The S-DALINAC and its experimental setups

E1 excitations around the particle threshold: the PDR
(TUD / U Giessen / RCNP + U Osaka / iThemba Labs / U Wits)

Electron scattering on $^{12}$C and the structure of the Hoyle state

Deuteron electrodisintegration under 180° and its importance for the primordial nucleosynthesis of the lightest nuclei

Supported by DFG under SFB 634
Key References for 3rd Lecture

**Pygmy Dipole Resonance:**

**Primordial Nucleosynthesis and Deuteron Photodesintegration:**

**Structure of the Hoyle State in \(^{12}\text{C}\) and Carbon Production in Stars:**
Experiments at the S-DALINAC

Status
1. Nuclear resonance fluorescence
2. (e,e') and 180° experiments
3. High-resolution (e,e') experiments

SFB
A. Polarized electron source
B. 14 MeV bremsstrahlung
C. 100 MeV bremsstrahlung for polarizability of the nucleon
D. Photon tagger
QCLAM Spectrometer
Si microstrip detector system:
4 modules, each 96 strips with pitch of 650 μm
Count rate up to 100 kHz
Energy resolution $1.5 \times 10^{-4}$
Considerable E1 strength is predicted and also observed below the $1\hbar\omega$ region.
E1 Excitations around the Particle Threshold

- Nuclear structure phenomenon
  
  Fundamental E1 mode below the GDR called Pygmy Dipole Resonance (PDR)

- Importance for understanding of exotic nuclei
  
  Will E1 strength be shifted to lower energies in neutron rich systems?

- Impact on nucleosynthesis
  
  Gamow window for photo-induced reactions in explosive stellar events
Impact on Nucleosynthesis

- **s-process**
- **r-process**
- **p- or \( \gamma \)-process**

PROTONS → NEUTRONS
Origin of the Photons

Cassiopeia A

Temperatures up to $3 \times 10^9$ K $\sim$ 200 keV
The Photon Density: Planck Spectrum

$T = 2.5 \times 10^9 \text{ K}$

typical threshold

$E_\gamma (\text{keV})$

$n_\gamma (\text{keV}^{-1} \text{fm}^{-3})$
What is the Relevant Energy Range?

Reaction rate: \[ \lambda(T) = c \int n_\gamma(E) \sigma(E) \, dE \]
Generation of Planck Spectra at the S-DALINAC

P. Mohr et al., PLB 488 (2000) 127
Photon Scattering off $^{138}\text{Ba}$

$^{138}\text{Ba}$

$E_{\text{max}} = 9.2$ MeV

A. Zilges et al., PLB 542 (2002) 43
E1 Strength Distribution in N=82 Nuclei

A. Zilges et al., PLB 542 (2002) 43, D. Savran et al., PLB 100 (2008) 232501
E1 Strength Distributions in Stable Sn Isotopes

+ Coulomb dissociation expt's at GSI on unstable $^{130}$Sn and $^{132}$Sn
Oscillations of a neutron or proton rich periphery vs. the core leads to isovector E1 excitations → role of PDR strength for determining the nuclear skin

- Soft Dipole Mode in exotic nuclei
- Located around 7 MeV in stable nuclei
- Up to 1% of EWSR in some stable nuclei → major contribution to the nuclear dipole polarizability

see e.g.: J. Chambers et al., PRC 50, R2671 (1994)  
P. van Isacker et al., PRC 45, R13 (1992)
What is the Microscopic Structure of the PDR?

Reminder: $^{208}\text{Pb}$

$^{208}\text{Pb}(\gamma,\gamma')$

$E_0 = 9.0\ \text{MeV}$

$\theta_\gamma = 130^0$

N. Ryezayeva et al., PRL 89, 272502 (2002)
Excellent agreement of QPM with experiment
Transition Densities

- PDR largely isoscalar
- Evidence for neutron density oscillations
- Similar results from the Milano and Munich groups
“Snapshots” of Velocity Distributions in $^{208}\text{Pb}$

Toroidal mode (within the PDR)

- **$E_x = 6.5 - 10.5 \text{ MeV}$**
- Toroidal (current) mode: zero sound wave
- Restoring force is not of hydrodynamic nature but elastic

GDR

- **$E_x > 10.5 \text{ MeV}$**
- Vibrational mode
Electric Dipole Strength and Vorticity

- **Vorticity density**: measure for the strength of the transverse current
Structure of Low-Energy E1 Modes

- How can we elucidate the structure of the low-energy E1 modes?

- Proton scattering at 0°
  - intermediate energy (300 MeV optimal)
  - high resolution
  - angular distribution (E1/M1 separation)
  - polarisation observables (spinflip / non-spinflip separation)

- Electron scattering (preferentially at 180°)
  - high resolution
  - transverse form factors needed
  - very sensitive to structure of the different modes
Proton Scattering at 0° on $^{208}$Pb

$^{208}$Pb($\bar{p},\bar{p}'$)

$E_p = 295$ MeV

$\Theta = 0° - 2.5°$

$\Delta E = 25$ keV
$\frac{d^2\sigma}{d\Omega dE}$ (mb/sr MeV)

Excitation Energy (MeV)

from ($\gamma,\gamma'$)

- E1
- E2
- M1
- J = 1

$^{208}$Pb($\bar{p},\bar{p}'$)

$E_p = 295$ MeV

$\Theta = 0^\circ - 2.5^\circ$
Measurement of Spin Observables

Scheme of the FPP / Grand Raiden Setup

\[ D_{SS'} \approx \frac{p'}{p_0} \]
At \( 0^\circ \), \( D_{SS'} = D_{NN'} \)

Total Spin Transfer \( \Sigma \) is given by:
\[ \Sigma \equiv \frac{3 - (2D_{SS} + D_{LL})}{4} \]

- 1 for \( \Delta S = 1 \)
- 0 for \( \Delta S = 0 \)

RCNP
\( E_0 = 295 \text{ MeV} \)
\( p_0 = 70 \% \)
Decomposition of the Cross Section into Spinflip / Non-Spinflip Parts

$^{208}\text{Pb}(\bar{p},\bar{p}')$

$E_p = 295\text{ MeV}$

$\Theta = 0^\circ - 2.5^\circ$
Multipole Decomposition of Cross Section

\[ \frac{d\sigma(\Theta)}{d\Omega} \bigg|_{\text{data}} = \sum_{\Delta L} a_{\Delta L} \frac{d\sigma(\Theta)}{d\Omega} \bigg|_{\text{DWBA}} \]

- Restrict angular distribution to \( \Theta = 4^\circ \) (response at larger angles too complex)
- \( \Delta L = 0 \rightarrow \) isovector spin M1
- \( \Delta L = 1 \rightarrow \) E1 (Coulomb + nuclear)
- \( \Delta L > 1 \rightarrow \) only E2 (or E3) considered
Multipole Decomposition of Cross Section: Examples

\( {}^{208}\text{Pb}(p,p') \)
\( E_p = 295 \text{ MeV} \)
\( \Theta = 0^\circ - 2.5^\circ \)

\( d^2\sigma / d\Omega dE \) (mb/sr MeV)

Excitation Energy (MeV)

\( \Delta E_x = 7.26-7.37 \text{ MeV} \)
\( \Delta E_x = 7.37-7.41 \text{ MeV} \)
\( \Delta E_x = 13.0-13.5 \text{ MeV} \)

\( d\sigma / d\Omega \) (mb/sr)

\( \Theta \) (deg)
Comparison of Both Methods

$\Delta S = 0$

$\Delta S = 1$

Total
B(E1) Strength: Low-Energy Region

$^{208}\text{Pb}(\gamma,\gamma')$

$^{208}\text{Pb}(p,p')$

$E_p = 295 \text{ MeV}$

$\Theta = 0^\circ - 0.8^\circ$

B(E1) ($e^2fm^2$)

Excitation Energy (MeV)
E1 Response in $^{208}\text{Pb}$

V.Yu. Ponomarev
(3 phonon resp. 2 phonon coupling, non-relativistic mean field)

E. Litvinova
(1 phonon $\otimes$ ph coupling, relativistic mean field)

Problem!
Polarized intermediate energy proton scattering at 0° is established to study B(E1) strength.

- PDR in $^{208}$Pb identified in ($\gamma,\gamma'$) and verified in ($\vec{p},\vec{p}'$)

- PDR fraction is $\sim 1\%$ EWSR and $5\%$ inverse EWSR (large contribution to the nuclear dipole polarizability)

- Polarized intermediate energy proton scattering at 0° is established to study B(E1) strength

- High-resolution study of $^{208}$Pb as reference case

- E1/M1 decomposition

- Detect PDR and toroidal signatures in (e,e') form factors and ($\vec{p},\vec{p}'$) angular distributions and spin-flip observables

- Importance of PDR in astrophysical processes
Astrophysical Importance of the Hoyle State

The Triple Alpha Process
(Helium Fusion)

http://outreach.atnf.csiro.au

Triple alpha reaction rate

\[ r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\frac{Q_{3\alpha}}{kT}\right) \]

\[ \Gamma_{rad} = \Gamma_{\gamma} + \Gamma_{\pi} = \frac{\Gamma_{\gamma}}{\Gamma} \cdot \frac{\Gamma}{\Gamma_{\pi}} \cdot \Gamma_{\pi} \]

(\(\alpha, \alpha', \gamma, \gamma\))

(\(p, p', e^+e^-\))

(\(e, e^-\) → ME → \(\Gamma_{\pi}\))

Reaction rate with accuracy \(\pm 6\%\) needed

S.M. Austin, NPA 758, 375c (2005)
**Uncertainties of the Astrophysical Relevant Quantities**

\[ r_{3\alpha} \propto \Gamma_{rad} \exp\left(-\frac{Q_{3\alpha}}{kT}\right) \]

\[ \Gamma_{rad} = \Gamma_{\gamma} + \Gamma_{\pi} = \frac{\Gamma_{\gamma}}{\Gamma} \cdot \frac{\Gamma_{\pi}}{\Gamma_{\pi}} \cdot \Gamma_{\pi} \]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{3\alpha} )</td>
<td>379.38 ± 0.20 keV</td>
<td>1.2 ( T_{\theta}=0.2 )</td>
</tr>
<tr>
<td>( \Gamma_{rad}/\Gamma )</td>
<td>( (4.12 \pm 0.11) \times 10^{-4} )</td>
<td>2.7</td>
</tr>
<tr>
<td>( \Gamma_{\pi}/\Gamma )</td>
<td>( (6.74 \pm 0.62) \times 10^{-6} )</td>
<td>9.2</td>
</tr>
<tr>
<td>( \Gamma_{\pi} )</td>
<td>( (62.0 \pm 6.0) \times 10^{-6} ) eV</td>
<td>9.7 [ Crannell et al. (1967) ]</td>
</tr>
<tr>
<td>( \Gamma_{\pi} )</td>
<td>( (59.4 \pm 5.1) \times 10^{-6} ) eV</td>
<td>8.6 [ Strehl (1970) ]</td>
</tr>
<tr>
<td>( \Gamma_{\pi} )</td>
<td>( (52.0 \pm 1.4) \times 10^{-6} ) eV</td>
<td>2.7 [ Crannell et al. (2005) ]</td>
</tr>
</tbody>
</table>

- Total uncertainty \( \Delta r_{3\alpha}/r_{3\alpha} = \pm 11.6\% \) presently
Transition Form Factor to the Hoyle State

$^{12}\text{C}(e,e')^{12}\text{C}$

$E_x = 7.65\text{ MeV}$

$0^+_1 \rightarrow 0^+_2$

- Extrapolation to zero momentum transfer
- Fourier-Bessel analysis

H. Crannell, data compilation (2005)
Measured Spectra

$^{12}\text{C}(e,e')$

$E_0 = 73 \text{ MeV}$

$\theta = 93^\circ$

Counts / $\mu$C

Excitation Energy [MeV]

$0^+_1$

$2^+_1$

$0^+_2$
Model-independent PWBA Analysis

\[
\left( \frac{d\sigma}{d\Omega} \right)_{PWBA} = 4\pi \left( \frac{e^2}{E_0} \right)^2 f_{rec} V_L(\theta) B(C_0, q)
\]

\[
4\pi B(C_0, q) = \left[ \langle 0^+_2 | \int \hat{\rho}_N j_0(qr) d^3r | 0^+_1 \rangle \right]^2
\]

\[
\langle r^\lambda \rangle_{tr} = \langle 0^+_2 | \int \hat{\rho}_N r^\lambda d^3r | 0^+_1 \rangle
\]

\[
ME = \langle r^2 \rangle_{tr}, \quad R^2_{tr} = \frac{\langle r^4 \rangle_{tr}}{\langle r^2 \rangle_{tr}}
\]

\[
\sqrt{4\pi B(C_0, q)} = \frac{q^2}{6} (ME) \left[ 1 - \frac{q^2}{20} R^2_{tr} + \cdots \right]
\]

\[
\Gamma_\pi \propto (ME)^2
\]

- Model-independent extraction of the partial pair width \( \Gamma_\pi \)
Model-independent PWBA Analysis

$^{12}\text{C}(e,e')^{12}\text{C}$
$E_x = 7.65 \text{ MeV}$
$0_1^+ - 0_2^+$

\[
\sqrt{4\pi} B(C0,q) = \frac{q^2}{6} (ME) \left[ 1 - \frac{q^2}{20} R_{tr}^2 + \cdots \right]
\]

- $ME = 5.37(7) \text{ fm}^2$, $R_{tr} = 4.30(12) \text{ fm}$ → $\Gamma_\pi = 59.6(16) \mu\text{eV}$
Fourier-Bessel Analysis

- Transition form factor is the Fourier-Bessel transform of the transition charge density

\[ F(q) = 4\pi \int_{0}^{\infty} \rho_{tr}(r) j_0(qr) r^2 \, dr \]

\[ \rho_{tr}(r) = \begin{cases} \sum_{\mu=1}^{\infty} a_{\mu} j_0(q_{\mu}r) & \text{for } r < R_c \\ 0 & \text{for } r \geq R_c \end{cases} \]

with

\[ q_{\mu} = \frac{\mu\pi}{R_c} \]

- Data should be measured over a broad momentum transfer range

- Uncertainty in the cut-off radius \( R_c \)
Fourier-Bessel Analysis

\[ \Gamma_{\pi} = 53.7(12) \, \mu eV \]

Remember:
Crannell et al. (2005): \( \Gamma_{\pi} = 52.0(14) \, \mu eV \)
Problems with FB Analysis and Cure

- Cut-off dependence
- Treatment of $q$-range where there are no data
- Non-physical oscillations of $\rho_{tr}$ at large radii
- Novel approach

\[
F_{tr}(q) = \frac{1}{Z} \cdot e^{-\frac{1}{2}(bq)^2} \cdot \sum_{n=1}^{n_{\text{max}}} c_n \cdot (bq)^{2n}
\]

\[
\rho_{tr}(r) = \frac{1}{b^3} \cdot e^{-\frac{1}{2}(\frac{r}{b})^2} \cdot \sum_{n=0}^{n_{\text{max}}} d_n \cdot \left(\frac{r}{b}\right)^{2n}
\]
Hoyle-State Transition Form Factor

\[ F_{\text{tr}}(q)^2 \]

\[ 12\text{C} \rightarrow 12\text{C} \]

\[ E_x = 7.654 \text{ MeV} \]

\[ 0_1^+ \rightarrow 0_2^+ \]
Hoyle-State Transition Density

Integral over $\rho_{tr}$: $r^4 \rightarrow ME \rightarrow \Gamma_\pi$
Transition Form Factor at low $q$

- Fit to low $q$ data very sensitive to experimental uncertainties
- However, global fit describes low $q$ data well
- Theoretical descriptions fail to describe the data
### Results

<table>
<thead>
<tr>
<th>Year</th>
<th>Analysis</th>
<th>Pair width</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>PWBA</td>
<td></td>
<td>Crannell et al.</td>
</tr>
<tr>
<td>1970</td>
<td>PWBA</td>
<td></td>
<td>Strehl</td>
</tr>
<tr>
<td>1970</td>
<td>Old average</td>
<td></td>
<td>Ajzenberg-Selove</td>
</tr>
<tr>
<td>2005</td>
<td>Fourier-Bessel</td>
<td></td>
<td>Crannell et al.</td>
</tr>
<tr>
<td>2008</td>
<td>PWBA</td>
<td></td>
<td>Present work</td>
</tr>
<tr>
<td>2008</td>
<td>Fourier-Bessel</td>
<td></td>
<td>Present work</td>
</tr>
<tr>
<td>2008</td>
<td>Global fit of world data</td>
<td></td>
<td>Present work</td>
</tr>
</tbody>
</table>

![Graph of $\Gamma_\pi$ vs. $\Gamma$]

- $\Gamma_\pi = 62.3(20) \mu$eV
- Uncertainty improved by a factor of about three
- Only $\Gamma_\pi/\Gamma$ needs still to be improved now
The Hoyle state is a prototype of $\alpha$-cluster states in light nuclei.

Cannot be described within the shell-model but within $\alpha$-cluster models.

Some $\alpha$-cluster models predict the Hoyle state to consist of a dilute gas of weakly interacting $\alpha$ particles with properties of a Bose-Einstein Condensate (BEC).

Comparison of high-precision electron scattering data with predictions of FMD and $\alpha$-cluster models.

Hoyle state cannot be understood as a true BEC.

M. Chernykh et al., PRL 98, 032501 (2007)
Some Theoretical Approaches Towards the Hoyle State: FMD model

- Antisymmetrized A-body state

\[ |Q\rangle = A(|q_1\rangle \otimes |q_2\rangle \otimes \ldots \otimes |q_A\rangle) \]

Single-particle states

\[ \langle x|q \rangle = \sum_i c_i \exp\left[ -\frac{(x - b_i)^2}{2a_i} \right] \otimes |\chi_{i}^{\uparrow}, \chi_{i}^{\downarrow} \rangle \otimes |\xi\rangle \]

Gaussian wave packets in phase space (\(a_i\) is width, complex parameter \(b_i\) encodes mean position and mean momentum), spin is free, isospin is fixed

Describes \(\alpha\)-cluster states as well as shell-model–like configurations

- UCOM interaction

Derived form the realistic Argonne V18 interaction

Adjusted to reproduce binding energies and charge radii of some “closed-shell” nuclei
Theoretical Approaches: $\alpha$-Cluster and “BEC” Models

- $\alpha$-cluster model
  - FMD wave function restricted to $\alpha$-cluster triangle configurations only

- “BEC” model
  - System of 3 $^4$He nuclei in 0s state (like $\alpha$ condensate)
  - Hoyle state is a “dilute gas” of $\alpha$ particles

- Volkov interaction
  - Simple central interaction
  - Parameters adjusted to reproduce $\alpha$ binding energy, radius, $\alpha-\alpha$ scattering data and ground state energy of $^{12}$C
  - Only reasonable for $^4$He, $^8$Be and $^{12}$C nuclei
12C Densities

- Ground state density can be tested via elastic form factor
- Transition density can be tested via transition form factor
- Note the depression of the central density
- Electron scattering as test of theoretical predictions
Elastic Form Factor

$^{12}\text{C}(e,e)^{12}\text{C}$

$E_x = 0.00$ MeV

$0^+_1$

\[ \frac{d\sigma}{d\Omega} \]

$\text{Exp}$

- FMD
- $\alpha$ cluster
- "BEC"

- Described well by FMD
Transition Form Factor to the Hoyle State

Described better by $\alpha$-cluster models

FMD might be improved by taking $\alpha-\alpha$ scattering data into account

H. Crannell, data compilation (2005)
What is the Actual Structure of the Hoyle State?

- Overlap with FMD basis states

|<1|0^+>| = 0.30 |<2|0^+>| = 0.25 |<3|0^+>| = 0.15 |<4|0^+>| = 0.08 |<5|0^+>| = 0.94
|<1|0^0>| = 0.72 |<2|0^0>| = 0.71 |<3|0^0>| = 0.61 |<4|0^0>| = 0.61 |<5|0^0>| = 0.04

- In the FMD and $\alpha$-cluster model the leading components of the Hoyle state are cluster-like and resemble $^8\text{Be} + ^4\text{He}$ configurations

- But in the “BEC” model the relative positions of $\alpha$ clusters should be uncorrelated
Model Predictions at Low Momentum Transfer

Theory systematically overpredicts experiment
Elastic and Transition Form Factors at Low Momentum Transfer

\[ |F_{el}(q^2)|^2 \approx 1 - \frac{q^2 \langle r^2 \rangle}{6} + \ldots \]

\[ F_{tr}(q^2) \propto \frac{q^2 \langle r^2 \rangle_{tr}}{6} - \frac{q^4 \langle r^4 \rangle_{tr}}{120} + \ldots \]

Slope is defined by \( \langle r^2 \rangle \) term

Slope is defined by \( \langle r^4 \rangle_{tr} \) term

\[ \Gamma_\pi \propto (ME)^2 \propto |F_{tr}(q = 0)|^2 \text{ also} \]
Summary

Hoyle state is very important in astrophysics

Pair width $\Gamma_\pi$ for the decay of the Hoyle state has been determined from $(e,e')$

Hoyle state is not a true “Bose-Einstein condensate”

$^8\text{Be} + \alpha$ structure

Outlook

$^{12}\text{C}$: $0^+_3$ and $2^+_2$ states

$^{16}\text{O}$: 6th excited $0^+$ state at 15.1 MeV is the “Hoyle” state? $\rightarrow ^{16}\text{O}(e,e'\alpha)$

Kyoto/Orsay (2008)
Deuteron Electrodisintegration under 180°

- Astrophysical motivation: Big-Bang nucleosynthesis

- Experiment: 180° electron scattering
  - High selectivity
  - High energy resolution

- Precision test of theoretical models
  - NN potentials
  - EFT

- Summary and outlook

N. Ryezayeva et al., PRL 100, 172501 (2008)
D, $^3$He, $^4$He, $^7$Li are synthesized
Test of Cosmological Standard Model

- Abundances depend on baryon/photon ratio (baryon density)

- Observational constraints: WMAP disagrees with spectroscopic information and/or BBN

- Critical density derived from $^4\text{He}$ and $^7\text{Li}$ is different from D

Uncertainty of $^7$Li Abundance

- Largest uncertainty from $p(n,\gamma)d$ reaction
- Relevant energy window 15 - 200 keV above threshold

S. Burles et al., PRL 82, 4176 (1999)
Potential model (AV18) calculations by H. Arenhövel

EFT calculations (J.-W. Chen and M.J. Savage, S. Ando et al.) are very similar

Scarce data at the threshold

M1 dominates: \(d(e,e')\) at 180°
Why Electron Scattering under 180°?

\[
\frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_L + \left( \frac{d\sigma}{d\Omega} \right)_T
\]

\[V_L \times |F_L(q)|^2\]

\[V_T \times |F_T(q)|^2\]

Scattering at 180° is ideal for measuring transverse excitations: M1 enhanced
180° System at the S-DALINAC

Diagram showing the layout of the system, including:
- Incident Beam
- Chicane
- Scattering Chamber
- Separating Magnet
- Target
- QCLAM Spectrometer
- Refocusing Quadrupoles
- Deflecting Coils
- To Faraday Cup

Scale: 0 to 1 m
Decomposition of the Spectra

- Absolute and relative normalization agree within 5 - 6%
Comparison to Potential Model and EFT Calculations

Excellent agreement with potential model (H. Arenhövel)

Deviations for EFT (H. Griesshammer) at higher $q$
Extraction of the Astrophysical $np \rightarrow d\gamma$ Cross Section

- $\frac{d\sigma}{d\Omega}(\theta = 180^\circ, q) \sim F_T^2(q)$

- $B(M1, q) \sim \frac{1}{q^2} F_T^2(q)$

- For $q \rightarrow k$ (photon point) take $q$-dependence of $B(M1,q)$ from elastic scattering $\rightarrow \Gamma_\gamma$

- $\sigma(d\gamma \rightarrow np) \sim \frac{1}{E_\gamma^2} \frac{\Gamma_n\Gamma_\gamma}{(E_\gamma - E_R)^2 + \Gamma^2/4}$

- Detailed balance $\rightarrow \sigma(np \rightarrow d\gamma)$
Importance for Big-Bang Nucleosynthesis

- BBN relevant energy window
- Precision test of modern theoretical models (potential model, EFT)
Summary

- 180° measurements of the M1 deuteron breakup
- Precision test of modern theoretical models (potential model, EFT)
- Excellent description of the data
- Precise prediction for $p(n,\gamma)d$ cross section possible in the astrophysically relevant region
- Latest BBN calculations use already EFT calculations

Outlook

- $^9\text{Be}(e,e^{'})$ under 180°