“Connecting Neutron Star Observables and Nuclear Reaction Studies”

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OU Nuclear Theory Group Pow-wow
February 2019
Game Plan:

Content:
- Motivate NS connection to nuclear physics
- Surface burning processes
- Ocean & outer crust processes
- Inner crust reactions

Structure:
- ~2 lecture/discussion sessions
  - Interrupt whenever you want
- Experiment & theory peppered throughout
- Typical order per topic:
  - Astro environment
  - Nuclear reactions that matter
  - How these reactions are determined

Nuclear physics of the outer layers of accreting neutron stars

Zach Meisel, Alex Deibel, Laurens Keek, Peter Shternin, and Justin Effritz
How do very high-density, “low” temperature objects behave?

Accreting Neutron Stars: Dense Matter Laboratories

- accretion disk
- atmosphere: $p, \alpha$-capture
- ocean: $^{12}\text{C}$-fusion, $e^-$-capture
- crust: $e^-$-capture, $n$-emission/capture, $\rho$-driven fusion
- core

X-ray flux

- "X-ray bursts" by W. Lewin et al., SSRv 1993
- "X-ray superbursts" by R. Cornelisse et al., A&A 2000
The approach to understanding dense matter behavior:

**Observations**
- Cooling transients:

**X-ray bursts:**
- Z. Meisel et al. JPhG 2018

**Models**

**Insight into Nature**
  - Mass
  - Radius
  - Mass
  - Radius


Z. Meisel ApJ 2018
What does this have to do with nuclear physics?

Nuclei accessible in the lab
- atmosphere ~1 cm
- ocean ~100 m
- outer crust ~0.5 km

Exotic/theoretical matter states
- inner crust ~0.5 km
- core ~10 km
The journey of a nucleus in a neutron star

1. Production from H, He, C burning

[Diagram showing neutron star components and nuclear reactions]

Production from H, He, C burning

- accretion disk
- atmosphere: \( p, \alpha \)-capture
- ocean: \(^{12}\text{C}\)-fusion, \( e^-\)-capture
- crust: \( e^-\)-capture, n-emission/capture, \( \rho \)-driven fusion
- core
The journey of a nucleus in a neutron star

2. Burial and electron-capture

\[ E_{\text{e, Fermi}} = 0.0 \]

This creates heat sources (EC heating) and sinks (urca cooling)

\begin{align*}
\text{atmosphere} & : \text{p,}\alpha\text{-capture} \\
\text{ocean} & : \text{\textsuperscript{12}C-fusion, e\textsuperscript{-}-capture} \\
\text{crust} & : \text{e\textsuperscript{-}-capture, n-emission/capture, } \rho\text{-driven fusion} \\
\text{core} & 
\end{align*}
This creates heat sources and determines the inner crust impurity.

The journey of a nucleus in a neutron star

3. Fusion and disintegration

This creates heat sources and determines the inner crust impurity.

- accretion disk
- atmosphere
  - p, α-capture
- ocean
  - 12C-fusion, e^-capture
- crust
  - n-emission/capture, ρ-driven fusion
- core
Type-I x-ray bursts: hydrogen & helium burning on the neutron star surface

- Hydrogen & helium burning on the neutron star surface
- X-ray flux
- Time (hours)
- Accretion disk
- Atmosphere: p,α-capture
- Ocean: 12C-fusion, e-capture
- Ocean: e-capture
- Crust: n-emission/capture, ρ-driven fusion
- Core


The rapid proton-capture ($rp$)-process: hydrogen & helium burning on the neutron star surface

Reaction sequence:
$3\alpha \rightarrow$ HCNO $\rightarrow$ ($\alpha$,p)-process $\rightarrow$ $rp$-process

X-ray flux $\rightarrow$

$190, 200, 210, 220, 230$

Time (s)

$\beta^+$ decay

($\alpha$,p)

(p,$\gamma$)
X-ray burst calculations are sensitive to nuclear physics

Model output:


Reaction rate adjustor:

XRB Modeler 2000

68Se(p,γ)69Br

Model:

X-ray flux →

Time (s)

0 50 100 150 200

68Se(p,γ)69Br

β+ decay

(p,γ)

(p,γ)

X-ray burst calculations are sensitive to nuclear physics.
rp-process reaction categories & rough locations

often referred to as “waiting points” in the literature

Ignition/Breakout

Branch Points

Cycles

ON RAMP

Waiting Points
Ignition/Breakout

thermonuclear runaway

Wiescher, Görres, & Schatz 1999
• Key reactions: \(3\alpha \rightarrow ^{12}\text{C}, ^{14}\text{O}(\alpha,p)^{17}\text{F}, ^{18}\text{Ne}(\alpha,p)^{21}\text{Na}, \) and \(^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}\)

• All are resonant reaction rates, so the question boils down to how well do we know the structure (excitation energies and partial widths) of the compound nucleus for each reaction

• Using units of MeV for \(E_{R,i}\) and \((\omega\gamma)_{R,i}\) and amu for \(A_i\),

\[
N_A\langle \sigma v \rangle_{N\text{ res.}} = \frac{1.54 \times 10^{11}}{(A_1A_2T_9)^{3/2}} \sum_{i=1}^{N} (\omega\gamma)_{R,i} \exp \left( -\frac{11.6045E_{R,i}}{T_9} \right) \text{cm}^3\text{mol s}
\]

where \(\omega = \frac{2J+1}{(2J_a+1)(2J_X+1)}\) and \(\gamma = \frac{\Gamma_{aX}\Gamma_{bY}}{\Gamma}\)

• We look for resonances near the Gamow window: \(E_G = 0.122 \left( \frac{Z_1^2Z_2^2A_1A_2}{(A_1+A_2)T_9^2} \right)^{1/3} \text{MeV}\), \(\Delta_G = 4\sqrt{\frac{E_Gk_BT}{3}} \text{MeV}\)

Gamow window estimate is approximate.
Have to calculate actual contributions to the rate:
Ignition/Breakout: Example of $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$

Controversy: Is there another state near the 938keV resonance?
Branch Points

- Competition between \((\alpha,p)\) and \((p,\gamma)\) reactions can lead to quite different network flow for \(^{22}\text{Mg}, ^{26}\text{Si}, ^{30}\text{S},\) and \(^{34}\text{Ar}\).
- \((p,\gamma)\) rate above branch-point is critical too (e.g. \(^{23}\text{Al}(p,\gamma)\) for \(^{22}\text{Mg}\) branch-point)
- \((p,\gamma)\) uncertainty from structure of the compound nucleus (levels and widths)
- \((\alpha,p)\) uncertainty from nuclear level densities and \(\alpha\)-optical potentials

Consider paths A vs B
Branch Points

Most interesting cases here are: $^{22}\text{Mg}(\alpha,p)$, where the LD and $\alpha\text{OMP}$ for $^{26}\text{Si}$ are needed and $^{23}\text{Al}(p,\gamma)$, though this case was just constrained by experiment.

For populating a high-LD region, use the statistical formalism. Calculate cross section via Hauser-Feshbach method:

$$\sigma_{X(a,b)Y}^{HF} = \pi \left(\frac{\lambda}{\pi}\right)^2 \sum_J \frac{2J+1}{(2J_a+1)(2J_X+1)} W_{ab} \frac{T_{aX}T_{bY}}{\sum_{chan} T_{chan}},$$

where $T_i$ are transmission coefficients and $W_{ab}$ is a width-fluctuation correction factor.

$W_{ab}$ is a small correction that enhances elastic scattering b/c the incoming and outgoing $T$ are correlated.

Get $T_i$ for particles from optical model potentials. For $\gamma$-rays, need $\gamma$-strength function.

Level density $\rho$ comes in because $T_i$ are sum over all final states:

$$T(U, J, \pi) = \sum_{b'} \left( \sum_k T_{b'}(U, J, \pi, E_k, I_k, \pi_k) + \right)$$

Integrate cross section for thermonuclear reaction rate:

$$\sqrt{\frac{8}{\pi\mu}} \frac{1}{(k_BT)^{3/2}} \int_0^\infty \sigma_{12}(E)\exp\left(-\frac{E}{k_BT}\right) dE$$

Consider paths A vs B.
Cycles

- When $S_\alpha$ is lower than $S_p$ in a compound nucleus, $(p,\gamma)$ and $(p,\alpha)$ compete
- $(p,\alpha)$ stalls energy generation and introduces $\alpha$ back into the system
- Need LD and $\gamma$SF for $^{60}$Zn and $^{64}$Ge
Cycles: Example of $^{59}\text{Cu}(p,\gamma)^{60}\text{Zn}$

*For statistical reactions*, want the probability to transmit particles/photons in/out of the nucleus (particle optical potentials and $\gamma$ strength functions) *and* the number of states to transmit to/from (nuclear level densities)
Cycles: Example of $^{59}\text{Cu}(p,\gamma)^{60}\text{Zn}$

The $\beta$-Oslo Technique @ NSCL/FRIB:

The $\beta$-Oslo technique determines the level density and $\gamma$-strength function needed for the statistical reaction rate.

This first application (April 2019) including proton-decay will simultaneously determine the proton optical potential.

\[ P(E_\gamma, E_x) = \rho(E_x - E_\gamma)T(E_\gamma) \]
Waiting points

- Stuck waiting for $\beta$-decay because $(p,\gamma)$- $(\gamma,p)$ equilibrium at $^{56}\text{Ni}$, $^{64}\text{Ge}$, $^{68}\text{Se}$, $^{72}\text{Kr}$, $^{100}\text{Sn}$
- Caused by:
  - low $(p,\gamma)$ Q-value
  - long half-life (~seconds)
- Also impacted by $p,\gamma$ rate on waiting-point proton-capture daughter
Waiting points

- The path of the rp-process is dictated by finding \((p, \gamma) - (\gamma, p)\) equilibrium nucleus

\[
\frac{\lambda_{\gamma,p}}{\lambda_{p,\gamma}} = \frac{n_p}{n_\gamma} \left( \frac{\mu_{\text{red}} c^2}{k_B T} \right)^{3/2} \exp \left( - \frac{Q_{p,\gamma}}{k_B T} \right) > 1, \quad \mu_{\text{red}} \approx 1 \quad n_\gamma = \frac{\pi (k_B T)^3}{(13c^3 \hbar^3)}
\]

For \(\rho \sim 10^6 \text{ g/cm}^3\), \(X(H) \sim 0.7\), and \(T \sim 1\text{GK}\), this turns out to be \(S_p \sim 1\text{MeV}\)

- So, waiting points have \(S_p \sim 1\text{MeV}\) and >second half-lives
Waiting points

- Completely dominated by reaction Q-value
- Need precise masses and excitation energies
- Major outstanding uncertainties: $^{65}\text{As}$ and $^{66}\text{Se}$ masses, $^{57}\text{Zn}$ $\beta$-branching

$$\frac{\lambda_{\gamma,p}}{\lambda_{p,\gamma}} = \frac{n_p}{n_\gamma} \left( \frac{\mu_{\text{red}} c^2}{k_B T} \right)^{3/2} \exp \left( -\frac{Q_{p,\gamma}}{k_B T} \right) \approx 1$$

Orange to red essentially only differ by shell-model calculations
How do we know which $rp$-process reactions matter?
Sensitivity studies: brute-force ways to see what matters

“Large” Impact on XRB LC

Z. Meisel et al. JFG 2018


“Large” Impact on XRB Ashes
(a.k.a. Neutron star surface abundances)


59Cu(p,γ)
The impact of rate variations doesn’t look very impressive. Are we sure they matter?

Consider the Clock Burster, GS 1826-24

Do reaction rate sensitivities matter for modeling this source?
*the models are one-dimensional
MESA output processing: stacking, smoothing, & averaging

- **Stacked**
- **Smoothed** (over ±1s)
- **Averaged**

*First burst is excluded from averaging*

**Burst train**

**Flux** [$10^{-9}$ erg cm$^{-2}$ sec$^{-1}$]

**Time** [hr]

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Meisel ApJ 2018
Model-observation comparisons were performed for the year 1998, 2000, 2007 burst epochs, for a grid of $z$ and $d$.

For highest $\dot{M}$ in a triplet, compared light curve to 2007 epoch at each point in a grid of modifications:

For highest $\dot{M}$ in a triplet, found the best-fit $(1+z)$ and $d\xi_b^{1/2}$, for an arbitrary time shift:

Applied the best-fit $(1+z)$ and $d\xi_b^{1/2}$ from the highest $\dot{M}$ in a triplet, and an arbitrary time shift, to LCs from all three $\dot{M}$:

\[
F(t) = \frac{L(t)}{4\pi \xi_b (1 + z)d^2} \\
t = t_0[1 + z]
\]
The clock-burster was reproduced, with stringent constraints on the astrophysical conditions.
Were these results sensitive to nuclear physics uncertainties?

Yes, but the impacts are not great enough to significantly change the best-fit astrophysical conditions.

This is great! Otherwise we would need to do a recursive study of nuclear physics sensitivities.

The natural question is whether the impact of nuclear uncertainties matter anyway.
Do the nuclear physics sensitivities matter? Yes.

Consider variations of the significant reaction rate uncertainties identified in Cyburt et al. 2016…

… and re-do the fit to the GS 1826-24 light curve

Meisel, Merz, & Medvid, In preparation
Reaction rate uncertainties lead to redshift uncertainties, which in-turn lead to uncertainties on the NS mass-radius. From a positive perspective, if we reduce these reaction rate uncertainties, we have a new mass-radius constraint.
Note: “Important” rates may be different for different conditions.
The journey of a nucleus in a neutron star

1. Production from H, He, C burning

- p, α-capture
- 12C-fusion, e- capture
- n-emission/capture, ρ-driven fusion
X-ray superbursts:
Carbon burning and photodisintegration in the ocean

- 4U 1820-303
- SAX J1808.4-3658
- GS 1826-24

accretion disk

atmosphere
- \(p,\alpha\)-capture
- \(^{12}\text{C}\)-fusion, e\(^{-}\)-capture

ocean
- e\(^{-}\)-capture

crust
- n-emission/capture, \(\rho\)-driven fusion

core
Model C-ignition depth is $\sim 10\times$ deeper than the fit C-ignition depth.
$^{12}\text{C} + ^{12}\text{C}$ fusion: enhanced or suppressed?

From R-matrix fit to different reaction accessing the same compound nucleus (trojan horse method)

*They fit their data using unphysical $J^{\pi}$

From direct measurements

*Their theory comparisons are out-of-the-box, except “hindrance” model is fit

Various surface burning processes lead to very different ash distributions.
Going lower: into the crust

- atmosphere: ~1 cm
- ocean: ~100 m
- outer crust: ~0.5 km
- inner crust: ~0.5 km
- core: ~10 km

[Diagram showing layers of a neutron star]
Cooling transients are sensitive to NS composition & thermal structure

Cooling transients

X-ray flux

Days

Accretion disk

atmosphere

p,α-capture

12C-fusion, e- capture

e- capture

Ocean

crust

n-emission/capture, p-driven fusion

core
Cooling transients are sensitive to NS composition & thermal structure

- Crust thermally relaxes: solving thermal diffusion results in a thermal timescale

\[ \rho C \frac{\partial T}{\partial t} = \nabla \cdot (K \nabla T) \]

\[ \tau = \left( \frac{(1 + z)}{4} \right) \left( \int_0^y \sqrt{c_p/(\rho K)} dy' \right)^2 \]

\[ K \propto Q_{\text{imp}} \]

See outer-crust at ~100 days
See inner crust at ~1000 days
See core at ~4000 days
First, consider the non-accreted crust

- Assuming a long cooling time, achieve $T=0$ thermodynamic equilibrium.
- Minimize energy: $E_{\text{total}}/A = E_{\text{nuclear}}/A + E_{\text{e-gas}}/A + E_{\text{lattice}}/A$.
- For LDM & BCC lattice:
  
  $E_{\text{total}}(A, Z, \mu_e)/A = m_pc^2Y_e + m_nc^2(1 - Y_e)$
  
  $- a_v + \frac{a_s}{A^{1/3}} + a_c A^{2/3} Y_e^2$
  
  $+ a_d(1 - 2Y_e)^2 + \frac{3}{4} Y_e \mu_e$
  
  $- C_\ell A^{2/3} Y_e^{5/3} \mu_e$.

- For inner crust, add neutron gas, modify LDM for compressibility, & choose a local $Z$-density to define “clusters”.

What if $N=82$ disappears?
The journey of a nucleus in a neutron star

2. Burial and electron-capture

This creates heat sources (EC heating) and sinks (urca cooling)
Surface ashes set the composition for most of the outer crust

- Interesting quantity is $Q_{\text{imp}}$, the variance of the charge distribution
  $$Q_{\text{imp}} = \frac{1}{n_{\text{ion}}} \sum_j n_j (Z_j - \langle Z \rangle)^2$$

- Sets ion-impurity scattering (dominates thermal conductivity for lower $T$ and/or deeper layers)

- At the surface:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>x-ray burst</th>
<th>Superburst</th>
<th>Stable burning</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle Z \rangle$</td>
<td>24</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>$\langle A \rangle$</td>
<td>52</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td>$Q_{\text{imp}}$</td>
<td>69</td>
<td>3</td>
<td>101</td>
</tr>
</tbody>
</table>
Buried nuclei undergo electron capture in the degenerate electron gas.
Buried nuclei undergo electron capture in the degenerate electron gas.
Buried nuclei undergo electron-capture, causing heat release.
Buried nuclei undergo electron-capture, OR cooling

System Energy

$E_{g_1}(Z,A)$

$E_{g_2}(Z-1,A)$

$E_{g_3}(Z-2,A)$

$E_{e,Fermi}$

$E_{e,Capture}$

$\beta$-neutrino cooling

"Urca" process

accretion disk

$\nu \leftrightarrow (Z,A) \leftrightarrow (Z-1,A)$

NS surface

density

$\nu \nu \nu$
The neutron star crust is peppered with local heat sources & sinks.
Mass surface sets global systematics of heating & cooling

**Maximum possible E release per EC**

**Urca cooling & deformation**


Heating depth & strength due to nuclear masses & $J_{\pi}^{x_S}$

A. Estrade et al. PRL 2011


to ground state
to excited state
Including EC heating transforms the transient light curve

Only deep crustal heating

...+ heat at shallower depths
Can then reproduce transient light curves

... & find the crust seems to be pretty pure

*cheating a bit: add extra shallow heating
What if accretion isn’t uniform? Get nonuniform heating

\[ \dot{E}_{GW} = 2\pi\nu N_{GW} = -\frac{32}{5} \frac{G(2\pi\nu)^6(I\varepsilon)^2}{c^5} \]

\[ \varepsilon \approx 1.7 \times 10^{-9} \frac{\Upsilon}{Z} \frac{\delta T}{10^7 \text{K}} \frac{2.44}{g_{14}} \left( \frac{R}{10 \text{ km}} \right)^{4} I_{45}^{-1} \left( \frac{|Q_{EC}|}{30 \text{ MeV}} \right)^{3} \]

This is one possibility for the slightly faster-than-expected spin down of PSR J1023+0038 (27% faster than expected from measured radio emission)
Surface burning ashes enrich the neutron star ocean & crust:

Ashes can undergo EC/β⁻-decay cycling, leading to strong ν-cooling:

This “Urca” cooling can substantially alter the accreted crust thermal profile:

Details depend on nuclear physics!
Urca cooling has a unique signature in cooling transients, indicative of past surface nuclear burning.
Urca cooling may impact X-ray superburst ignition

Cooling can drive the carbon ignition deeper to 10x deeper column depth.
Urca cooling strengths depend sensitively on nuclear physics.

\[ L_{\nu} \approx L_{34} \times 10^{34} \text{ erg s}^{-1} \left( \frac{X}{2} T_9^5 \left( \frac{g_{14}}{2} \right)^{-1} R_{10}^2 \right) \]

\[ L_{34} = 0.87 \left( \frac{10^6 \text{ s}}{f_{t}} \right) \left( \frac{A}{56} \right) \left( \frac{Q_{\text{EC}}}{4 \text{ MeV}} \right)^5 \left( \frac{\langle F \rangle^*}{0.5} \right) \]

Surface burning (e.g. XRB) ashes

Intrinsic nuclear properties

Masses

Structure

Reaction rates

Weak transition rates

NS-crust processes

rp-process
Mass Impact Example: $^{56}\text{Ti}-^{56}\text{Sc}-^{56}\text{Ca}$

Z. Meisel & S. George
IJMS 2013
Z. Meisel et al.
PRL 114 2015
Z. Meisel et al.
PRL 115 2015
Z. Meisel et al.
PRC 2016
Z. Meisel et al. In Preparation
The cycling rate is set by the weak rate

- Get weak rate from wavefunction overlap & phase space integral:
  \[ \lambda = \frac{G_F^2 m_e^5 c^4}{2\pi^3 h^7} |M_{fi}|^2 f(Z_d, Q) = \frac{\ln(2)}{t_{1/2}} \]
- Rephrase as the comparative half-life, \( f_t \),
  \[ f_t = \frac{2\ln(2)\pi^3 h^7}{G_F^2 m_e^5 c^4} \frac{1}{|M_{fi}|^2} \]
- Need Q-value, half-life, & branching ratio
  - or measure \( J^\pi \) and estimate \( f_t \) from \( \Delta J^\Delta \pi \)
  - or calculate \( \psi \)-overlap

- \( f_t \) in \( L_\nu \) is \( \frac{f_t \beta + f_t EC}{2} \)

L_\nu only depends linearly on \( f_t \), but \( f_t \) can span orders of magnitude

W. Meyerhof, Elements of Nuclear Physics (1967)
W.-J. Ong et al. 2019
EC near neutron drip ($S_n=0$) broadens abundance distribution. Emitted n can be captured or just contribute to n-gas.

EC into excited states must be calculated, unless charge-exchange measurements are possible.

$n$-drip sets-in around ~20-40MeV for nuclei in surface burning ashes.
Superthreshold (EC, xn) Cascades (SECs) find equilibrium

The journey of a nucleus in a neutron star

3. Fusion and disintegration

This creates heat sources and determines the inner crust impurity

accretion disk

- atmosphere: p,α-capture
- ocean: $^{12}$C-fusion, e-capture
- crust: e-capture, n-emission/capture, ρ-driven fusion
- core
Pycnonuclear (density-driven) fusion

- Zero-point oscillation of nuclei around equilibrium positions enables nuclear fusion
- Rates span orders of magnitude & uncertainties are essentially decoupled from terrestrial nuclear physics input

![Graphical representation of pycnonuclear fusion processes](image)

- Main uncertainties from ion correlations & lattice structure
  *(impacts vibration amplitudes)*
Pycnonuclear reactions purify the inner crust

\[ Q_{\text{inner}}^{1\text{mp}} = 13.0, 15.7, 15.9, 14.4, 13.4, 11.2 \]
\[ Q_{\text{inner}}^{1\text{mp}} = 12.9, 14.5, 14.4, 15.5, 13.4, 13.2 \]
Ultimately, pycnonuclear reactions + SEC dissolve nuclei into neutrons.
Wind up with similar heating independent of assumptions

~2-4 MeV/u total

*Distribution sets time for break in transient light curve, magnitude alters T-gradient & therefore cooling timescale
Surface composition driven to cold-catalyzed state

- Gibbs free-energy per nucleon (i.e. baryon chemical potential)
  \[ \mu_b(P) = \frac{[BE(P) + P]}{n_b(P)} \]
- approximating \( T = 0 \)
  - Minimizing \( \mu_b \) winds up with the ground state of the crust at that pressure
- Non-catalyzed crust is a heat reservoir & crust reactions drive material to the ground state
  - Initial \( \mu_b \) are pretty similar because \( BE/A \) for most stable nuclei is about the same
  - Total heating then mostly depends on the equilibrium composition at the crust-core transition, which mostly depends on the EoS (since EoS determines \( P_{\text{crust-core}}(\rho_{\text{crust-core}}) \)
Concept: weakly bound neutron tunnels into nearby nucleus where it would be more bound

1. Assume Fermi’s golden rule for the transition probability:
\[ W = \frac{2\pi}{\hbar} |M|^2 \rho \approx 10^{22} \left( \frac{M}{1 \text{MeV}} \right)^2 \frac{\rho}{1 \text{MeV}^{-1}} \text{s}^{-1} \]

2. Say the density of states is \( \rho = 1 \text{MeV}^{-1} \)

3. For the wavefunction overlap of the matrix element, assume they overlap in an asymptotic region described by:
\[ \Psi_a \approx A_a \frac{r_a}{r'} \exp(-\kappa r') \]

4. Take the first-order result from the integral for the wave-function overlap:
\[ M \approx \frac{3 \hbar^2}{2 m_n} \frac{1}{\sqrt{r_d r_a}} \frac{\exp(-\kappa l)}{l} \]

5. Volume-average the transition probability, weighting by the density of correlated neutron donor & acceptor nuclei
\[ \lambda = \int W(l) n_a(l) d^3l \]
\[ n_a(l) = n_a g_{ad}(l) \]

6. Use previous approximations for the pair correlation function and use a saddle-point approximation for the integral to get an analytic form for the rate:
\[ \lambda = 4\pi n_a l^3_{pk} \sqrt{\frac{\pi l_{pk}}{a_{ad} \Gamma_{ad}}} W(l_{pk}) g_{ad}(l_{pk}) \]
(very approximate) neutron transfer reaction rates

Fast enough to burn-out some urca nuclei in hours
Guess for the n-transfer impact

• Work is ongoing to assess the impact in a crust network calculation …but let’s guess what will happen anyways

• Rates are fastest for low $S_n$ donors ($\sim < 3\text{MeV}$)
  - high $Q_{EC}$
  - low-Z acceptors

• So, a few MeV from n-drip (where EC,xn might happen anyways), we might expect urca nuclides to donate their neutron to the highest X(A) low-Z nucleus (whatever A=28 is at that depth)

• That will re-shuffle odd-A abundances into A=29

• For Urca candidates, A=29 has one of the deepest capture depths (largest QEC) and has $S_{n}>3\text{MeV}$,
  …so this Urca cooling would be enhanced

\[
\begin{array}{|c|c|}
\hline
\text{EC Parent} & |Q_{EC}| (\text{MeV}) \\
\hline
^{29}\text{Mg} & 13.3 \\
^{31}\text{Al} & 11.8 \\
^{33}\text{Al} & 13.4 \\
^{55}\text{Sc} & 12.1 \\
^{57}\text{Cr} & 8.3 \\
^{59}\text{V} & 10.7 \\
^{59}\text{Mn} & 7.6 \\
^{63}\text{Cr} & 14.7 \\
^{65}\text{Fe} & 10.3 \\
^{65}\text{Mn} & 11.7 \\
\hline
\end{array}
\]
FRIB will drastically expand our experimental reach

Fast beam rates in pps

Reaccelerated beam rates in pps

Meisel et al. JPG 2018
New tools at FRIB multiply the impact, e.g. SECAR

G. Berg et al. NIMA 2018

K. Schmidt et al. NIMA 2018
Areas for improvement (in terms of nuclear physics)

- Targeted indirect measurements & calculations for key rp-process reaction rates
- Direct measurements of rp-process reaction rates
- Measurements of $^{12}\text{C}+^{12}\text{C}$ to lower energies
- $N=82$ evolution with decreasing $Z$
- Accurate electron-capture rate calculations
- Charge-exchange measurements off stability for electron-capture rates
- Measurement & calculation of structure of exotic nuclides (for EC and EC,xn)
- Less approximate estimates for neutron-transfer rates