Light nuclei under magnetic field and the lithium problem

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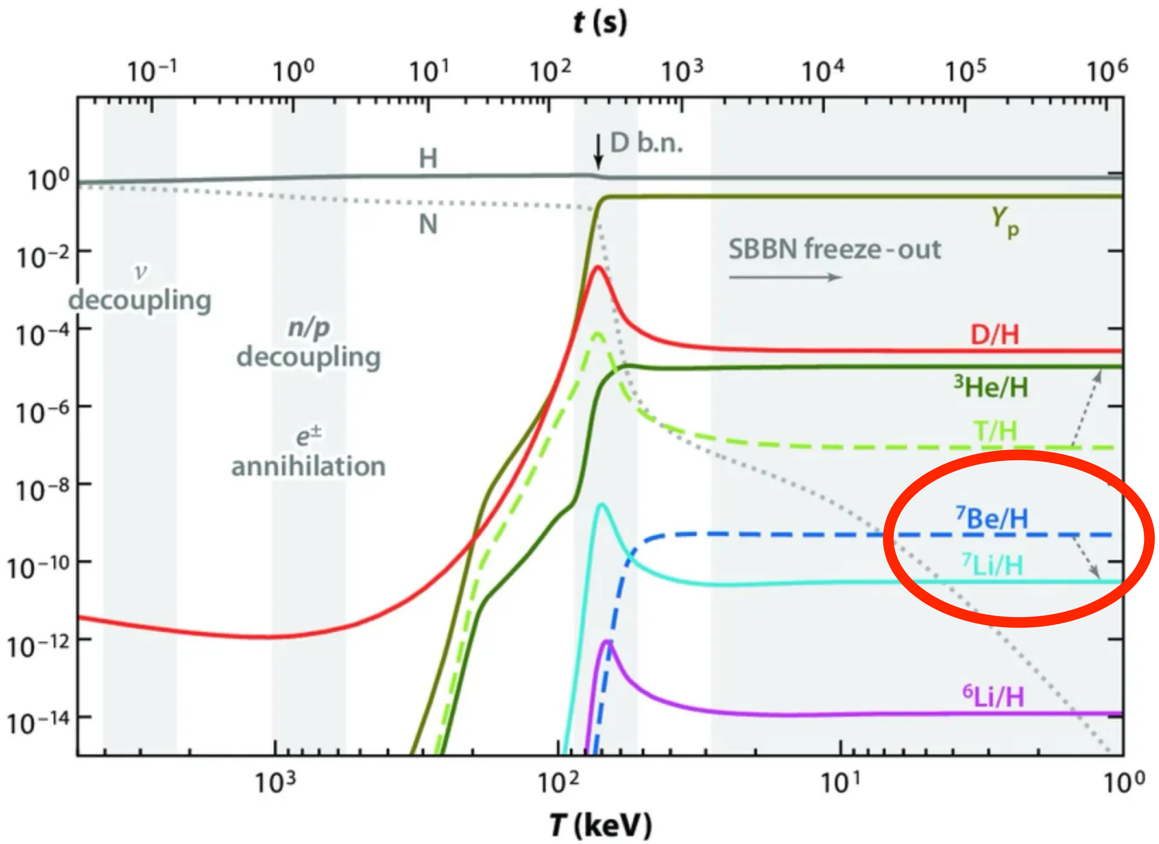
Based on NY, arXiv:2509.03684 [nucl-th].

Lithium problem

Abundance of light nuclei can be calculated with nuclear reaction data

P. Descouvemont et al., Atom. Data Nucl. Data Tabl. **88**, 203 (2004).



Too much ^{7}Be → ^{7}Li in theory !

https://tritonstation.com/2025/05/16/the-deuterium-lithium-tension-in-big-bang-nucleosynthesis/

Theory : ^{7}Li/H = 5 x 10^{-10}

Observed : ^{7}Li/H = 1.6 x 10^{-10}

➡ **Theory x3 excess!**

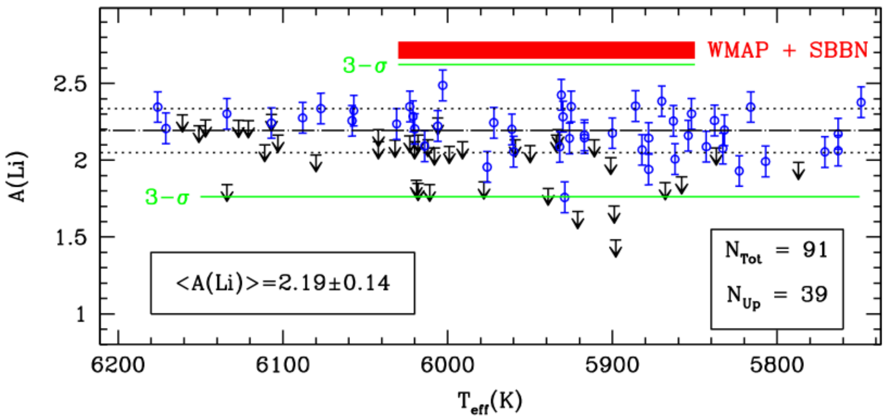
How to observe ^{7}Li abundance at BBN

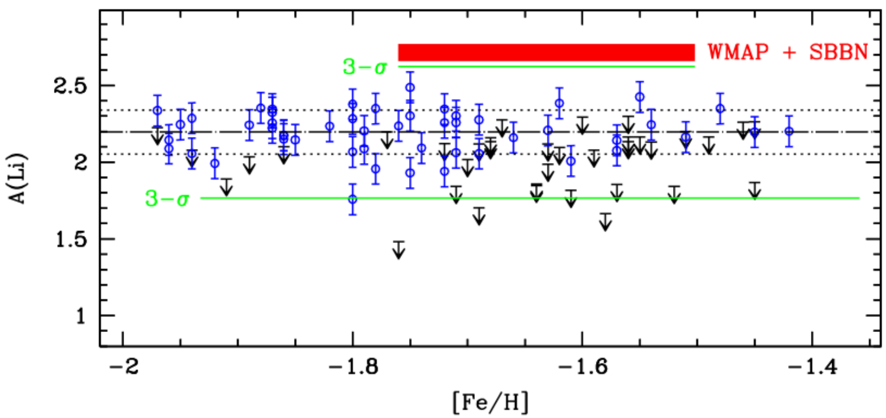
Count ^{7}Li in metal-poor stars

⇒ Almost constant ^{7}Li abundance for most of stars (Spite plateau)

⇒ ^{7}Li number is expected to be conserved since early Universe

F. Spite and M. Spite, Astron. Astrophys. **115**, 357 (1982).





L. Monaco et al., Astron. Astrophys. **519** (2010) L3.

^{7}Li abundance does not depend on temperature and metallicity (=age)

⇒ ^{7}Li conserved since BBN

Existing approaches to resolve Lithium problem

- **Revise experimental data**

  Reduction of ～10% for ^{7}Be+n→2α S. Hayakawa et al., Astrophys. J. Lett. **915**, L13 (2021).

- **Refine ^{7}Li abundance of metal-poor stars**

  Transport inside stars? Still debates Fu, Bressan, Molaro, Marigo, Spite, MNRAS **452**, 3256 (2015); O. D. Miranda, Astron. Astrophys. **701** (2025) A164.

- **Add new interactions or long-lived particles beyond standard model**

  Not discovered in LHC exp., fine-tuning problem, …

  Ellis, Kawasaki, Pospelov, Kamimura, …

- **Magnetic field?**

  Primordial magnetic field reduces ^{7}Li yield : partial resolution?

  Luo, Kajino, Kusakabe, Mathews, Astrophys. J. **872** (2019) 172.

  Screening of Coulomb barrier by plasma electrons?

  Park, Luo, Kajino, Phys. Rev. D **109**, 103002 (2024).

  What about the nuclear deformation?

  NY, arXiv:2509.03684 [nucl-th].

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  Recommended by Gemini (2026)

- Add new interactions or long-lived particles beyond standard model

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- Magnetic field?

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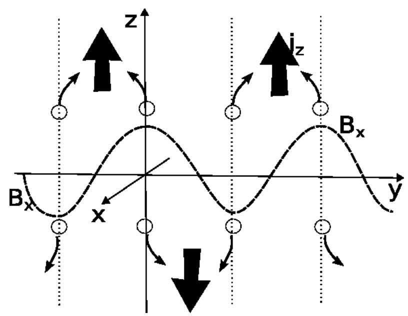
Magnetic field in plasma

Magnetic field was present in the early Universe

Magnetic field is not screened, has very long range effect

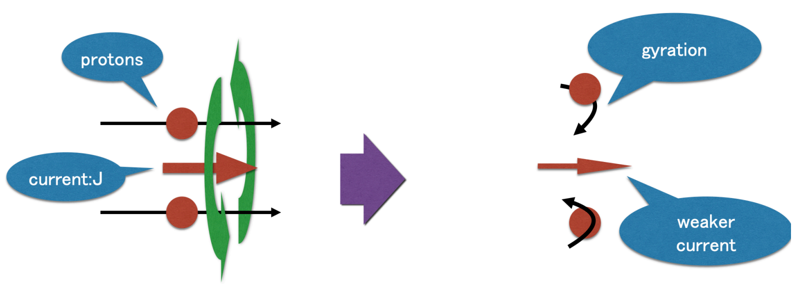
Plasma is unstable, magnetic field is generated by instability



Weibel instability :

Positive feedback between concentration of charged current and magnetic field

Magnetic field in plasma has an upper limit : Alfven current limit



Alfven current limit $\sim O(m_e) \sim T_{BBN}$

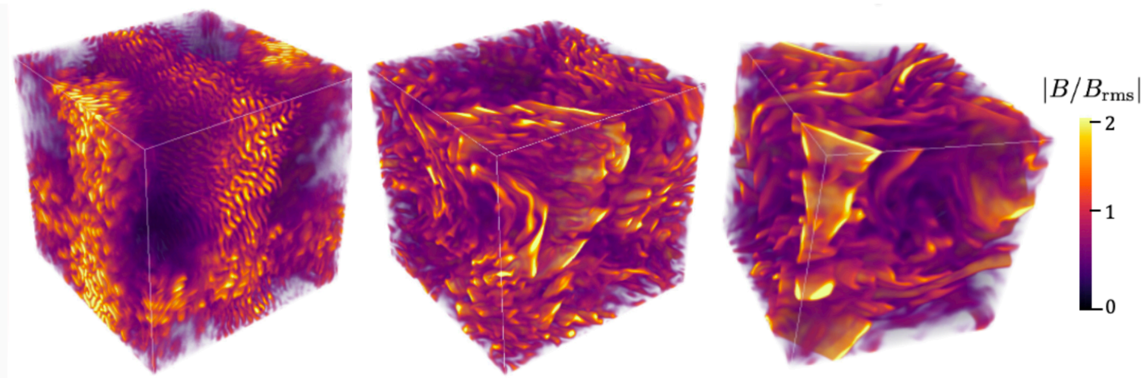
M. Takamoto et al., Astrophys. J. Lett. **860** (2018) 1, L1.

Strong magnetic field $\sim \alpha_{QED} T_{BBN}^2$?

Effect of magnetic field at BBN era is important?

Enhancement of magnetic field ?

Simulation of plasma with magnetic field

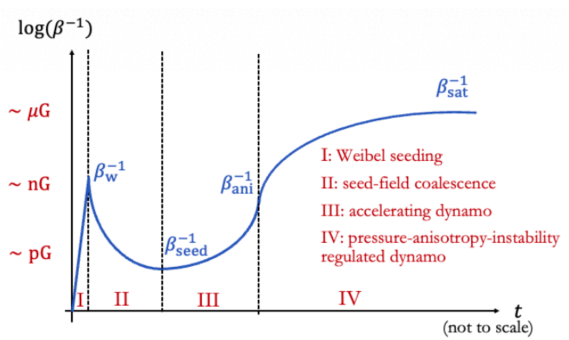


(This is not a full simulation with all BBN components)

M. Zhou et al., arXiv:2308.01924 [astro-ph.HE]

Typical magnetic field at BBN era : B $\sim 10^{11}$ G

$\sim$ (0.1 MeV)^2



Dynamo effect may further enhance magnetic field !

Still no consensus of magnetic field strength, but definitely existed at BBN era

What we did

Nucleon spin and orbital AM shifted by magnetic field B

Asymptotic exponential damp of wave function changes under B

Change low energy nuclear reactions with far penetration ?

May affect BBN yield ?

Objective:

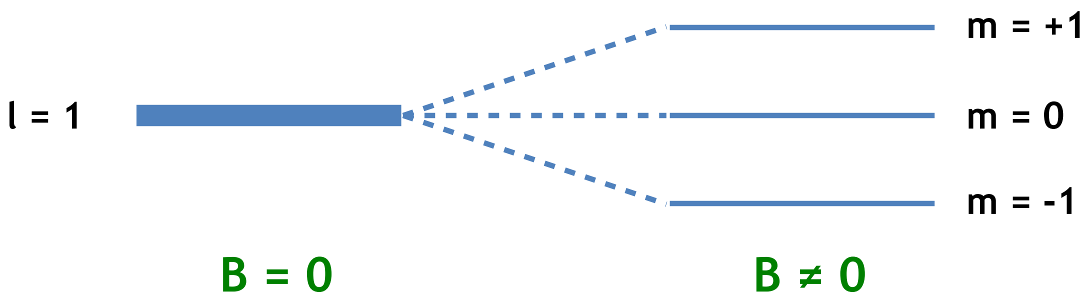
Evaluate the change of the structure of ^{2}H, ^{3}H, ^{3}He, ^{6}Li under magnetic field.

Solve Schroedinger eq. under magnetic field : Gaussian expansion method !

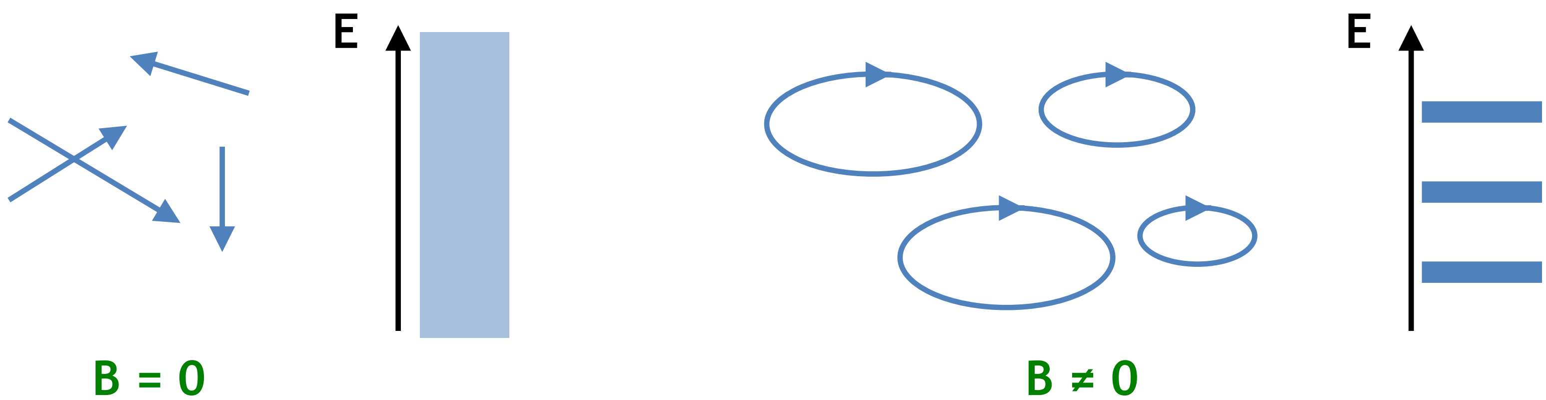
Effects of magnetic field on structure of composite systems

Magnetic field induces characteristic effects

Zeeman splitting



Cyclotron motion : 2-d confining force, formation of Landau levels



Hamiltonian of system under magnetic field

$$H = \sum_i^A \left[\frac{1}{2m_i} \left(\vec{p}_i - Q_i e \vec{A} \right)^2 - \vec{\mu}_i \cdot \vec{B} + m_i \right] + \sum_{i<j} V(\vec{r}_i - \vec{r}_j)$$

Using the symmetric gauge $\vec{A}(\vec{r}_i) = \frac{1}{2}\vec{B} \times \vec{r}_i$ and ignoring the center of mass motion, we have

$$H \approx \frac{\vec{p}^{\,2}}{m_N} \underbrace{- \frac{e}{2m_N}\vec{B} \cdot \vec{L} - (\vec{\mu}_p + \vec{\mu}_n) \cdot \vec{B}}_{\text{Zeeman splitting}} + \underbrace{\frac{e^2}{32 m_N} \left(\vec{B} \times \vec{r} \right)^2}_{\text{2D confining force}} + V(\vec{r})$$

- Typical (maximal) Zeeman splitting may be evaluated by polarizing the system along the magnetic field.

  ⇒ Leading contribution, only affects nuclei with nonzero spin

- 2D confining force : higher order in α_{QED}, small

Gaussian expansion method

How to solve few-body Schroedinger equation?

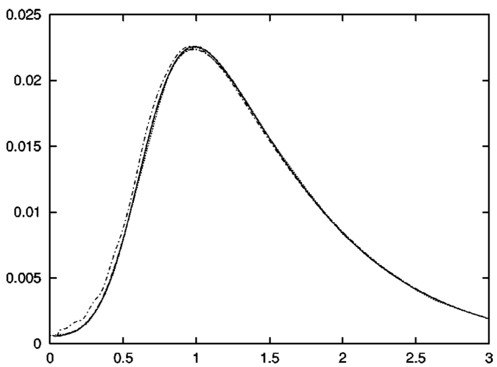
We use the Gaussian expansion method.

A sophisticated method to calculate few-body system

E. Hiyama *et al.*, Prog. Part. Nucl. Phys. **51**, 223 (2003).

- Basis function: $\phi_{lm}(\mathbf{r}) = \sum_n N_{nl} \sum_k C_{lm,k} e^{-\nu_n (\mathbf{r}-\mathbf{D}_{lm,k})^2}$
- Variational method
- Successful in the benchmark calculation of ^{4}He binding energy

  H. Kamada et al., Phys. Rev. C **64**, 044001 (2001).



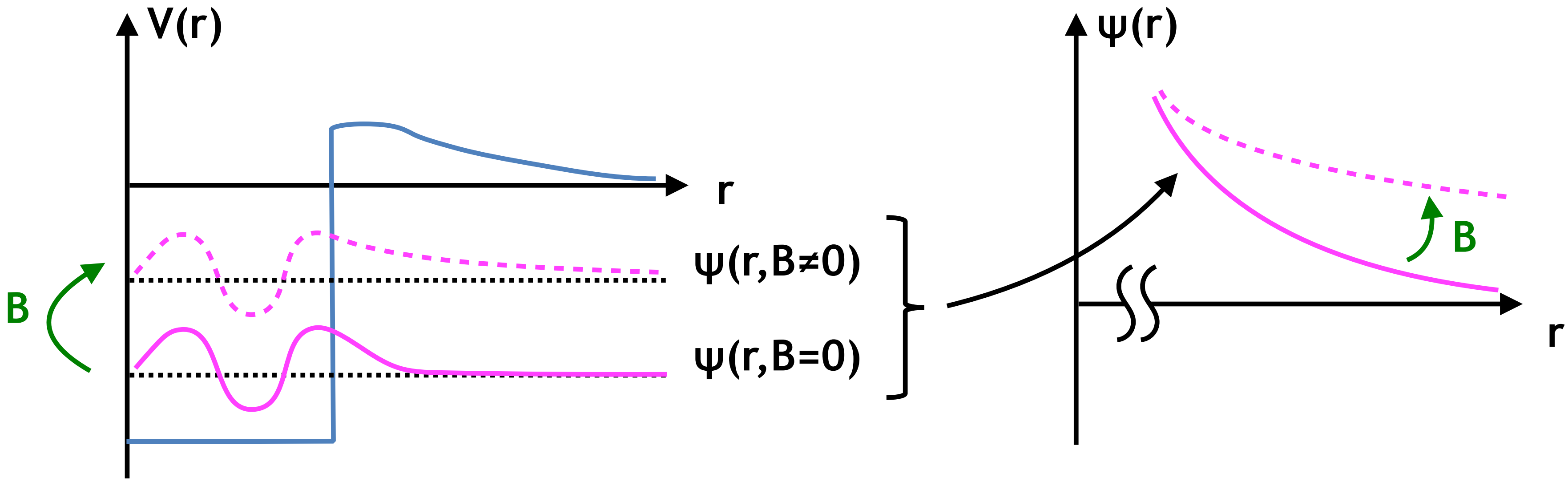
^{4}He Density distribution

- It was applied in many subjects:
  Nuclei, Hypernuclei, atoms, hadrons, astrophysics, particle physics…

We expect accurate calculation of structure!

What we expect

Magnetic field shifts nucleon energy (Zeeman effect)



⇒ Exponential tail changes N.B. $\psi(r) \sim e^{-\sqrt{2m(V_0 - E)}\ r}$

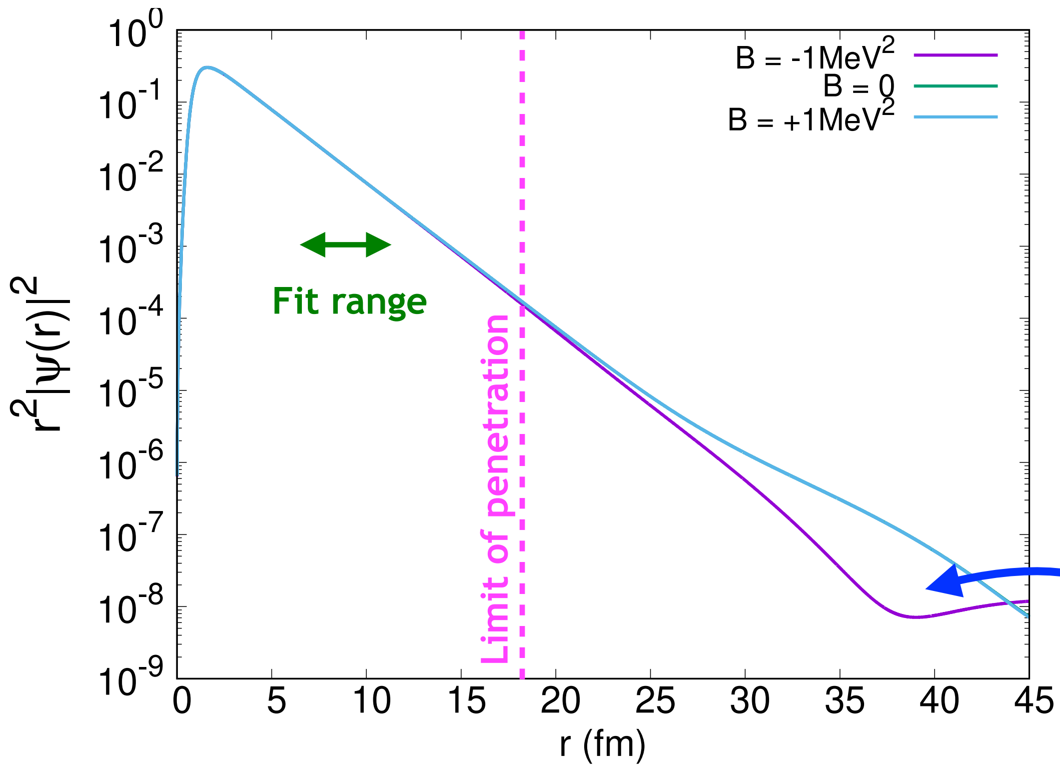
⇒ Enhancement of wave function / density at long distance !

Convenient to parametrize with asymptotic relative factor :

$$\frac{\rho_N(r)|_{B_z=B}}{\rho_N(r)|_{B_z=0}} \underset{r\to\infty}{\sim} e^{C_N(B)r}$$ (= enhancement due to magnetic field)

⇒ Qualitatively yields cross section enhancement !

Result of ^{2}H : Zeeman effect (real magnetic field at BBN)



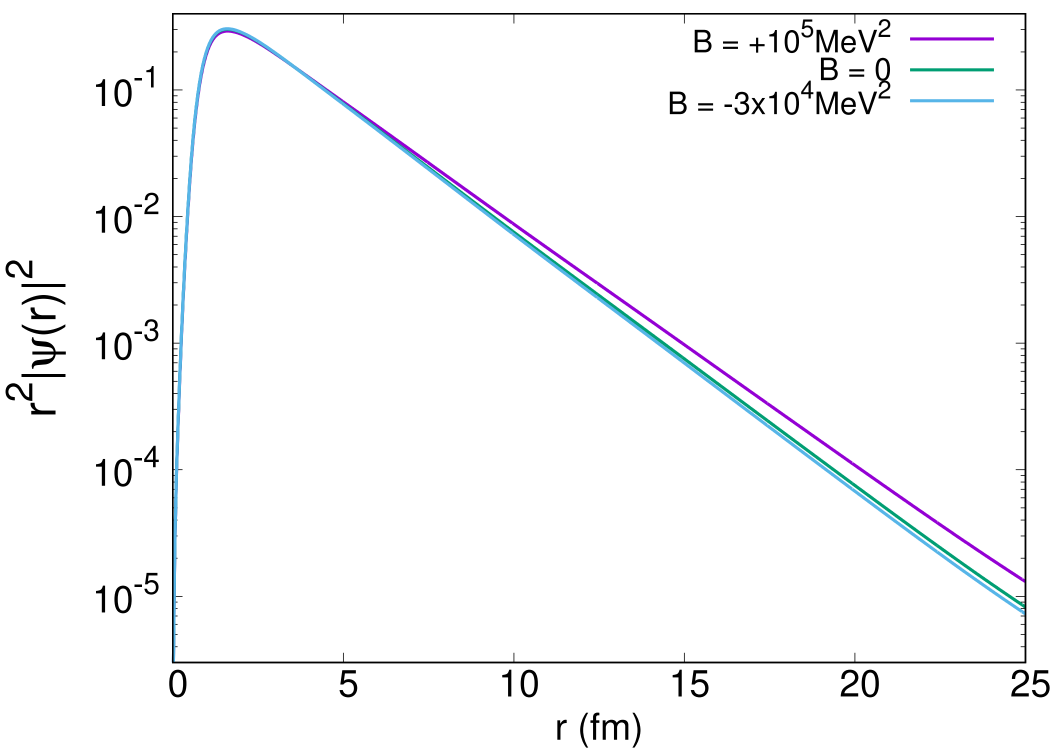
Tail behavior (beyond 20 fm) affected by large uncertainty,
quantification very difficult in variational method (c.f. triple alpha reaction)

⇒ We fit exponential damp in stable range (e.g. [7:12] fm)

The effect is too small for the deuteron at typical penetration depth
with BBN energy (0.1 MeV ～ 18 fm)

NY, arXiv:2509.03684 [nucl-th].

Result of ^{2}H : Zeeman effect (test with large magnetic field)



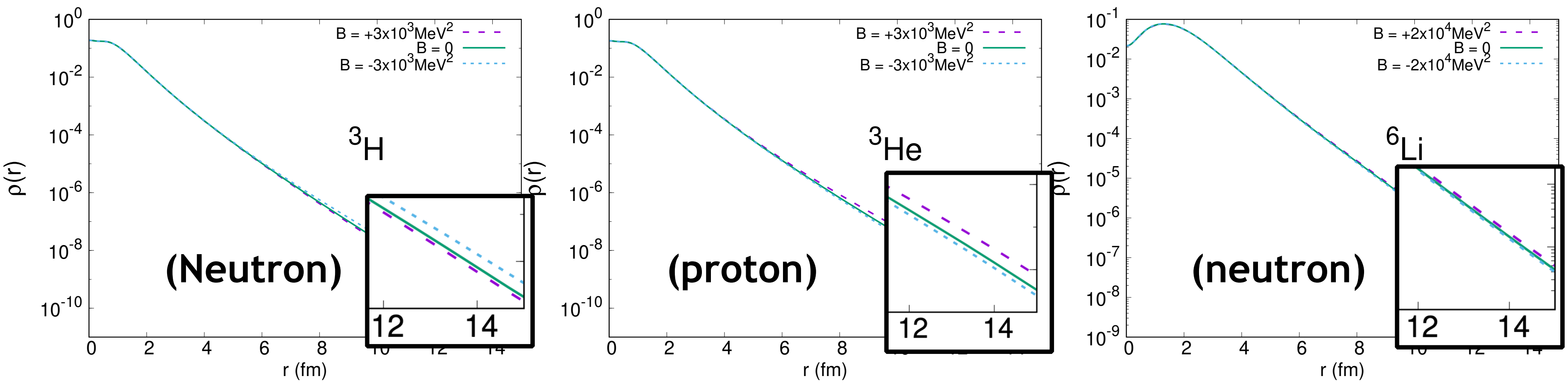
Change of exponential damp because magnetic field lifts the energy of spin and orbital angular momentum of states

⇒ Enhancement of wave function tail !

The effect is too small for the deuteron at typical penetration depth with BBN energy, but might be significant for larger nuclei with larger Coulomb barrier

NY, arXiv:2509.03684 [nucl-th].

Results of ^{3}H, ^{3}He, ^{6}Li



Exponential damp changes as expected !

Let us extract asymptotic relative factor : $\frac{\rho_N(r)|_{B_z=B}}{\rho_N(r)|_{B_z=0}} \sim e^{C_N(B)r} \quad (r \to \infty)$

Fit Taylor coefs. of exponent : $C_N(B) \approx C_N^{(1)} B + C_N^{(2)} B^2$

Nucleus	N	$C_N^{(1)}$ [MeV^{-2}.fm^{-1}]	$C_N^{(2)}$ [MeV^{-4}.fm^{-1}]
^{2}H	p, n	1.5×10^{-6}	2.8×10^{-12}
^{3}H	p	2.3×10^{-6}	-1.7×10^{-10}
	n	-1.5×10^{-5}	2.6×10^{-9}
^{3}He	p	1.7×10^{-5}	2.3×10^{-9}
	n	1.7×10^{-7}	2.0×10^{-10}
^{6}Li	p	5.4×10^{-7}	5.0×10^{-12}
	n	6.1×10^{-7}	4.0×10^{-12}

(Fitted in range [7:12] fm)

⇒ ^{3}H, ^{3}He sensitive to B

⇒ Small 2nd order coefs.

Exponent almost linear in B !

NY, arXiv:2509.03684 [nucl-th].

Enhancement does not resolve Lithium problem

^{3}He+α → ^{7}Be cross section is shifted by O(1) factor with B ∼ 800MeV^2 at BBN

⇒ Larger than typical magnetic field at BBN ∼O(0.1)MeV^2 ,

but there is another problem

In early Universe, nuclear polarization and magnetic field are fluctuating

⇒ Average 0 !

Take the average of asymptotic relative factor $\frac{e^{-C_N^{(1)}Br} + e^{+C_N^{(1)}Br}}{2} \geq 1$

⇒ Reaction rate always enhanced due to exponential dependence !

⇒ Enhancement aggravates Lithium problem…

We need other mechanisms

NY, arXiv:2509.03684 [nucl-th].

Possible resolutions of ^{7}Li problem

- Enhance ^{7}Be + p → ^{8}B (→α+α+β$^+$) at BBN era by magnetic field

  Large magnetic field (~10^{15}G) needed (assuming ^{7}Be = ^{3}He+α clusters)

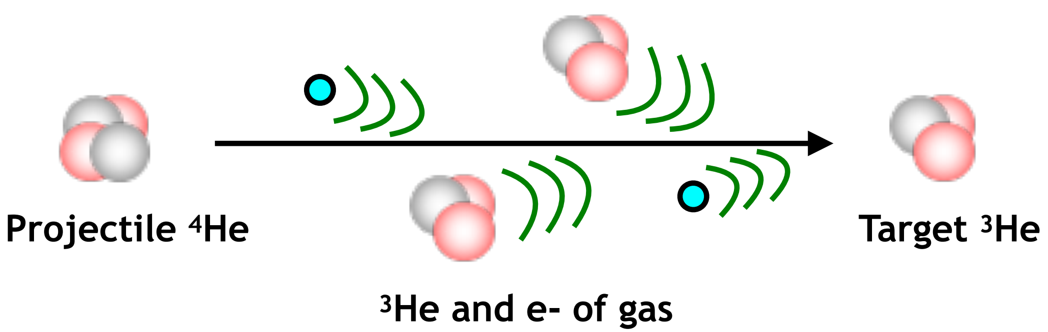
  ⇒ Evaluation of magnetic at BBN is needed (Weibel instability, dynamo,…)

  ⇒ Calculation of magnetic response of ^{7}Be is needed (ab initio ideally)

  Other possibility :
  Screening Coulomb barrier by electron under weak magnetic field ?

  Park, Luo, Kajino, Phys. Rev. D **109**, 103002 (2024).

- Enhance α + ^{3}He → ^{7}Be by systematic magnetic field of experiment



Magnetic field from passing near non-targets ?

α + ^{3}He → ^{7}Be exp. data are input of BBN simulation ⇒ affect BBN ^{7}Li yield

NY, arXiv:2509.03684 [nucl-th].

Summary

- We calculated the structure modification of ^{2}H, ^{3}H, ^{3}He, and ^{6}Li under magnetic field with Gaussian expansion method.
- Exponential tail of nucleon density shifts due to Zeeman effect : nuclear reaction rate is always enhanced at low energy by the magnetic field, even for fluctuating B with average 0!
- We proposed 2 solutions :
  (1) Increase $^{7}Be + p \rightarrow {}^{8}B$ by magnetic field at BBN.
  (2) Systematics of $^{3}He + \alpha$ reaction measurement due to magnetic field in experimental setup ?

Future prospects:

- Magnetic field is important systematics in low energy experiments?