Theoretical study of the $\alpha + d \rightarrow {}^6\mathrm{Li} + \gamma$ radiative capture and its implications for Big Bang Nucleosynthesis

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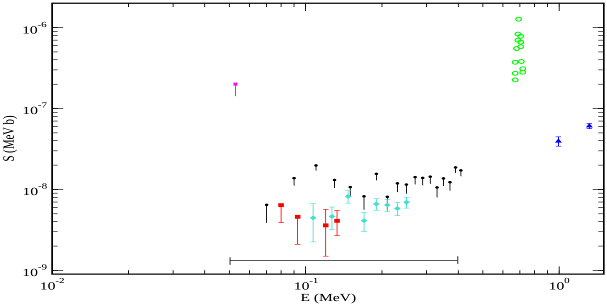
Results obtained in collaboration with:

- **Alessandro Grassi** (Master degree)
- G. Mangano e O. Pisanti (Napoli)

A. Grassi, G. Mangano, L.E. Marcucci, and O. Pisanti, arXiv:1707.09232, accepted in PRC

Motivations (I)

- $\alpha + d \rightarrow {}^6\mathrm{Li} + \gamma$: only reaction in BBN which produced ^{6}Li
- Asplund *et al.* (2006): experimental ^{6}Li/^{7}Li vs. BBN prediction: 2 orders of magnitude larger $\Rightarrow$ *Second lithium problem*
- If $\alpha + d \rightarrow {}^6\mathrm{Li} + \gamma$ underestimated $\rightarrow$ effects on ^{7}Li prediction (*First lithium problem*)
- BBN energy window: 50–400 keV. Poor experimental situation



Motivations (II)

Theoretical studies:

- Nollett *et al.*: "partially" *ab-initio* calculation
  - VMC for ^{6}Li but $\alpha + d \rightarrow$ two-body problem
  - IA+MEC for M_1 transition: consistent with zero
  - E_1 and E_2: LWA vs. Full very similar
- All other studies within a two-body framework $\Rightarrow$ crucial $V_{\alpha d}$
  - Hammache *et al.*, V_H (central + SO): ok B_6 & $\alpha + d$ scatt., no ANC
  - Tursunov *et al.*, V_T (central): ok B_6, $\alpha + d$ scatt. & ANC
  - Mukhamedzhanov *et al.*, V_M: same as V_H, corrected to get ANC
  - Dubovichenko: V_D (central + tensor): ok B_6, μ_6 & Q_6, no $\alpha + d$ scatt. & ANC

^{6}Li Observables	Experiment
B_6 [MeV]	1.475
μ_6 [n.m.]	-0.822
Q_6 [fm^2]	-0.0818(17)
C_0 [fm$^{1/2}$]	2.30(12) or 2.50(16)

^{6}Li g.s. $\equiv 1^+ \Rightarrow {}^3S_1 + {}^3D_1$

$$C_0 = \lim_{r \to +\infty} \frac{\varphi(r)}{W_{-\eta,\ell+1/2}(r)}\bigg|_{\ell=0}$$

Present calculation

- Two-body framework: α & d structureless constituents of ^{6}Li
- Used **all** the potentials in the original version (V_H, V_T, V_M), or corrected (V_D refitted to get $\alpha + d$ scatt.)
- New potential: V_D *healed* to get the correct ANC $\rightarrow$ V_G
  - "most realistic $\alpha + d$ potential" (V_G)
  - study of model-dependence
  - study of importance of D-states
- Long wavelength approximation: E_1 (suppressed) and E_2 (no M_1)

$$
\begin{aligned}
E_\Lambda(q) &\propto Z_e^{(\Lambda)}\,(qr)^\Lambda \\
Z_e^{(\Lambda)} &\equiv Z_d\left(\frac{m_\alpha}{m_\alpha + m_d}\right)^\Lambda + Z_\alpha\left(-\frac{m_d}{m_\alpha + m_d}\right)^\Lambda \\
&\rightarrow [Z_e^{(1)}]^2 \simeq 1.6\times 10^{-5} \quad \& \quad [Z_e^{(2)}]^2 \simeq 0.44
\end{aligned}
$$

From a "wrong" ANC to a "correct" one

Construction of a phase-equivalent potential which reproduces C_0^{EXP}

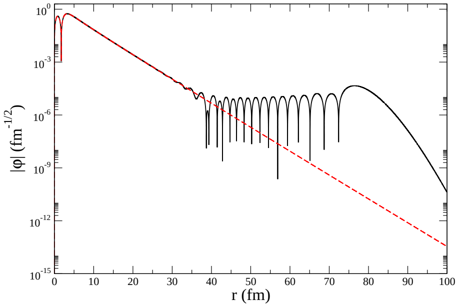
$$
\begin{aligned}
[T + V(r)]\,\varphi(r) &= E\varphi(r) \\
V(r) &\rightarrow V(r) + V_N(r) \\
V_N(r) &= -2\frac{\hbar^2}{2\mu}\frac{\mathrm{d}^2}{\mathrm{d}r^2}\ln\left[1 + (\tau - 1)\int_0^r \varphi^2(x)\mathrm{d}x\right] \\
\varphi_N(r) &= \sqrt{\tau}\frac{\varphi(r)}{1 + (\tau - 1)\int_0^r dx x^2\varphi^2(x)} \\
\lim_{r\to\infty}\varphi_N(r) &= \frac{\varphi(r)}{\sqrt{\tau}} \\
C_0 &= \frac{C_0^{old}}{\sqrt{\tau}}
\end{aligned}
$$

- Fix τ such that $C_0 = C_0^{EXP}$
- Generalized procedure for coupled channel

A.M. Mukhamedzhanov *et al.*, PRC **83**, 055805 (2011)

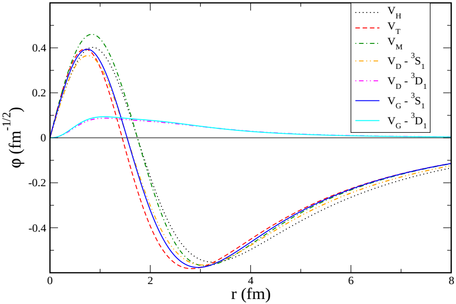
Numerical methods (I)

- Numerov method for bound (coupled-channel) and single-channel scattering states
- Variational method (expansion on a basis of Laguerre polynomials) for bound and scattering states

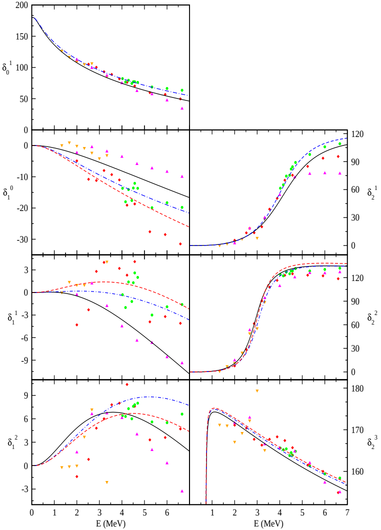


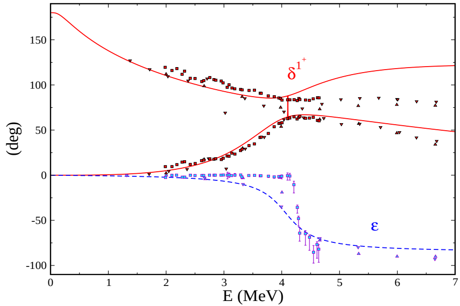
The ^{6}Li nucleus

Potential	B_6 [MeV]	C_0 [fm$^{1/2}$]	μ_6 [n.m.]	Q_6 [fm^2]
V_H	1.474	2.70	0.857	0.286
V_T	1.475	2.31	0.857	0.286
V_M	1.4735	2.30	0.857	0.286
V_D	1.4735	2.50	0.848	-0.066
V_G	1.4735	2.30	0.848	-0.051
EXP.	1.474	2.30	0.822	-0.082



The $\alpha + d$ scattering phase shifts

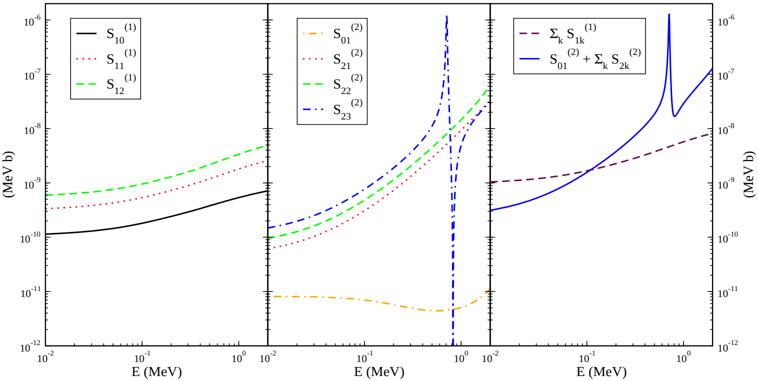




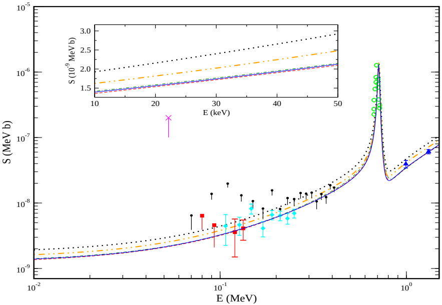
Results (I)

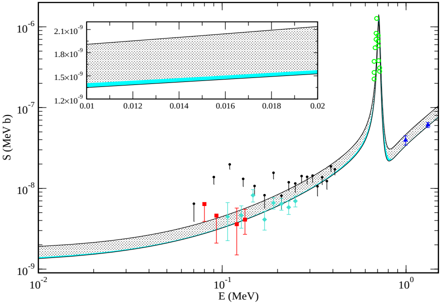
$$\sigma(E) = \sum_{\ell_i J_i \Lambda} \sigma^{(\Lambda)}_{\ell_i J_i}(E) \quad \Rightarrow \quad S(E) = \sum_{\ell_i J_i \Lambda} S^{(\Lambda)}_{\ell_i J_i}(E)$$

$$S^{(\Lambda)}_{\ell_i J_i}(E) = E\, \sigma^{(\Lambda)}_{\ell_i J_i}(E)\, \exp(2\pi\eta)$$



Results (II)





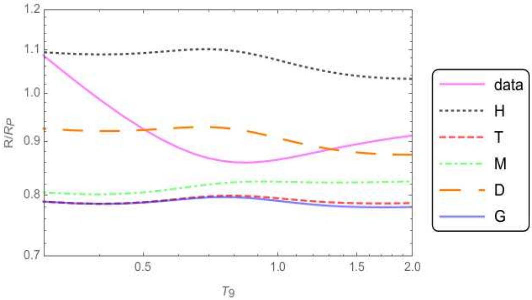
- Agreement with the data (easy...)
- Large differences between those potentials which reproduce the ANC and those which do not reproduce the ANC
- No significant contribution from *D*-states
- "Theoretical uncertainty" $\sim$ 20 % when ANC in not reproduced
- "Theoretical uncertainty" $\sim$ few % when ANC is reproduced

The ^{6}Li primordial abundance

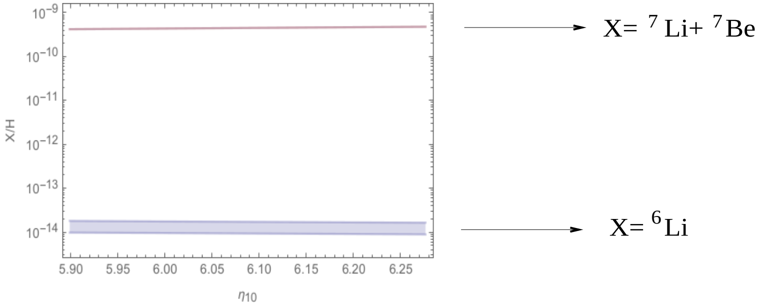
- Using PArthENoPE, study the ^{6}Li/H abundance

	NACRE 1999	Exp. data	V_H	V_T	V_M	V_D	V_G
^{6}Li/H $\times 10^{14}$	1.1	1.7	1.4	1.1	1.1	1.0	0.93

- ^{6}Li/H $= (0.9 - 1.4) \times 10^{-14}$ at Planck 2015 $\Omega_b h^2 = 0.00226$
- No enhancement



The ^{7}Li+^{7}Be primordial abundance



^{7}Li+^{7}Be/H= $(4.2 - 4.7) \times 10^{-10}$

- No dependence on the potential model used for the $\alpha + d$ reaction
- No changes respect to previous BBN predictions
- The Asplund *et al.* results are still unexplained

Future plan

- From a two-body to a three-body problem ($\alpha + n + p$)
  $\Rightarrow$ HH method for non-equal mass particles (work in progress)
- Work in progress to study the reaction within a "fully" *ab-initio* approach, solving a six-body problem
  (HH method for $A = 6$: see J. Dohet-Eraly's talk)
  $\longrightarrow$ Alex Gnech (PhD project)