$\alpha + d \rightarrow {}^6Li + \gamma$ astrophysical S-factor and its implications for Big Bang Nucleosynthesis

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Objectives

1. Analyses of the current phenomenological $\alpha - \mathbf{d}$ potentials in order to study the $\alpha + \mathbf{d} \rightarrow {}^6\mathbf{Li} + \gamma$ reaction at astrophysical energies.
2. Checking of the importance of the tensor contribution to the astrophysical *S*-factor. This tensor component is included in two new potentials.
3. Estimation for the theoretical error on the *S*-factor and compare the predictions with experimental data.

Introduction

- The interest for the $\alpha + \mathbf{d} \rightarrow {}^6\mathbf{Li} + \gamma$ reaction has grown recently due to the so-called *second Lithium problem*, *i.e.* a theoretical underestimation by a factor 1000 for the primordial ^{6}**Li** abundance with respect to experimental measurements. The primordial ^{6}**Li** abundance has been inferred from observations of spectral lines in old halo stars, where it is supposed to be the same as it was after the Big Bang Nucleosyntheses.

Quantum model

- The quantum approach to study the reaction starting from a 6-body framework proved to be complex and it still requires better numerical accuracy.
- The framework adopted uses the following approximations
  - The ^{6}**Li** nucleus has been considered to be a bound state of structureless α and **d** particles
  - The initial scattering state has been expanded in partial waves components and only states with $\ell \leq 2$ have been considered
  - The current operator have been decomposed to multipole moments operators and only electric dipole and quadrupole interactions have been kept
  - non relativistic approach for the nuclear current and Hamiltonian

Potential models

- The potential models for the $\alpha - \mathbf{d}$ interaction should reproduce
  - the ^{6}**Li** binding energy
  - the ^{6}**Li** asymptotic normalization coefficient (ANC)
  - the ^{6}**Li** magnetic dipole μ_6 and electric quadrupole $\mathbf{Q_6}$ moments
  - the $\alpha - \mathbf{d}$ partial scattering phase shifts
  - the ^{6}**Li** resonance at 711 keV
- **5** potential models have been adopted
  - a Wood-Saxon potential with a spin-orbit interaction ($\mathbf{V_H}$ [1])
  - a Gaussian potential ($\mathbf{V_T}$ [2])
  - a modified version of $\mathbf{V_H}$ to reproduce the ^{6}Li ANC ($\mathbf{V_M}$ [3])
  - a Gaussian potential with a **tensor term** $\Rightarrow \mu_6$ and $\mathbf{Q_6}$ + modified to fit the $\ell = 1$ and $\ell = 2$ phase shifts ($\mathbf{V_D}$ [4])
  - a **new** potential model with **tensor term** $\Rightarrow \mu_6$, $\mathbf{Q_6}$ and ^{6}Li ANC ($\mathbf{V_{ND}}$ [5])

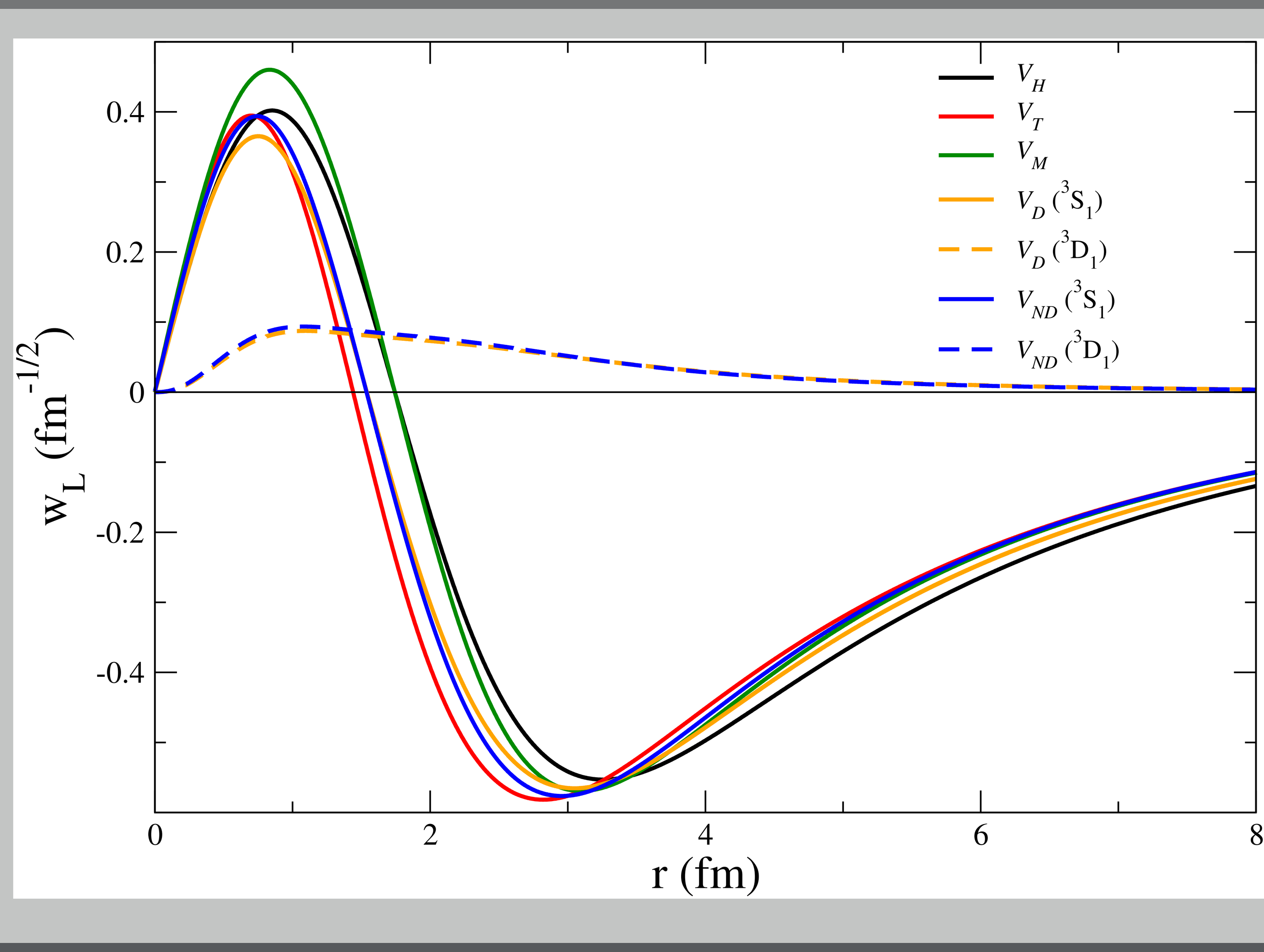
Bound state results

	$\mathbf{B_6}$	μ_6	$\mathbf{Q_6}$	$\mathbf{C_0}$
	MeV	μ_N	fm^2	fm$^{-1/2}$
$\mathbf{V_H}$	1.474	0.857	0.286	2.70
$\mathbf{V_T}$	1.475	0.857	0.286	2.31
$\mathbf{V_M}$	1.474	0.857	0.286	2.30
$\mathbf{V_D}$	1.4735	0.848	-0.066	2.50
$\mathbf{V_{ND}}$	1.4735	0.848	-0.051	2.30
Exp.	1.474	0.822	-0.082	2.30

$\mu_6 = \mu_d$, $\mathbf{Q_6} = \mathbf{Q_d}$ for potentials without tensor term

$\mathbf{P_D} = 1.59\%$ (1.76%) for $\mathbf{V_D}$ ($\mathbf{V_{ND}}$)

The ^{6}Li wave function



The S factor

- The observable of interest has been chosen to be the astrophysical *S*-factor, defined as

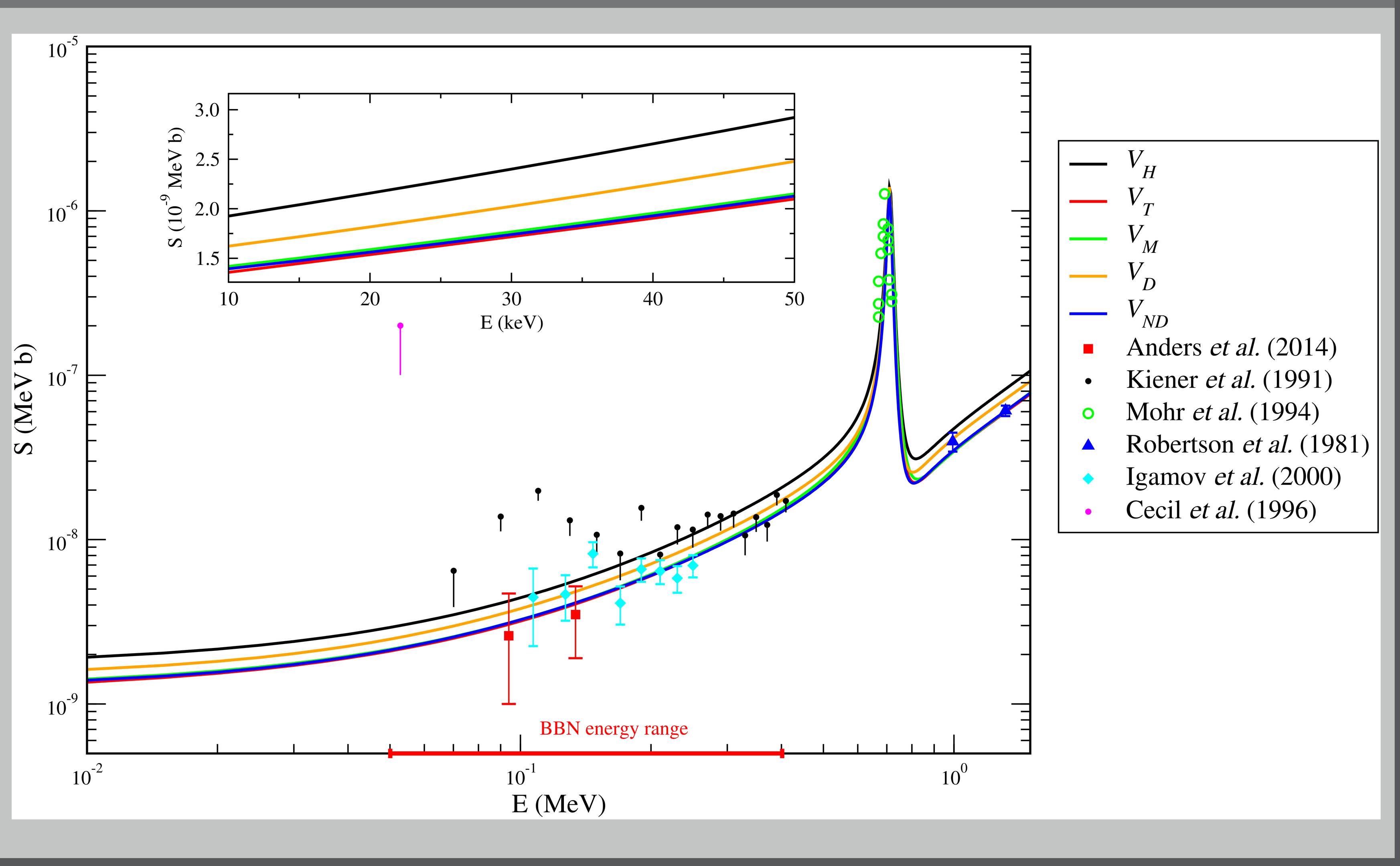
$$\mathbf{S(E)} = \sigma(\mathbf{E})\ \mathbf{E}\ \exp(\sqrt{\mathbf{E_G}/\mathbf{E}})$$

where $\mathbf{E_G} = 2\mu(\pi\alpha \mathbf{Z}_\alpha \mathbf{Z_d})^2$.

- the cross section $\sigma(\mathbf{E})$ is then expressed as a function of the electric and magnetic multipole operators ($\mathbf{E}_\Lambda^{\ell_i S_i J_i}$ and $\mathbf{M}_\Lambda^{\ell_i S_i J_i}$, respectively) as

$$\sigma(\mathbf{E}) = \frac{32\pi^2}{(2\mathbf{J}_\alpha + 1)(2\mathbf{J_d} + 1)\mathbf{v_r}} \frac{\alpha}{1 + \mathbf{q}/\mathbf{m_6}} \mathbf{q} \sum_{\Lambda \geq 1} \sum_{\ell_i S_i J_i} \left[\left| \mathbf{E}_\Lambda^{\ell_i S_i J_i} \right|^2 + \left| \mathbf{M}_\Lambda^{\ell_i S_i J_i} \right|^2 \right]$$

Results: data vs calculations



Conclusion

From the results showed in the above graph it can be stated that

- the ANC plays a crucial role for low astrophysical energies, as it can be seen from the fact that the three results for the potential which reproduce the ANC overlap
- the contribution for the ^{6}**Li** D-state is negligible
- it is impossible to rule out any of the studied potentials, due to the largeness of experimental data
- the theoretical uncertainty is **3%** for the models which reproduce the ANC and it grows to **17%** considering all models

References

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