).

G.M. Griffiths , E.A. Larson, and L. P. Robertson, Can. J. Phys. **40**, 402 (1962).

A. Coc and E. Vangioni *J. Phys.: Conf. Ser.* 202 (2010) 012001.

L. Damone, M. Barbagallo, M. Mastromarco, A. Mengoni, L. Cosentino, et al., Phys. Rev. Lett. **121**, 042701 (2018), and `ttps://twiki.cern.c`/twiki/bin/view/NTOFPublic/Be7npPaperDraft

S.Q. Hou, J.J. He, S. Kubono, and Y.S. Chen, Phys. Rev. C **91**, 055802 (2015).

S.Hayakawa, Proceedings of the *15th International Symposium on Nuclei in the Cosmos (NIC2018)*, Laboratori Nazionali del Gran Sasso, L?Aquila - Assergi, Italy June 24–29 2018

M. Barbagallo, A. Musumarra, L. Cosentino, E. Maugeri, S. Heinitz, A. Mengoni, et al., Phys. Rev. Lett. **117**, 152701 (2016)

R.V. Wagoner, W.A. Fowler and F. Hoyle Astrophys. J. **148** (1967) 3

A. Coc, E. Vangioni–Flam, P. Descouvemont, A. Adahchour, and C. Angulo, Astrophys. J. **600**, 544 (2004) `[astro-ph/0309480]`.

A. Coc, S. Goriely, Y. Xu, M. Saimpert, and E. Vangioni, Astrophys. J. **744**, 158 (2012).

G.R. Caughlan, W.A. Fowler, At. Data Nucl. Data Tables **40**, 283 (1988).

P.D. Parker, Astrophys. J. Phys. Rev. **175** (1972) 261–264.

R. W. Kavanagh, Nucl. Phys. **18** (1960) 492.

N. Chakraborty, B.D. Fields and K.A. Olive, Phys. Rev. D **83**, 063006 (2011).

C. Broggini, L. Canton, G. Fiorentini and F.L. Villante, Journal of Cosmology and Astroparticle Physics **06** (2012) 030.

Angulo C, Casarejos E, Couder M *et al.* 2005 Astrophys. J. Lett. **630** L105

O.S. Kirsebom, and B. Davids, Phys. Rev. C **84**, 058801 (2011).

O'Malley P D, Bardayan D W, Adekola A S *et al.*2011 Phys. Rev. C **84** 042801

Scholl C, Fujita Y, Adachi T *et al.*2011 Phys. Rev. C **84** 014308

N. Rijal, I. Wiedenhöver, J.C. Blackmon, M. Anastasiou, L.T. Baby, D.D. Caussyn, P. Höflich, K.W. Kemper, E. Koshchiy and G.V. Rogachev, `arXiv:1808.07893 [nucl-ex]`

R. de Souza, C. Iliadis, and A. Coc, Astrophys. J. *submitted*

R. de Souza, S. Reece Boston, A. Coc and C. Iliadis, Phys. Rev. C *submitted*

EXFOR at `http://www.nndc.bnl.gov/exfor/exfor.htm`

Koehler, P. E., Bowman, C. D., Steinkruger, F. J., et al. 1988, Phys. Rev. C, 37, 917 `exfor/servlet/X4sGetSubent?reqx=7682&subID=13163004`

K.K.Sekharan, H.Laumer, B.D.Kern, F.Gabbard, Nucl. Instrum. Methods **133**, 253 (1976)

M. Wang, G. Audi, A.H. Wapstra, F.G. Kondev, M. MacCormick, X. Xu, and B. Pfeiffer, Chinese Physics C **36** (2012) 1603

R.C. Hanna, Phil.Mag. 46, 381 (1955)

Gibbons, J. H., & Macklin, R. L. 1959, Physical Review, 114, 571

Adahchour, A., & Descouvemont, P. 2003, Journal of Physics G Nuclear Physics, 29, 395

Borchers, R. R., & Poppe, C. H. 1963, Physical Review, 129, 2679

Poppe, C. H., Anderson, J. D., Davis, J. C., Grimes, S. M., & Wong, C. 1976, Phys. Rev. C, 14, 438

Yu.M.Gledenov, T.S.Zvarova, M.P.Mitrikov, R.S.Mitrikova, Yu.P.Popov, V.I.Salatskiy, Fung-Van-Zuan, 1.Int.Conf.on Neutron Physics, Kiev,14-18 Sep 1987 Vol.2, p.232 (EXFORT).

Book: Atlas of Neutron Resonances, S.F.Mughabghab, 2006

Červená, J., Havránek, V., Hnatowicz, V., et al. 1989, Czechoslovak Journal of Physics, 39, 1263

Martín-Hernández, G., Mastinu, P., Maggiore, M., et al. 2016, Phys. Rev. C, 94, 034620

Martín-Hernández et al., Phys. Rev. C, *submitted*.

I. Tomandl, J. Vack, U. Kster, L. Viererbl, E. A. Maugeri, S. Heinitz, D. Schumann, M. Ayranov, J. Ballof, R. Catherall, K. Chrysalidis, T. Day Goodacre, D. Fedorov, V. Fedosseev, K. Johnston, B. Marsh, S. Rothe, J. Schell, and Ch. Seiffert, Phys. Rev. C, *in press*.