## Reaction : $^4$He($\alpha$n,$\gamma$)$^9$Be

We assume that the capture proceeds in two steps: a metastable $^8$Be is formed, which then captures a neutron. The formation of $^5$He followed by an $\alpha$ capture is neglected because of the short lifetime of $^5$He. The rate is calculated with an extension of the model presented in NO85 (see also GÖ95 for a simple, but crude approximation),

$$N_{\rm A}^2\langle\sigma v\rangle^{\alpha\alpha n} = N_{\rm A}\left(\frac{8\pi\hbar}{\mu_{\alpha\alpha}^2}\right)\left(\frac{\mu_{\alpha\alpha}}{2\pi k_{\rm B}T}\right)^{3/2}\int_0^\infty \frac{\sigma_{\alpha\alpha}(E)}{\Gamma_\alpha(^8{\rm Be},E)}\exp(-E/k_{\rm B}T)N_{\rm A}\langle\sigma v\rangle^{n\,^8{\rm Be}}\,E\,dE,$$

where $\mu_{\alpha\alpha}$ is the reduced mass of the $\alpha + \alpha$ system, and $E$ is the energy with respect to threshold. The elastic cross section and the corresponding parameters are discussed in the comments related to the $^4$He($\alpha\alpha,\gamma$)$^{12}$C reaction. The $N_{\rm A}\langle\sigma v\rangle^{n\,^8{\rm Be}}$ rate assumes that $^8$Be is formed at an energy $E$ different from the energy $E_{^8{\rm Be}}$ of the $^8$Be ground-state resonance, and that it is bound. This rate is given by

$$N_{\rm A}\langle\sigma v\rangle^{n\,^8{\rm Be}} = N_{\rm A}\frac{8\pi}{\mu_{n\,^8{\rm Be}}^2}\left(\frac{\mu_{n\,^8{\rm Be}}}{2\pi k_{\rm B}T}\right)^{3/2}\int_0^\infty \sigma_{n\,^8{\rm Be}}(E';E)\exp(-E'/k_{\rm B}T)\;E'\,dE',$$

where $\mu_{n\,^8{\rm Be}}$ is the reduced mass of the n + $^8$Be system and $E'$ is the energy with respect to its threshold (which varies with the formation energy $E$). We parametrize $\sigma_{n\,^8{\rm Be}}(E';E)$ as

$$\sigma_{n\,^8{\rm Be}}(E';E) = \sum_{J=1/2,5/2}\frac{1}{8}(2J+1)\,\frac{\pi\hbar^2}{2\mu_{n\,^8{\rm Be}}E'}\,\frac{\Gamma_n(^9{\rm Be}^J,E')\Gamma_\gamma(^9{\rm Be}^J,E'+E)}{(E'-E_{\rm r}^J+E-E_{^8{\rm Be}})^2+\frac{1}{4}\Gamma_n(^9{\rm Be}^J,E')^2},$$

where the sum runs over the $1/2^+$, $1/2^-$ and $5/2^+$ resonances at energies $E_{\rm r}^J$. This expression is related to the measured $^9$Be($\gamma$,n)$^8$Be photoneutron cross section. Early experimental data for the photoneutron cross section are summarized in LA66 and in BE67. The BE67 data are criticized in BA68a. We adopt the FU82 data around the $1/2^+$ resonance and the HU75 data at higher energies. For the $1/2^+$ resonance located just above threshold, we take the BA83 parametrization of the FU82 data. The neutron width of this $s$ wave resonance is given by $\Gamma_n(^9{\rm Be}^J,E') = \sqrt{E'/E_{\rm r}^J}\;\Gamma_n$, and its E1 $\gamma$ width by $\Gamma_\gamma(^9{\rm Be}^J,E'+E) = (E_T+E'+E-E_{^8{\rm Be}})^3/(E_T+E_{\rm r}^J)^3\;\Gamma_\gamma$, where the photon threshold energy $E_T$ is 1.644 MeV and $E_{\rm r}^J = 67$ keV, $\Gamma_n = 0.227$ MeV, $\Gamma_\gamma = 0.51 \pm 0.10$ eV. The error is deduced from Table 3 of FU82. The adopted $\gamma$ width differs from the value in KU87, which is not consistent with the KU87 electron scattering data (F.C. Barker, private communication). The $5/2^-$ resonance is neglected [BU98]. The broad $1/2^-$ resonance at $E_{\rm r}^J = 1.12 \pm 0.12$ MeV should be important at high temperatures [BU98]. Its total width is $1.08 \pm 0.11$ MeV and we assume $\Gamma_\gamma = 1$ WU for an M1 decay (0.45 eV) with an error of 80 % (see also DE89). For the $5/2^+$ resonance at $E_{\rm r}^J = 1.385$ MeV, we assume constant widths ($\Gamma_n = 0.282 \pm 0.011$ MeV from AJ88). The $\gamma$ width obtained from electron scattering in CL68 does not allow reproducing the photoneutron cross section of HU75. The adopted value $\Gamma_\gamma = 0.90 \pm 0.45$ eV is derived from this cross section with an increased error because of the smaller value in CL68. The differences with CA88 are due to many factors. We perform all integrations numerically. The adopted $\alpha$-width of the $^8$Be ground state is reduced [see $^4$He($\alpha\alpha,\gamma$)$^{12}$C]. Our rate is significantly larger below $T_9 = 0.025$ because of the energy dependence of $\Gamma_\alpha(^8{\rm Be},E)$, which is neglected in CA88. At higher temperatures, the rates differ because the photoneutron cross section in CA88 is parametrized as $\sigma_{\gamma n} = 1.6\exp(-4E)$ mb (with $E$ in MeV), rather than as a sum over resonances.

| $T_9$ | low | adopt | high | exp | ratio | $T_9$ | low | adopt | high | exp | ratio | $T_9$ | low | adopt | high | exp | ratio |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.001 | 2.14 | 3.90 | 5.80 | -59 | - | 0.04 | 1.48 | 1.90 | 2.33 | -15 | 0.4 | 0.5 | 5.90 | 7.50 | 9.09 | -7 | 0.7 |
| 0.002 | 1.43 | 2.50 | 3.66 | -47 | - | 0.05 | 2.01 | 2.58 | 3.15 | -13 | 0.4 | 0.6 | 5.78 | 7.34 | 8.91 | -7 | 0.7 |
| 0.003 | 0.79 | 1.35 | 1.95 | -41 | - | 0.06 | 5.01 | 6.43 | 7.84 | -12 | 0.4 | 0.7 | 5.38 | 6.84 | 8.30 | -7 | 0.7 |
| 0.004 | 3.35 | 5.58 | 8.00 | -38 | - | 0.07 | 4.80 | 6.14 | 7.48 | -11 | 0.5 | 0.8 | 4.89 | 6.22 | 7.56 | -7 | 0.7 |
| 0.005 | 1.28 | 2.11 | 3.00 | -35 | 1E58 | 0.08 | 2.53 | 3.24 | 3.94 | -10 | 0.5 | 0.9 | 4.40 | 5.60 | 6.80 | -7 | 0.7 |
| 0.006 | 1.21 | 1.96 | 2.78 | -33 | 1E45 | 0.09 | 0.90 | 1.15 | 1.40 | -9 | 0.5 | 1 | 3.93 | 5.00 | 6.08 | -7 | 0.8 |
| 0.007 | 4.61 | 7.39 | 10.4 | -32 | 1E36 | 0.1 | 2.44 | 3.12 | 3.79 | -9 | 0.5 | 1.25 | 2.96 | 3.78 | 4.60 | -7 | 0.8 |
| 0.008 | 0.94 | 1.48 | 2.07 | -30 | 1E29 | 0.11 | 5.42 | 6.92 | 8.41 | -9 | 0.5 | 1.5 | 2.26 | 2.89 | 3.52 | -7 | 0.8 |
| 0.009 | 1.20 | 1.88 | 2.62 | -29 | 1E24 | 0.12 | 1.04 | 1.33 | 1.61 | -8 | 0.5 | 1.75 | 1.76 | 2.26 | 2.75 | -7 | 0.8 |
| 0.01 | 1.08 | 1.69 | 2.34 | -28 | 1E20 | 0.13 | 1.78 | 2.27 | 2.76 | -8 | 0.5 | 2 | 1.40 | 1.80 | 2.20 | -7 | 0.8 |
| 0.011 | 0.75 | 1.16 | 1.60 | -27 | 1E17 | 0.14 | 2.80 | 3.57 | 4.34 | -8 | 0.6 | 2.5 | 0.93 | 1.21 | 1.49 | -7 | 0.8 |
| 0.012 | 4.15 | 6.37 | 8.77 | -27 | 1E14 | 0.15 | 4.11 | 5.23 | 6.35 | -8 | 0.6 | 3 | 6.69 | 8.87 | 11.0 | -8 | 0.9 |
| 0.013 | 1.93 | 2.95 | 4.04 | -26 | 1E12 | 0.16 | 5.70 | 7.25 | 8.80 | -8 | 0.6 | 3.5 | 5.05 | 6.83 | 8.61 | -8 | 1.0 |
| 0.014 | 0.78 | 1.18 | 1.61 | -25 | 1E10 | 0.18 | 0.96 | 1.22 | 1.49 | -7 | 0.6 | 4 | 3.97 | 5.48 | 6.99 | -8 | 1.0 |
| 0.015 | 2.76 | 4.17 | 5.69 | -25 | 1E8 | 0.2 | 1.43 | 1.82 | 2.21 | -7 | 0.6 | 5 | 2.67 | 3.83 | 5.01 | -8 | 1.2 |
| 0.016 | 0.89 | 1.33 | 1.81 | -24 | 1E7 | 0.25 | 2.74 | 3.48 | 4.22 | -7 | 0.6 | 6 | 1.94 | 2.88 | 3.83 | -8 | 1.5 |
| 0.018 | 0.70 | 1.05 | 1.42 | -23 | 1E5 | 0.3 | 3.93 | 4.99 | 6.06 | -7 | 0.7 | 7 | 1.48 | 2.26 | 3.04 | -8 | 1.7 |
| 0.02 | 4.27 | 6.29 | 8.48 | -23 | 1E3 | 0.35 | 4.84 | 6.14 | 7.45 | -7 | 0.7 | 8 | 1.16 | 1.81 | 2.47 | -8 | 1.9 |
| 0.025 | 2.11 | 2.99 | 3.92 | -21 | 2.0 | 0.4 | 5.44 | 6.90 | 8.37 | -7 | 0.7 | 9 | 0.94 | 1.48 | 2.03 | -8 | 2.1 |
| 0.03 | 3.88 | 5.05 | 6.24 | -19 | 0.4 | 0.45 | 5.77 | 7.33 | 8.89 | -7 | 0.7 | 10 | 0.77 | 1.23 | 1.70 | -8 | 2.3 |