Nuclear Astrophysics

Aurora Tumino
(EXPERIMENTAL) NUCLEAR ASTROPHYSICS

- study energy generation processes in stars
- study nucleosynthesis of the elements

• What is the origin of the elements?
• How do stars/galaxies form and evolve?
• What powers the stars?
• How old is the universe?
• ...

NUCLEAR PHYSICS

KEY for understanding

MACRO-COSMOS intimately related to MICRO-COSMOS
... Everything starts from the B²FH review paper of 1957, the basis of the modern nuclear astrophysics. This work has been considered as the greatest gift of astrophysics to modern civilization.

The elements composing everything from planets to life were forged inside earlier generations of stars!

Nuclear reactions responsible for both ENERGY PRODUCTION and CREATION OF ELEMENTS
1. H burning $\rightarrow$ conversion of H to He
2. He burning $\rightarrow$ conversion of He to C, O ...
3. C, O and Ne burning $\rightarrow$ production of A: 16 to 28
4. Si burning $\rightarrow$ production of A: 28 to 60
5. s-, r- and p-processes $\rightarrow$ production of A>60
6. Li, Be, and B from cosmic rays
Nuclear reactions in stars:  

a) produce energy  
b) synthesise elements

stars = cooking pots of the Universe

for reaction:  \( 1+2 \rightarrow 3+4 \)

Total reaction rate:

\[
R_{12} = (1+\delta_{12})^{-1} N_1 N_2 \langle \sigma v \rangle_{12} \text{ reactions cm}^{-3} \text{ s}^{-1}
\]

\( N_i = \text{number density} \)

\[
\langle \sigma v \rangle = \int \sigma(v)\phi(v)v dv
\]

Energy production rate:

\[
\epsilon_{12} = R_{12} Q_{12}
\]

reaction Q-value:

\[
Q = [(m_1+m_2)-(m_3+m_4)]c^2
\]

Mean lifetime of nucleus 1 against destruction by nucleus 2

\[
\tau_2(1) = \frac{1}{N_2 \langle \sigma v \rangle}
\]

energy production as star evolves

\[
\langle \sigma v \rangle = \text{KEY quantity}
\]

change in abundance of nuclei X

to be determined from experiments and/or theoretical considerations
stellar reaction rate \[ \langle \sigma v \rangle = \int \sigma(v) \phi(v) v dv \]

need: a) velocity distribution \( \phi(v) \)
b) cross section \( \sigma(v) \)

**a) velocity distribution**

interacting nuclei in plasma are in thermal equilibrium at temperature \( T \)
also assume non-degenerate and non-relativistic plasma
⇒ Maxwell-Boltzmann velocity distribution

\[
\phi(v) = 4\pi \left( \frac{\mu}{2\pi kT} \right)^{3/2} v^2 \exp \left( - \frac{\mu v^2}{2kT} \right)
\]

with \( \mu = \frac{m_p m_T}{m_p + m_T} \) reduced mass

\( v = \) relative velocity

\[ kT \sim 8.6 \times 10^{-8} T[K] \text{ keV} \]

**example:** Sun \( T \sim 15 \times 10^6 \text{ K} \) \( \Rightarrow \) \( kT \sim 1 \text{ keV} \)
b) cross section

no nuclear theory available to determine reaction cross section a priori

cross section depends sensitively on:

- the properties of the nuclei involved
- the reaction mechanism

and can vary by orders of magnitude, depending on the interaction

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Force</th>
<th>$\sigma$ (barn)</th>
<th>$E_{\text{proj}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{15}\text{N}(p,\alpha)^{12}\text{C}$</td>
<td>strong</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>$^{3}\text{He}(\alpha,\gamma)^{7}\text{Be}$</td>
<td>electromagnetic</td>
<td>$10^{-6}$</td>
<td>2.0</td>
</tr>
<tr>
<td>$p(p,e^+\nu)d$</td>
<td>weak</td>
<td>$10^{-20}$</td>
<td>2.0</td>
</tr>
</tbody>
</table>

1 barn = $10^{-24}$ cm$^2$ = 100 fm$^2$

in practice, need **experiments AND theory** to determine stellar reaction rates
reaction mechanisms:

I. direct (non-resonant) reactions
II. resonant reactions
**I. direct (non-resonant) process**

one-step process

direct transition into a bound state

example: radiative capture \( A(x, \gamma)B \)

\[ \sigma_\gamma \propto \left| \left\langle B | H_\gamma | A + x \right\rangle \right|^2 \]

\( H_\gamma = \) electromagnetic operator describing the transition

- reaction cross section proportional to **single matrix element**
- can occur at **all projectile energies**
- **smooth energy dependence** of cross section

other direct processes: stripping, pickup, charge exchange, Coulomb excitation
II. resonant process

two-step process

e.g. resonant radiative capture $A(x, \gamma)B$

1. Compound nucleus formation
   (in an unbound state)

   $E_{cm} \rightarrow E_r$

   $S_x \rightarrow A+x$

   $Q$

2. Compound nucleus decay
   (to lower excited states)

   $\Gamma$

   $\gamma$

\[
\sigma_\gamma \propto \left| \langle E_f | H_\gamma | E_r \rangle \right|^2 \left| \langle E_r | H_B | A + x \rangle \right|^2
\]

- compound decay probability $\propto \Gamma_\gamma$
- compound formation probability $\propto \Gamma_x$

- reaction cross section proportional to two matrix elements
- only occurs at energies $E_{cm} \sim E_r - Q$
- strong energy dependence of cross section

N. B. energy in entrance channel $(Q+E_{cm})$ has to match excitation energy $E_r$ of resonant state, however all excited states have a width $\Rightarrow$ there is always some cross section through tails
example: \textbf{resonant reaction} $A(x, \alpha)B$

1. Compound nucleus formation (in an unbound state)

\[ \text{C} \]

2. Compound nucleus decay (by particle emission)

\[ \text{B} \]

N. B. energy in entrance channel $(S_x + E_{cm})$ has to match excitation energy $E_r$ of resonant state, however all excited states have a width \(\Rightarrow\) there is always some cross section through tails
reactions with charged particles
charged particles → **Coulomb barrier**

**Coulomb potential**

- \( E_{\text{coul}} \sim Z_1 Z_2 \) (MeV)
- \( E_{\text{kin}} \sim kT \) (keV)
- \( r_0 \)
- \( r \)

energy available: from thermal motion during **static burning**: \( kT \ll E_{\text{coul}} \)

- \( T \sim 15 \times 10^6 \) K (e.g. our Sun) \( \Rightarrow kT \sim 1 \) keV

reactions occur through **TUNNEL EFFECT**

- tunneling probability \( P \propto \exp(-2\pi\eta) \)

**Gamow peak**: energy of astrophysical interest where measurements should be carried out

- \( kT \ll E_0 \ll E_{\text{coul}} \)
- \( 10^{-18} \text{ barn } < \sigma < 10^{-9} \text{ barn} \)

major experimental challenges
Gamow peak: most effective energy region for thermonuclear reactions

\[ E_0 \pm \Delta E_0/2 \] energy window of astrophysical interest

\[ E_0 = f(Z_1, Z_2, T) \]

varies depending on reaction and/or temperature

Examples: \( T \sim 15 \times 10^6 \) K \( (T_6 = 15) \)

<table>
<thead>
<tr>
<th>reaction</th>
<th>Coulomb barrier (MeV)</th>
<th>( E_0 ) (keV)</th>
<th>area under Gamow peak ( \sim &lt;\sigma v&gt; )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p + p )</td>
<td>0.182</td>
<td>5.9</td>
<td>( 7.0 \times 10^{-6} )</td>
</tr>
<tr>
<td>( \alpha + ^{12}C )</td>
<td>2.242</td>
<td>56</td>
<td>( 5.9 \times 10^{-56} )</td>
</tr>
<tr>
<td>( ^{16}O + ^{16}O )</td>
<td>10.349</td>
<td>237</td>
<td>( 2.5 \times 10^{-237} )</td>
</tr>
</tbody>
</table>

STRONG sensitivity to Coulomb barrier

separate stages: H-burning, He-burning, C/O-burning ...
Experimental approach

measure $\sigma(E)$ over as wide a range as possible, then **extrapolate** down to $E_0$!

\[
\sigma(E) = \frac{1}{E} \exp(-2\pi\eta) S(E)
\]

**CROSS SECTION**

\[
S(E) = E\sigma(E) \exp(2\pi\eta)
\]

**S-FACTOR**

**DANGER OF EXTRAPOLATION**!
Gamow peak for $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ at $T = 0.2\text{GK}$

cross section and astrophysical S-factor for non-resonant reaction

Iliadis, Nuclear Physics of Stars, 2007
Reaction rate for resonant reactions

\[ \langle \sigma v \rangle = \int \sigma(v)\phi(v)vdv = \int \sigma(E)\exp(-E/kT)EdE \]

here Breit-Wigner cross section

\[
\sigma(E) = \pi\lambda^2 \frac{2J + 1}{(2J_1 + 1)(2J_T + 1)} \frac{\Gamma_1 \Gamma_2}{(E - E_R)^2 + (\Gamma/2)^2}
\]

integrate over appropriate energy region

\[ E \sim kT \quad \text{for neutron induced reactions} \]
\[ E \sim \text{Gamow window} \quad \text{for charged particle reactions} \]

if compound nucleus has an excited state (or its wing) in this energy range

⇒ RESONANT contribution to reaction rate (if allowed by selection rules)

typically:

- resonant contribution dominates reaction rate
- reaction rate critically depends on resonant state properties
stellar reaction rates include contributions from

- **direct transitions** to the various bound states
- all **narrow resonances** in the relevant energy window
- **broad resonances** (tails) e.g. from higher lying resonances
- **broad subthreshold resonances** with their higher energy tail
- any **interference term**

**total rate**

\[
\langle \sigma v \rangle = \sum_i \langle \sigma v \rangle_{DCi} + \sum_i \langle \sigma v \rangle_{Ri} + \langle \sigma v \rangle_{tails} + \langle \sigma v \rangle_{int}
\]
**Quiescent burning modes**

- stable nuclei
- timescales \( \sim 10^9 \) y
- \( E_0 \sim \) few keV
- \( 10^{-18} \) barn < \( \sigma < 10^{-9} \) barn
- extrapolations
- background
- long measurements
- pure targets
- high beam currents
- underground laboratories

**Explosive burning modes**

- unstable nuclei
- timescales \( \sim 10^{-3} - 10^2 \) s
- \( E_0 \sim \) MeV
- unknown nuclear properties
- low beam intensities
- beam-induced background
- radioactive ion beams
- large area detectors
- high detection efficiency
→ we need to improve the signal-to-noise ratio
### Laboratory for Underground Nuclear Astrophysics

1400 m-rock thickness above the Laboratory represents a natural shield for cosmic ray flux → reduction by one million times;

<table>
<thead>
<tr>
<th>400 kV Accelerator</th>
<th>$E_{\text{beam}} \approx 50 - 400 \text{ keV}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{max}} \approx 500 \mu A$ protons</td>
<td>$I_{\text{max}} \approx 250 \mu A$ alphas</td>
</tr>
<tr>
<td>Energy spread $\approx 70 \text{ eV}$</td>
<td>Long term stability $\approx 5 \text{ eV/h}$</td>
</tr>
</tbody>
</table>
LUNA = Laboratory for Underground Nuclear Astrophysics

LUNA - Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp chain


@ lowest energy:

\[ \sigma \approx 20 \text{ fb} \rightarrow 1 \text{ count/month} \]

\[ \sigma \approx 9 \text{ pb} \rightarrow 50 \text{ counts/day} \]

only two reactions studied directly at Gamow peak
Main Sources of Background:

- **natural radioactivity** (mainly from U and Th chains and from Rn)
- **cosmic rays** (muons, $^1_3\text{H}$, $^7\text{Be}$, $^{14}\text{C}$, ...)
- neutrons from ($\alpha,n$) reactions and fission

**ideal location:** underground + low concentration of U and Th
...but... further problem at astrophysical energies → → → →

S(E) enhancement experimentally found due to the Electron Screening

\[ S(E)_s = S(E)_b \exp(\pi \eta U_e / E) \]

\[^3\text{He} + \ ^2\text{H} \rightarrow \text{p} + \ ^4\text{He}\]
Electron Screening

In astrophysical plasma:
- the screening, due to free electrons in plasma, can be different \(\rightarrow\) we need \(S(E)\)_b to evaluate reaction rates

A theoretical approach to extract the electron screening potential \(U_e\) in the laboratory is needed

Experimental studies of reactions involving light nuclides have shown that the observed exponential enhancement of the cross section at low energies were in all cases significantly larger (about a factor of 2) than it could be accounted for from available atomic-physics model, i.e. the adiabatic limit \((U_e)_{ad}\)

Although we try to improve experimental techniques to measure at very low energy \(\rightarrow\)

\(S_b(E)\)-factor extracted from extrapolation of higher energy data
- to measure cross sections at never reached energies (no Coulomb suppression), where the signal is below current detection sensitivity
- to get independent information on $U_e$
- to overcome difficulties in producing the beam or the target (Radioactive ions, neutrons..)
- **NOTE:** Measurements require careful validation. Data analysis needs nuclear reaction models

- **Coulomb dissociation**
  ...to determine the absolute $S(E)$ factor of a radiative capture reaction $A+x \rightarrow B+\gamma$ studying the reversing photodisintegration process $B+\gamma \rightarrow A+x$

- **Asymptotic Normalization Coefficients (ANC)**
  ...to determine the $S(0)$ factor of the radiative capture reaction, $A+x \rightarrow B+\gamma$ studying a peripheral transfer reaction into a bound state of the $B$ nucleus

- **Trojan Horse Method (THM)**
  ...to determine the $S(E)$ factor of a charged particle reaction $A+x \rightarrow c+C$ selecting the Quasi Free contribution of an appropriate $A+a(x+s) \rightarrow c+C+s$ reaction
Trojan Horse Method

Basic principle: astrophysically relevant two-body $\sigma$ from quasi-free contribution of an appropriate three-body reaction

$$A + a \rightarrow c + C + s \quad \rightarrow \quad A + x \rightarrow c + C$$

$a: x \oplus s$ clusters

Quasi-free mechanism

✓ only $x - A$ interaction
✓ $s =$ spectator ($p_s \sim 0$)

$$E_A > E_{\text{Coul}} \Rightarrow \begin{array}{l}
\text{NO Coulomb suppression} \\
\text{NO electron screening}
\end{array}$$

$$E_{q.f.} = E_{q.f.} = \frac{m_x}{m_x + m_A} E_A - B_{x-s} \pm \text{intercluster motion}$$

plays a key role in compensating for the beam energy

$$E_{p.f.} \approx 0$$
Energy and position signals for the detected particles were processed by standard electronics together with the single relative times.

4.2.2 Data Analysis I

Heavy charged particles lose energy by Coulomb interaction with electrons and the nuclei of the absorbing materials. The collision of heavy charged particles with free and bound electrons results in the ionization or excitation of the absorbing atom, whereas the interaction with the nuclei leads only to a Rutherford scattering between the two types of nuclei. Thus the energy spent by the particle in electronic collisions results in the creation of electron-hole pairs, whereas the energy spent in nuclear collision is used in the detection process. The concepts of specific ionization loss $dE/dx$ and of range $R$ can be used to summarize the interaction of heavy charged particles in semiconductor detectors when nuclear collisions are unimportant. The specific ionization loss measures the amount of energy lost by the particle per unit-length of its track; the range indicates how deeply the particle penetrates the absorbing material. The basic physical concepts of these mechanisms can be typical experimental setup for THM measurements

Typical experimental setup for THM measurements

Coincidence detection of any two of the three particles in the exit channel
Li burning

\( ^6\text{Li} + d \rightarrow \alpha + \alpha \) via \( ^6\text{Li}^6\text{Li} \rightarrow \alpha + \alpha + \alpha \)

\( S_0 = 16.9 \text{ MeV b} \)

<table>
<thead>
<tr>
<th>( U_e ) (ad)</th>
<th>( U_e ) (THM)</th>
<th>( ^6\text{Li} + d )</th>
<th>( U_e ) (Dir)</th>
<th>( ^6\text{Li} + d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>186 eV</td>
<td>340 ( \pm ) 50 eV</td>
<td>330 ( \pm ) 120 eV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( ^7\text{Li} + p \rightarrow \alpha + \alpha \) via \( ^7\text{Li} + d \rightarrow \alpha + \alpha + n \)

\( S_0 = 55 \pm 3 \text{ keV b} \)

<table>
<thead>
<tr>
<th>( U_e ) (ad)</th>
<th>( U_e ) (THM)</th>
<th>( ^7\text{Li} + p )</th>
<th>( U_e ) (Dir)</th>
<th>( ^7\text{Li} + p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>186 eV</td>
<td>330 ( \pm ) 40 eV</td>
<td>300 ( \pm ) 160 eV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( ^6\text{Li} + p \rightarrow \alpha + ^3\text{He} \) via \( ^6\text{Li} + d \rightarrow \alpha + ^3\text{He} + n \)

\( S_0 = 3 \pm 0.9 \text{ MeV b} \)

<table>
<thead>
<tr>
<th>( U_e ) (ad)</th>
<th>( U_e ) (THM)</th>
<th>( ^6\text{Li} + p )</th>
<th>( U_e ) (Dir)</th>
<th>( ^6\text{Li} + p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>186 eV</td>
<td>435 ( \pm ) 40 eV</td>
<td>440 ( \pm ) 80 eV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C. Spitaleri et al., PRC60 (1999) 055802
C. Spitaleri et al., PRC63 (2001) 005801
A. Tumino et al., PRC67 (2003) 065803
Reactions measured so far at or near Gamow region:

\[ ^3\text{He}(^3\text{He},2p)^4\text{He} \quad ^1\text{H}(p,\gamma)^3\text{He} \quad ^{14,15}\text{N}(p,\gamma)^{15}\text{O} \quad ^3\text{He}(^4\text{He},\gamma)^7\text{Be} \quad ^{25}\text{Mg}(p,\gamma)^{26}\text{Al} \]

\[ ^2\text{H}(^4\text{He},\gamma)^6\text{Li} \quad ^{17}\text{O}(p,\gamma)^{18}\text{F} \quad ^{17}\text{O}(p,\alpha)^{14}\text{N} \ ... \]

Many critical reactions for astrophysics **BEYOND** current capabilities

Some of the poorly known nuclear reactions with stable and photon beams

Heavy ion reactions: \(^{12}\text{C}+^{12}\text{C}, {^{16}\text{O}}+^{16}\text{O}, ^{12}\text{C}+^{16}\text{O} \)

Neutron sources: \(^{13}\text{C}(a,n)^{16}\text{O}, ^{22}\text{Ne}(a,n)^{25}\text{Mg}, ^{17}\text{O}(a,n)^{20}\text{Ne} \)

Capture reactions: \(^3\text{He}(a,\gamma)^7\text{Be}, ^{12}\text{C}(a,\gamma)^{16}\text{O} \)

Most of these reactions are resonant:

\[
\langle \sigma v \rangle_{12} = \left( \frac{2\pi}{\mu_{12}kT} \right)^{3/2} \hbar^2 (\omega \gamma)_{R} \exp \left( -\frac{E_R}{kT} \right)
\]

**NOTE**

Exponential dependence on energy means:

- small uncertainties in \( E_R \) (even a few keV) imply large uncertainties in reaction rate
abundances of Ne, Na, Mg, Al, ... in AGB stars and nova ejecta affected by many \((p, \gamma)\) and \((p, a)\) reactions

shaded areas indicate order of magnitude(s) uncertainties

Both reactions involved in the explosive hydrogen burning in the novae and in the nucleosynthesis path of $^{18}\text{F}$, of special interest in novae observations in the $\gamma$-ray wavelengths → LUNA experiment

In explosive conditions, the reaction rate is dominated by contributions from narrow resonances at $E_{\text{c.m.}}=65$ and 183keV → THM experiment

Experimental details:

Direct experiment: LUNA underground 400 kV accelerator, $E_{\text{c.m.}}=160-370$ keV, 200µA p-beam on solid $\text{Ta}_2\text{O}_5$ targets. Deep underground environment of LNGS + 4pi 10cm thick lead shielding leads to a reduction of the background events by a factor of 2500 with respect to surface measurements. Prompt $\gamma$-rays detected by HPGe detectors + target activation technique. Since $^{18}\text{F} \beta^+$ decays to the ground state of $^{18}\text{O}$, it is possible to determine its activity through the detection of the 511-keV $\gamma$ ray from the positron annihilation. Targets used solely for the activation measurements were irradiated for several hours in order to saturate the $^{18}\text{F}$ activity, using the same experimental setup of the prompt $\gamma$-ray measurements.


THM experiment: 41 MeV $^{17}\text{O}$ beam on a CD$_2$ target, 150 $\mu$g/cm$^2$ thick. Detection setup consisting of telescopes made up of ionization chambers/Si detectors as $\Delta E$ and silicon PSD as E-detectors.

M.L. Sergi et al. PRC (R) (2010)
The abundance of key isotopes such as $^{18}$F, $^{18}$O, $^{19}$F, $^{15}$N evaluated through nova models calculations, are now obtained with a precision of 10%.
importance: evolution of massive stars

astrophysical energy: 1 - 3 MeV

minimum measured E: 2.1 MeV (by γ-ray + part. spectroscopy)

extrapolations differ by 3 orders of magnitude

complicated by the presence of resonant structures even in the low-energy part of the excitation function

large uncertainties in astrophysical models of stellar evolution and nucleosynthesis
\[ ^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne} \text{ and } ^{12}\text{C}(^{12}\text{C}, p)^{23}\text{Na} \text{ reactions via the Trojan Horse Method applied to the} \]

\[ ^{12}\text{C}(^{14}\text{N}, \alpha^{20}\text{Ne})^{2}\text{H} \text{ and } ^{12}\text{C}(^{14}\text{N}, p^{23}\text{Na})^{2}\text{H} \text{ three-body processes} \]

\[ ^{2}\text{H} \text{ from the } ^{14}\text{N as spectator} \]

Observation of \(^{12}\text{C} \text{ cluster transfer in the } ^{12}\text{C}(^{14}\text{N},d)^{24}\text{Mg}^* \text{ reaction} \]  
(R.H. Zurmühle et al. PRC 49(1994) 5)

**QUASI-FREE MECHANISM**

✓ only \(^{12}\text{C} - ^{12}\text{C} \text{ interaction} \)
✓ \(d = \text{ spectator} \)

\[ E_{14N} = 30 \text{ MeV} > E_{\text{Coul}} \]

⇒ NO Coulomb suppression
⇒ NO electron screening

\[ E_{\text{QF}} = E_{14N} \frac{m_{^{12}\text{C}}}{m_{^{14}\text{N}}} \cdot \frac{m_{^{12}\text{C}}}{m_{^{12}\text{C}} + m_{^{12}\text{C}}} - 10.27 \text{ MeV} \]

Our Experiment with the THM

$^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$ and $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ reactions via the Trojan Horse Method applied to the $^{12}\text{C}(^{14}\text{N},\alpha^{20}\text{Ne})^2\text{H}$ and $^{12}\text{C}(^{14}\text{N},p^{23}\text{Na})^2\text{H}$ three-body processes.

$^2\text{H}$ from the $^{14}\text{N}$ as spectators.

Observation of $^{12}\text{C}$ cluster transfer in the $^{12}\text{C}(^{14}\text{N},d)^{24}\text{Mg}^*$ reaction (R.H. Zurmühle et al. PRC 49(1994) 5)

$E_{^{14}\text{N}} = 30$ MeV $> E_{\text{Coul}}$

\[ p_1 + ^{23}\text{Na}^* + d \quad p_0 + ^{23}\text{Na} + d \]

\[ \alpha_1 + ^{20}\text{Ne}^* + d \quad \alpha_0 + ^{20}\text{Ne} + d \]
Thank you!