Indirect methods in nuclear astrophysics

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Nuclear Physics for Astrophysics

• Motivation
• Direct vs indirect measurements: pro & cons
• Indirect methods
• Examples
• Particular: use of RIBs (Radioactive Ion beams)
**Radiative capture reactions**

* Radiative capture reactions $A(p, \gamma)B$, $A(\alpha, \gamma)$, $A(n, \gamma)$

* **Non-resonant** or resonant reactions.

* At low energy, the probability that the incoming charged particle penetrates the Coulomb barrier:

\[
P = \exp(-2\pi\eta), \quad \eta(E) = \frac{Z_1 Z_2 e^2}{\hbar v}
\]

* The cross section – astrophysical S-factor:

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

* Reaction rate per particle pair (in distr):

\[
\langle \sigma v \rangle = \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left(-\frac{E}{kT} - \frac{b}{E^{1/2}}\right) dE
\]

- Reactions (that matter) take place in the Gamow energy window.
- Direct, or non-resonant part

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**Stars are cold!**

$E_p = 10s-100s \text{ keV}$

* C. Rolfs and W. Rodney, “Cauldrons in the Cosmos”.

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![Diagram](Image)
Warning:
- we plot and say “we determine the astrophysical S-factor”
- but we measure cross sections
Direct measurements – problems and solutions

- Low cross sections →
  - measure longer?!
  - No, bc background issues!
- Background from
  - Cosmic rays
  - Environment radioactivity
- Solution: shielding
  - Passive
  - Active
  - Underground
- Low cross sections
  - High current accelerators
  - Targets …
  - Detect what?!
EXPERIMENTAL SOLUTIONS

IMPROVEMENTS TO REDUCE THE BACKGROUND

-(UNDERGROUND LABORATORY)

Use of laboratory with natural shield

(underground physics—for instance LUNA experiment at LNGS-Italy)

\[ ^{2}\text{H}(p,\gamma)^{3}\text{He} \]

Stars are cold!

NO EXTRAPOLATION

Talk M. Junker,
Carpathian school Sinaia 2012
3MV tandetron in Bucharest - suitable for nuclear astrophysics: α and light ion beams & ultralow background lab in saltmine
\[ \gamma \text{ spectrum } E_{\text{lab}} = 5.2 \text{ MeV} \]

\[ \beta-\gamma \text{ coinc at } 6 \text{ MeV} \]

\[ \sim 150 \text{ ev in } 67.5h (2.8 \text{ days}) \text{ for } \gamma-1369 \text{ keV} \]
Two big problems:
1. very small energies and very small cross sections \( \Rightarrow \) indirect methods
2. reactions in stars involve(d) radioactive nuclei \( \Rightarrow \) use RNB

mass, \( T_{1/2} \) resonances

site, path?! mass, \( T_{1/2} \)

+ fission barriers ?!
Nuclear Astrophysics

Indirect methods – measurements at lab energies → cross sections at stellar energies

Experiments at 10, … 100, 300 MeV/nucleon to assess cross sections at 10, 100, 300 keV

Indirect methods in NPA with RNB (w. examples)

A. Coulomb dissociation
B. Transfer reactions (ANC method)
C. Breakup of loosely bound nuclei
D. Resonance spectroscopy – β-decay, resonant elastic scattering, etc
E. Trojan Horse Method (non-RNB so far! Just starting …)
Indirect methods for nuclear astrophysics

- Measurement at lab energies
- Extract (nuclear structure) information
- Calculate astrophysical S-factor or reaction rates
- Comparison with (reaction) calculations

Need good additional knowledge (data). Reliable absolute values
**B. Transfer reactions: the ANC method**

Transfer reaction:\! A + d → B + a peripheral (absorption)

- **Transfer matrix element:**
  \[ M = \left< \chi_f^{(-)} I_{Bp}^A | \Delta V | I_{ap}^d \chi_i^{(+)} \right> \]

- **Transfer amplitude**:
  \[ \frac{d\sigma}{d\Omega} = \sum \left[ S \left| \frac{d\sigma}{d\Omega} \right| S \right] \]

- **Semi-microscopic process**

  - JLM interaction (LT ea, PRC, 2000)

- **Transfer reaction cross-section**
  \[ \sigma_{(p,\gamma)} \propto \left( C_{Bp}^A \right)^2 \]

  - (Christy and Duck, 1963)
  - Parker and Tombrello, 1964)

ANC - independent on binding potential geometry!
OMP knowledge crucial for reliable absolute values!

NA: proton-nucleus also peripheral

**Transfer reaction cross-section**:

\[ I_{nlj}^A(r) = \left< A-1 | A \right>_nlj = S^{1/2} \phi_{nlj}(r) \]

\[ I_{nlj}^A(r) \approx C_{Bp}^A W^{-n_A+\frac{1}{2}} \left( 2 \kappa_{Bp} r_{Bp} \right) \]
Cross sections for \((p, \gamma)\) from 
p-transfer reactions with RNB from MARS

\[ \begin{align*}
\text{Momentum Achromat} \\
\text{Recoil Separator} \\
\text{(MARS)}
\end{align*} \]

\[ \begin{align*}
\Delta E - \text{PSD 65, 110 \, \mu m} \\
E - \text{500 \, \mu m}
\end{align*} \]

\[ \begin{align*}
\text{12N @12 MeV/ u} \\
99\% \text{ pure, 4 mm dia} \\
\text{Melamine target}
\end{align*} \]

\[ \begin{align*}
\text{12C @23 MeV/ u} \\
\text{H}_2 \text{ cryotarget}
\end{align*} \]

Four telescope system (“the cross”):

\[ \begin{align*}
\Delta E - \text{PSD 65, 110 \, \mu m} \\
E - 500 \, \mu m
\end{align*} \]
Example $^{12}\text{N}@12$ MeV on $\text{N}_6\text{C}_3\text{H}_6$ and C

- Primary beam: $^{12}\text{C}@23$ MeV/u 150 pnA
- Secondary beam: $^{12}\text{N}@12$ MeV/u $2\times10^5$ pps
- Elastic $\theta_{\text{cm}}=8-60$ deg.
- Fit OMP from folding JLM– no param adjust!
- Transfer $^{14}\text{N}(^{12}\text{N},^{13}\text{O})^{13}\text{C}$ – fit w. DWBA extract ANC
- $^{12}\text{N}(p,\gamma)^{13}\text{O}$ rate evaluated from ANC
$^{14}\text{N}(^{12}\text{N},^{13}\text{O})$ proton-transfer react $\Rightarrow$ $^{12}\text{N}(p,\gamma)^{13}\text{O}$ (rap I,II proc)

ANC, S-factor 0-2 MeV

Reaction rate

# Transfer Reaction:

\[ ^{13}\text{C}(^{22}\text{Ne},^{23}\text{Ne})^{12}\text{C} \]

# Elastic Scattering:

1. \(^{22}\text{Ne} \rightarrow ^{13}\text{C}\)
2. \(^{22}\text{Ne} \rightarrow ^{12}\text{C}\)

Bean @ 12 MeV/A

Targets 100 µg/cm²

\[ C^2_{d_{5/2}} \left( ^{23}\text{Ne} \right) = 0.86 \pm 0.08 \pm 0.12 \text{ fm}^{-1} \]

\[ S_{d_{5/2}} \left( ^{23}\text{Al} \right) = S_{d_{5/2}} \left( ^{23}\text{Ne} \right) \Rightarrow \]

\[ C^2_{d_{5/2}} \left( ^{23}\text{Al} \right) = \left( 4.63 \pm 0.77 \right) \times 10^3 \text{ fm}^{-1} \]

* OMPs from the entrance/exit channels \(\rightarrow\) DWBA.

* The Angular distribution for:

Transfer Reaction \(p_{1/2} \rightarrow d_{5/2}\) (Q=0.254 MeV)

* The reaction is \textit{Peripheral}

\[ \text{T. Al-Abdullah, thesis & PRC 2010} \]
Semi-microscopic double folding potentials for nucleus-nucleus collisions

Double folding procedure:

\[ V(R) = \int d\vec{r}_1 d\vec{r}_2 \rho(r_1) \rho(r_2) v_{\text{eff}}(\rho, E, \vec{s}), \vec{s} = \vec{r}_1 + \vec{R} - \vec{r}_2 \]

- HFB densities (to best match the surfaces)
- tried various effective interactions (M3Y, DDM3Y, JLM, etc…)
- Settled for JLM
- Smearing w. range parameters \( t_v = 1.2 \text{ fm}, t_w = 1.75 \text{ fm} \)
- Renormalizations needed \( N_v, N_w \)
- JLM - uses eff inter of Jeukenne, Lejeune and Mahaux (PRC 16, 1977)
- n-nucleus Bauge ea (PRC 58, 1998):
  - energy and density dependent
  - independent geometry for real and imaginary potentials
  - normalization independent of partners
  - reproduces ELASTIC and TRANSFER data
- Checked for loosely bound p-shell nuclei stable beams ~ 10 MeV/u
  - Found \( N_v = 0.37(2), N_w = 1.0(1), t_v = 1.20 \text{ fm}, t_w = 1.75 \text{ fm} \)
- Extended to RNB: \(^7\text{Be}, ^8\text{B}, ^{11}\text{C}, ^{12}\text{N}, ^{13}\text{N}, ^{17}\text{F}\) on \(^{12}\text{C}, ^{14}\text{N}\) targets

\[ U(r) = N_V V(r, t_v) + iN_W W(r, t_W) \]
JLM works for a range of energies
E/A=15-50 MeV/u

Works for transfer reactions
Optical Model Potentials for Nucleus-Nucleus collisions for RNBs

Essential to make credible DWBA calc needed in transfer studies
Have established semi-microscopic double folding using JLM effective interaction:
- Established from exps with stable loosely bound p-shell nuclei: $^6$Li, $^{10}$B, $^{13}$C, $^{14}$N ... @ 10 MeV/u
- Independent real and imaginary parts, energy and density depend.
- Parameters: renormalization coeff. ($N_v\sim0.4$-0.5, $N_w=1.0$)
- Predicts well elastic scatt for RNBs: $^7$Be, $^8$B, $^{11}$C, $^{12}$N, $^{13}$N, $^{17}$F, $^{14}$C, ...
- Good results for transfer reactions (tested where possible)

TECSA
Texas-Edinburgh-Catania Silicon Array

- high-efficiency array of annular sector silicon detectors to be used to measure the angular distribution of reactions with radioactive beams from MARS in inverse kinematics
- 8 or 16 Y Y1-300 Micron Semiconductor LTD. silicon detectors
- can be used at to measure reactions at either backward or forward angles
- Commissioning run performed in May 2010 with collaborators: d(\textsuperscript{14}C,p)\textsuperscript{15}C at 11.7 MeV/nucleon used to verify ANC from HI neutron transfer
- d = 2.8, 5, 12, 20 cm covering $\theta_{\text{lab}} = 102^{\circ}$ to $165^{\circ}$ ($\theta_{\text{CM}} = 4.5^{\circ}$ to $32.2^{\circ}$)

BT Roeder et al, NIM A634 (2011)71
$d(^{14}\text{C},p)^{15}\text{C}$ 11.7 MeV/nucleon: TECSA

ADWA calculation using FRESCO with CH89 nucleon potentials
Results $^{14}$C(n,$\gamma$)$^{15}$C

$^{14}$C+$^{13}$C elastic

Double folding

- Optical model calculation with a double folding procedure using the JLM
  (Jeukenne-Lejeune-Mahaux) effective interaction
- Calculation smoothed using a Gaussian distribution to reflect angular resolution of
  the detector which was observed using the five finger mask
- Comparison of experimental angular distribution with calculation give optical model
  normalizations and ranges $N_0=0.45$, $N_0=0.90$, $r_0=1.2$ fm and $r_0=1.25$ fm

<table>
<thead>
<tr>
<th>ANC</th>
<th>$C^2_{250}$ (fm$^4$)</th>
<th>$C^2_{450}$ $\times 10^3$ (fm$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L. Trache et al. 2002</td>
<td>1.48$\pm$0.18</td>
<td></td>
</tr>
</tbody>
</table>
| N.C. Summers and F.M.
  Nunes 2008        | 1.64$\pm$0.03         |                                   |
| Y. Pang et al. 2007 | 2.14                  |                                   |
| A.M. Mukhamedzhanov et al.,
  2011              | 1.72$\pm$0.31         | 3.7$\pm$0.7                       |
| This work         | 1.96$\pm$0.16         | 4.23$\pm$0.38                     |

$^{14}$C(n,$\gamma$)$^{15}$C exp-theory

FIG. 10. (Color online) Comparison between this measurement
(Shaded band) and previous cross results at $E_c.m.$ $= 23.3$ keV.
Open squares refer to theoretical estimates while full circles refer
to experiments including Coulomb-breakup studies. The only open
circle refers to the measurement by Beer et al. before the renormalization
based on the new mass and linearity data information (see text).
The respective references from left to right are [7,8,33] (theoretical)
and [9-12,34,35] (experimental).

Direct capture rate calculated + latest direct measurement (Reifarth 2008)

M. McCleskey et al., Phys Rev C 89, 044605 (2014)
Nuclear and Coulomb dissociation

Breakup

Model-independent shape w. ANC (Whittaker function)
Explosive H-burning in novae: “\(^{22}\text{Na observation}\)”

- novae: explosive H-burning of accreting material in binaries star-WD. ~ 30/yr.
- \(\gamma\) rays from the decay of long-lived isotopes like \(^{26}\text{Al}\) have been detected
- \(E=1.275\) MeV \(\gamma\) ray following the decay of \(^{22}\text{Na}\) predicted, but not observed by space gamma-ray telescopes

\[ \begin{align*}
^{24}\text{Si} & \quad 140\text{ ms} \\
^{23}\text{Al} & \quad 0.5\text{s} \\
^{22}\text{Mg} & \quad 3.9\text{s} \\
^{21}\text{Na} & \quad 23\text{s} \\
^{20}\text{Ne} & \quad 
\end{align*} \]

\[ \begin{align*}
^{24}\text{Al} & \quad 2.1\text{s} \\
^{23}\text{Mg} & \quad 11\text{s} \\
^{22}\text{Na} & \quad 2.6\text{y} \\
^{21}\text{Ne} & \quad \\
^{22}\text{Ne} & \quad \\
\end{align*} \]

\[ \begin{align*}
^{22}\text{Na} & \quad >99.9\% \\
^{22}\text{Ne} & \quad 2^+ \\
\end{align*} \]

\[ \begin{align*}
^{22}\text{Na} & \quad \gamma 1.275 \text{ MeV} \\
^{23}\text{Mg} & \quad \gamma 1.275 \text{ MeV} \\
\end{align*} \]

\[ \begin{align*}
^{22}\text{Na} & \quad (p,\gamma) \\
^{22}\text{Na} & \quad \beta^+\nu \\
\end{align*} \]

\[ \begin{align*}
^{22}\text{Na} & \quad \text{depletion in novae: how does it happen?} \\
\text{Depleted via?} & \quad \{ \\
^{22}\text{Mg}(p,\gamma)^{23}\text{Al} & \leftrightarrow \text{direct & res. capture} \\
^{22}\text{Na}(p,\gamma)^{23}\text{Mg} & \leftrightarrow \text{resonant capture} \\
\end{align*} \]

- what are the stellar reaction rates for the \(^{22}\text{Mg}(p,\gamma)^{23}\text{Al}\) and \(^{22}\text{Na}(p,\gamma)^{23}\text{Mg}\)?

- what about \(^{22}\text{Mg}(p,\gamma)^{23}\text{Al}(p,\gamma)^{24}\text{Si}\) seq. 2p capture? Imp in XRB
Cocktail beam (mid-target energies):
- $^{24}$Si 53 MeV/u
- $^{23}$Al 50 MeV/u
- $^{22}$Mg 47 MeV/u
- $^{21}$Na 43 MeV/u
- $^{20}$Ne 39 MeV/u

High-resolution spectrometer
- large angular acceptances: 4° (horiz. & vertic. planes)
- broad momentum acceptance: $\Delta p/p = 7\%$

A. Banu et al., NIC10 2008 & PRC 84, 015803 (2011)
$^{23}\text{Al} \rightarrow ^{22}\text{Mg} + p$

Proton removal (sought)

$^{12}\text{C}(^{22}\text{Mg},^{22}\text{Na})^{12}\text{N}$

Charge exchange (new & unexpected)

$^{23}\text{Al} \rightarrow ^{22}\text{Mg} + p$

Proton removal (sought)
Results from $^{23}$Al breakup

$\Gamma(^{23}$Al)$ \sim$ 200 MeV/ c and $J^\pi = 5/2^+$

If $b^2$ is s.p. ANC:

$C^2 = b^2 \frac{\sigma_{exp}}{\sigma_{calc}} = 3.90 \pm 0.44 \times 10^3 \text{ fm}^{-1}$
Complementarities: Coulomb and nuclear dissociation

Similar results from mirror system: $^{22}\text{Ne} + n \rightarrow ^{23}\text{Ne}$

$^{13}\text{C}(^{22}\text{Ne}, ^{23}\text{Ne})^{12}\text{C}$ n-transfer @12MeV/u assuming $S_n = S_p$

$\Gamma_{\gamma} = 7.2 \pm 1.4 \times 10^{-7}$ eV, which was obtained from the Coulomb dissociation of $^{23}\text{Al}$ at 50 MeV/u [46], is adopted here to evaluate the resonant reaction rate, which is given by

$$N_A \langle \sigma v \rangle = 0.12 T_9^{-3/2} \exp \left( -\frac{4.47}{T_9} \right).$$

Results from $^{24}\text{Si}$ breakup

$C^{(24\text{Si})_{gs}} = 62.4 \pm 7.1 \text{ fm}^{-1}$

$SF = 2.5 - 2.9$

$\Rightarrow$ first exp determination of the direct comp of $^{23}\text{Al}(p,\gamma)^{24}\text{Si}$!

$^{22}\text{Mg}(p,\gamma)^{23}\text{Al}(p,\gamma)^{24}\text{Si}$

seq. 2p capture imp in XRB

Note: exp made with 30 pps!

A. Banu et al, PRC 86, 015806 (2012)
The reaction is important in the hot pp chains, in explosive H burning, at large temperatures, for creating alternative paths across the A=8 mass gap (see e.g. M. Wiescher et al., Ap. J. 343 (1989)352.)

\[ \text{pp IV } ^8\text{B}(p,\gamma)^9\text{C}(\beta^+\nu)^9\text{Be} \text{ and } \text{rap I } ^8\text{B}(p,\gamma)^9\text{C}(\alpha,p)^{12}\text{N}(p,\gamma)^{13}\text{O}(\beta^+\nu)^{13}\text{N}(p,\gamma)^{14}\text{O}. \]

Use breakup of \(^9\text{C} \rightarrow ^8\text{B}+p\) at intermediate energies to obtain \(^8\text{B}(p,\gamma)^9\text{C}\) at astrophysical energies.

Existing data from:
B. Blank et al., Nucl Phys A624 (1997) 242
\(^9\text{C} @285 \text{ MeV/u on C, Al, Sn and Pb targets}\)
Trache et al. ANC from breakup, 2002
Beaumel (ANC from (d,n) reaction)
T. Motobayashi et al. – Coulomb dissociation

**Future:** exp NP1412-SAMURAI29R1 @ RIBF

\(^9\text{C} \rightarrow ^8\text{B}+p\) breakup for \(^8\text{B}(p,\gamma)^9\text{C}\)

**Astrophysical S-factor**
\(^8\text{Be}(p, \gamma)^9\text{C} – \text{astrophysical interest}\)

H-burning in *hot pp chain* (*pp IV and rap I*)

at high \(T, \rho\) in metal-poor environment

\(T_9 \sim 0.1-1.0, \rho \sim 10^5 \text{ g/cm}^2\)

super-massive stars in early Universe?

\(^7\text{Li}\) synthesis in novae?

…..

\[ E_{\text{Gamow}} \sim 75-350 \text{ keV at } T = 0.1-1.0 \times 10^9 \text{ K} \]

\(\rightarrow\) capture through continuum dominates
Setup

$^{16}\text{O}$ primary beam with two BigRIPS settings for $100 \text{ AMeV}$ and $300\text{ AMeV}$ common to other HI-p experiments

DALI2: not necessary for $^{9}\text{C} \rightarrow ^{8}\text{B} + p$, but useful for $^{9}\text{C} \rightarrow \text{Be} + 2p$

The “standard” SAMURAI setting $\Rightarrow$ better for “$k_x$” measurements?
\(^9\text{C}\) nuclear breakup @ 100MeV/u. Theor estimates by Glauber calc

Interested in the accuracy of absolute values of cross sections. What different models, parameters, codes (and theoreticians) give?!

Note: \(^9\text{C} \rightarrow ^7\text{Be} + 2p\) large cs

Calculated momentum distributions from 1p-breakup of \(^9\text{C}\) at 100 MeV/u on a C target. Calculations with two different geometries of the binding potential for the last proton are shown (see text for details).

Figure 3. Calculated momentum distributions from 1p-breakup of \(^9\text{C}\) at 100 MeV/u on a C target. Calculations with two different geometries of the binding potential for the last proton are shown (see text for details).
AT RIKEN
Secondary beam → target → LI + HI tracking → SAMURAI → proton and HI hodoscopes

Breakup

$XY - UV$ Si planes after target/before SAMURAI

Possible:

a) SSD-SSD --- SSD --- SSD-SSD
b) DSSD ---- SSD ---- DSSD

Problems:

i) Delta e- problem & ii) p threshold issues
Test rigs at WU, TAMU and HIMAC with existing PCB mounting

Test with the 2D TTT (300 um)

AREA ➔ 97.3 × 97.3 mm

# strips ➔ 128 x 128 ➔ 256 per Si, 512 per pair

Pitch ➔ 756 um

Si type ➔ available in both n and p (intrinsic). We have one of each

Thickness ➔ available in both 300 and 500 μm, we have 300 μm.

pf ➔ 300 μm: 0.35 pf/mm² = 26 pf/st; 500 μm: 0.21 pf/mm² = 15.4 pf/st

Si –TTT (WU)  Si in chamber (TAMU)  External view (WU)
Summary B-C

• Indirect methods w RNB – valuable tool for nuclear astrophysics
• Accuracies of 10-15% can be obtained
• Q: Good enough?!
• For better accuracies more work needed, including systematic studies and development of structure and reaction theories (and codes):
  – Work close to proton drip line makes continuum important, antisym, etc...
• Combination of methods is important
• Q: what are the most imp reactions ?!
Resonant Reaction Rates

* **Resonant** reaction is a two-step process.

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

* The cross section (Breit-Wigner):

\[ \sigma(E) = \frac{\lambda}{4\pi} \frac{2J + 1}{(2J_1 + 1)(2J_2 + 1)} \frac{\Gamma_p \Gamma_\gamma}{(E - E_r)^2 + \left( \frac{\Gamma}{2} \right)^2} \]

* The contribution to the reaction rate:

\[ \langle \sigma v \rangle_{\text{res}} = \left( \frac{2\pi}{\mu kT} \right)^{3/2} \hbar^2 \omega \gamma \exp\left( -\frac{E_r}{kT} \right) \]

where

\[ \omega \gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_I + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_{\text{tot}}} \]

\( \omega \gamma \) = resonance strength

* C. Rolfs and W. Rodney, “Cauldrons in the Cosmos”.

* To determine
Summary

• Replaced direct radiative p-capture reactions \((p,\gamma)\) with:
  - Proton transfer (or n-transfer in mirror)
  - Coulomb or nuclear p-dissociation
  - Beta-delayed p-decay

  a) indirect methods
  b) RNBs or stable beams

• Lessons learned:
  1. Seek the relevant quantities (ex: SF vs ANC)
  2. Model or parameter independent
  3. Combination of methods is useful – availability important
  4. Need more in terms of supportive information for reliable calculations: theories, models (and codes), effective n-n interactions, systematics ...
  → still need good stable beam data
  OMP, reaction models, ...
Collaborators

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