Experiments in Nuclear Astrophysics I (charged-particle induced)

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Marco Pignatari, University of Victoria, Canada
Michael Wiescher, University of Notre Dame
**Scope**

Other Lectures:
- ...nuclei far from stability
- ...under extreme conditions
- ...stellar explosions

This Lecture
- ...at or close to stability
- ...stable beam reactions

↓

“classical” low-energy nuclear astrophysics

Nuclear Structure ↔ \( T \approx 1 \text{ GK} \) Nuclear Properties
- resonances
- spin & widths of levels
- e.g. CNO cycle
- masses
- Lifetime
- e.g. r-process
Outline

Historical Remarks
- from Rutherford to B²FH

From Experiment to Reaction Rate
- formalism

Experiments
- CNO cycle
- neutron sources
- $^{12}C + ^{12}C$

Future
Henri Becquerel
(15.12.1852 – 25.8.1908)
Nobel Prize in Physics (1903)

Becquerel wrapped a fluorescent substance, potassium uranyl sulfate, in photographic plates and black material in preparation for an experiment requiring bright sunlight.

Marie Skłodowska Curie
(7.11.1867 – 4.7.1934)

- first systematic studies of radioactive substances (with her husband Pierre Curie)
- first used the term “radioactive”
- discovery of Polonium & Radium
- 1st victim of radiation
- founder of Nuclear Medicine

Nobel Prize in Physics (1903)
Nobel Prize in Chemistry (1911)
Ernest Rutherford,  
(30.8.1871–19.10.1937)  

The Birth of Nuclear Physics  

I. XXXIX. The Scattering of α and β Particles by Matter and the Structure of the Atom. By Professor E. Rutherford, F.R.S., University of Manchester *.

Philosophical Magazine, Series 6, vol. 21, May 1911, p. 669-688

It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Rutherford Scattering Law is a fundamental discovery!!

Based on experiments by Geiger and Marsden

On a Diffuse Reflection of the α-Particles.

By H. Geiger, Ph.D., John Harling Fellow, and E. Marsden, Hatfield Scholar, University of Manchester.

(Communicated by Prof. E. Rutherford, F.R.S. Received May 19.—Read June 17, 1909.)

Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 82, No. 557 (Jul. 31, 1909), pp. 495-500

Expection: all events within <2°
It is difficult to avoid the conclusion that these long-range atoms arising from the collision of α-particles with nitrogen are not nitrogen atoms, but probably charged atoms of hydrogen or atoms of mass 2. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with swift α-particles, and that the atom liberated formed a constituent part of the nitrogen nucleus.

But is it possible to admit that such a transmutation is occurring? It is difficult to assert, but perhaps more difficult to deny, that this is going on. Sir Ernest Rutherford has recently been breaking down the atoms of oxygen and nitrogen, driving out an isotope of helium from them; and what is possible in the Cavendish laboratory may not be too difficult in the Sun. I think that the suspicion has been generally entertained that the stars are the crucibles in which the lighter atoms which abound...
Proton or alpha induced reaction as energy source of stars??
(a matter of discussion in the 1920’s)

Protons:
- 4p->4He has highest energy gain
  (from mass spectroscopy, Ashton)
Alphas:
- mainly He in sun’s surface
- forming He from 4 protons
- need high proton energies
to overcome Coulomb barrier

ON THE COMPOSITION OF THE SUN’S ATMOSPHERE
BY HENRY NORRIS RUSSELL

ABSTRACT

The energy of binding of an electron in different quantum states by neutral and singly ionized atoms is discussed with the aid of tables of the data at present available. The structure of the spectra is next considered, and tables of the ionization potentials and the most persistent lines are given. The presence and absence of the lines of different elements in the solar spectrum are then simply explained. The excitation potential, $E$, for the strongest lines in the observable part of the spectrum is the main factor. Almost all the elements for which this is small show in the sun. There are very few solar lines for which $E$ exceeds 5 volts; the only strong ones are those of hydrogen.


Z. Physik, 52, 510, 1928

ZUR QUANTENTHEORIE DES ATOMKERNES.

Von G. Gamow, z. B. in Göteborg.

Mit 5 Abbildungen. (Vorgangsweise am 2. August 1928.)

Es wird der Versuch gemacht, die Prozesse der α-Ausstrahlung auf Grund der Wellenablauftheorie zu unterzeichnen und den experimentell festgestellten Zusammenhang zwischen Zerfallskonstanten und Energie der α-Teilchen theoretisch zu erklären.

§ 1. Es ist schon öfters* die Vermutung ausgesprochen worden, daß im Atomkern die nicht-coulombischen Anziehungskräfte eine sehr wichtige Rolle spielen. Über die Natur dieser Kräfte können wir viele Hypothesen machen.

Es können die Anziehungen zwischen den magnetischen Momenten der einzelnen Kernbauelemente oder die von elektrischer und magnetischer Polarisation herrührenden Kräfte sein.

Jedenfalls nehmen diese Kräfte mit wachsender Entfernung vom Kern sehr schnell ab, und nur in unmittelbarer Nähe des Kerns überwiegen sie den Einfluß der Coulombischen Kraft.

Aus Experimenten über Zerstreueung der α-Strahlen können wir schließen, daß, für schwere Elemente, die An-
Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York
(Received September 7, 1938)

It is shown that the most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons. These reactions form a cycle in which the original nucleus is reproduced, viz. $^{14}\text{C} + \text{H} = ^{15}\text{N}$, $^{15}\text{N} = ^{14}\text{C} + \text{e}^+$;

$^{14}\text{N} + \text{H} = ^{15}\text{O}$, $^ {15}\text{O} = ^{14}\text{N} + \text{e}^+$, $^{14}\text{N} + \text{H} = ^{15}\text{C}$ + He$^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle ($\S$7).

CNO-cycle
Bethe-Weizsäcker cycle

First electrostatic accelerator 1930
(Cockcroft-Walton)

First experimental informations about proton-induced reactions

Physikalische Zeitschrift 39, 633–46, 1938
Also before 1957: Several publications by E.E. Salpeter, W.A. Fowler and others
How does B2FH compares to today?

<table>
<thead>
<tr>
<th></th>
<th>B2FH</th>
<th>now</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}(p,\gamma)$</td>
<td>$S = 1.2 \pm 0.2$</td>
<td>$1.6 \pm 0.3$</td>
</tr>
<tr>
<td>$^{14}\text{N}(p,\gamma)$</td>
<td>$S = 3.0 \pm 0.6$</td>
<td>$1.7 \pm 0.1$</td>
</tr>
<tr>
<td>$^{20}\text{Ne}(p,\gamma)$</td>
<td>$S \approx 7$</td>
<td>$\approx 7$</td>
</tr>
<tr>
<td>$^{12}\text{C}(\alpha,\gamma)$</td>
<td>$S_{300} = 345$</td>
<td>$150 \pm 50$</td>
</tr>
<tr>
<td>$^{13}\text{C}(\alpha,n)$</td>
<td>$S_{190} = 5 \cdot 10^5$</td>
<td>$\approx 7$</td>
</tr>
</tbody>
</table>

Marion and Fowler (Ma57) have recently discussed the rates of the $^{13}\text{C}(\alpha,n)$ and $^{15}\text{N}(\alpha,n)$ reactions. For the $^{13}\text{C}(\alpha,n)$ reaction they find $S_\alpha = 2.1 \times 10^{14} T_e^{-4}$ keV barn so that the $^{13}\text{C}$ lifetime is

Sub-threshold states

Extrapolation of cross section to energies of interest requires detailed knowledge of nuclear structure!!
In the "penetrability region," the cross section may be written
\[ \sigma = \text{const} \cdot P_p P_q / E, \quad (647) \]
since the factor \( \lambda^2 \) in (645a) is proportional to \( 1/E \). This formula was first suggested by Gamow and is well confirmed for small energies of the incident particle (§78).

In many cases, the cross sections \( \sigma \) for such reactions have been measured in the laboratory as a function of energy for fairly low energies (100 kev and up). If the compound nucleus formed has no resonance levels in the region corresponding to these kinetic energies, then the cross section is approximately of the form
\[ \sigma = (S/E) \exp(-2\pi\rho Z_1 Z_2 / \hbar v), \quad (7) \]
where \( E \) and \( v \) are the kinetic energy and velocity, respectively, of particle 1 (relative to particle 2) and \( S \) is a constant (in units of ev barn). A simple formula
\[ \sigma(E) \propto \pi \lambda^2 \propto \frac{1}{E}. \]

Energy dependencies of nuclear cross sections
\[ \sigma(E) \propto \exp(-2\pi\eta). \]
Reaction Rates

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

nonresonant reaction

\[ S(E) \approx \text{constant} \]

resonant reaction

\[ S(E) \approx \text{Breit-Wigner} \]

Resonance Strength:

\[ \omega \gamma = \omega \frac{\Gamma_a \Gamma_b}{\Gamma} \]

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

\[ \Gamma_p (E << E_C) \sim \exp (-k \cdot E_R^{-1/2}) \]
Yield Of Narrow Resonances
(Number of Reactions Per Incoming Projectile)

\[ Y = \int_{E - \xi}^{E} (\sigma / \epsilon) \, dE \]

\[ Y = \frac{\sigma_R \Gamma}{2 \epsilon} \left[ \tan^{-1} \frac{E - E_R}{\Gamma / 2} - \tan^{-1} \frac{E - E_R - \xi}{\Gamma / 2} \right] = \frac{\sigma_R \Gamma}{2 \epsilon} \left[ \frac{\pi}{2} + \tan^{-1} \frac{E - E_R}{\Gamma / 2} \right]. \]

\[ \Gamma \ll \xi \]

\[ Y_{\text{max}}(\infty) = \frac{\pi \sigma_R \Gamma}{2 \epsilon} = \frac{\lambda^2}{2 \epsilon} \omega \gamma \]

\[ \epsilon = \epsilon_a + (i/a) \epsilon_i \quad \text{(in cm-system!)} \]

Target = \( A_a l_i \)
Cold CNO Cycle $T < 0.2$ GK

Branching point
Measurements of $^{15}\text{N}(p,\gamma)^{16}\text{O}$
Underground and above ground measurements of gamma rays are shown below. The graph displays the counts of gamma rays as a function of energy (E [keV]) for both underground and above ground conditions. The energy range spans from 0 to 10,000 keV.

Gran Sasso (elev. 2912m)

Notre Dame (elev. 212m)

1400 m below:
Final Result

-well constraint by large energy range

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$S(0)_{\gamma}$ (keV b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rolfs 1974 [12]</td>
<td>64 ± 6</td>
</tr>
<tr>
<td>Barker 2008 (RR) [16]</td>
<td>≈ 50-55</td>
</tr>
<tr>
<td>Barker 2008 (HH) [16]</td>
<td>≈ 35</td>
</tr>
<tr>
<td>Mukhamedzhanov [15]</td>
<td>36.0 ± 6.0</td>
</tr>
<tr>
<td>Present</td>
<td>39.6 ± 2.6</td>
</tr>
</tbody>
</table>
Hot CNO Cycles $T > 0.2$ GK

Breakout at $T > 0.4$
The nuclear trigger of X-ray Bursts

break-out from HCNO cycles: $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$, $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$

Interplay of:
- CNO feeding by $3\alpha$
- CNO breakout
- H left after burst

bursts are not the same
Reaction Rate of $^{15}$O($\alpha$, $\gamma$)$^{19}$Ne

- Reaction Rate

$N_A < \sigma v > \propto T^{-3/2} \omega \gamma e^{-E_R / kT}$

determined by resonance energy $E_R$ and strength $\omega \gamma$

where $\omega \gamma = \frac{2J_R + 1}{(2J_p + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma$

- Three measurable quantities characterize the resonance strength:
  $J$, $\Gamma_\gamma$, and $B_\alpha$
What experimentalists need to do for $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$

**Direct measurement is difficult!**

- An intense ($10^{11}$/s) radioactive $^{15}\text{O}$ beam gives a count rate of <1/hr (estimated at ISAC, TRIUMF)

\[
\omega \gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} \cdot \frac{\Gamma_\alpha \cdot \Gamma_\gamma}{\Gamma} \\
\sim B_\alpha \Gamma_\gamma \\
\sim Y(^{19}\text{Ne})
\]

**Indirect method has been approached many times!**

- Populate $\alpha$-unbound states in $^{19}\text{Ne}$
- Measure lifetimes or gamma widths
- Measure $\alpha$-decay branching ratios $B_\alpha$

\[
^{17}\text{O}(^{3}\text{He},n-\gamma)^{19}\text{Ne} \\
^{19}\text{F}(^{3}\text{He},t-\alpha)^{19}\text{Ne}
\]
“Indirect” approach: lifetime

$E_\gamma = E_{\gamma 0} \left(1 + F(\tau) \beta \cos \theta \right)$

Measured lifetime $\tau = 13 \pm 9 \text{ fs}$

or $\Gamma = 51 \pm 43_{-21} \text{ meV}$

TRIUMF 2006 $\tau = 11 \pm 8 \text{ fs}$

or $\Gamma = 60 \pm 40_{-25} \text{ meV}$

LWFG86: $\Gamma = 73 \text{ meV}$

$E_x = 4034.5 \pm 0.8 \text{ keV}$
“Indirect” approach: branching ratio B

\[ \omega \gamma = \frac{2J_R + 1}{(2J_p + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma \]

\[ N_A < \sigma v > \propto T^{-3/2} \omega \gamma e^{-E_R/kT} \]

After 20+ years
Neutron sources for the s-process

Main Component A>100
- low mass AGB stars
- T = 0.1 GK
- $N_n \sim 10^7 /\text{cm}^{-3}$
- s-process at $kT = 8 \text{ keV}$
- Time scale: a few 10,000 years

Weak Component A< 100
- core He burning in massive stars
- T = 0.3 GK
- $N_n \sim 10^6 /\text{cm}^{-3}$
- s-process at $kT = 25 \text{ KeV}$
- Time scale: Last few 10,000 years

Shell C burning in massive stars
- T = 1 GK
- $N_n \sim \text{up to } 10^{12} /\text{cm}^{-3}$
- s-process at $kT = 90 \text{ KeV}$
- Time scale: 1 year
  (not the “typical” s-process)
Core Helium Burning

Ash of the CNO-cycles

weak component of s-Process A<100

Hubble Space Telescope Betelgeuse
Simple "1-Zone" Model

12.6 million years
s-Process (Main Component A>100)

TP-AGB Stars

meteorite inclusions

Fluorine Lines Observed On Surface of AGB Star

$^{29,30}$Si isotope ratios

$^{22}$Ne($\alpha,n$)$^{25}$Mg

Convective Envelope
protons mixed downward by semiconvection

$^{12}$C(p,$\gamma$)$^{13}$N($\beta^+$$\nu$)$^{13}$C

$^{13}$C($\alpha,n$)$^{16}$O

flash driven convective pocket
ingestion

Large Mass Loss $\rightarrow$ Chemical Evolution

Jorissen et al.
Shell Carbon Burning

burns on the ashes of He-Burning $^{12}\text{C},^{16}\text{O},^{20,22}\text{Ne}$ and $^{25,26}\text{Mg}$

main energy source: $^{12}\text{C}+^{12}\text{C}$

main neutron source: $^{22}\text{Ne}(\alpha,n)$

possible neutron source at end of burning: $^{25,26}\text{Mg}(\alpha,n)$

well known at 1GK
residual from He burning
→ how much is left at end of He burning?
Small production branch:
$^{20}\text{Ne}(p,\gamma)^{21}\text{Na}(\beta^+)^{21}\text{Ne}(p,\gamma)^{22}\text{Na}(\beta^+)$

Most abundant isotopes at end of burning:
$^{16}\text{O},^{20}\text{Ne},^{23}\text{Na}$ and $^{24}\text{Mg}$
Neutron sources (Flux)

Light element nucleosynthesis:
$^{16}\text{O},^{20}\text{Ne},^{23}\text{Na},^{24}\text{Mg}$

M. Pignatari, PhD Thesis
C shell poisons

Neutron poisons: $^{16}\text{O}, ^{22}\text{Ne}, ^{25}\text{Mg}, ^{26}\text{Mg}(n,\gamma)$

alpha “poisons”: $^{16}\text{O}, ^{20}\text{Ne}(\alpha,\gamma), ^{22}\text{Ne}(\alpha,n)$

but

$^{17}\text{O}(\alpha,n),(\alpha,\gamma)$
$^{17}\text{O}(n,\alpha)$
$^{17}\text{O}(p,\alpha)$
(similar for $^{21}\text{Ne}$)

competition of reaction channels determines neutron recycling efficiency

proton “poisons”: $^{17}\text{O}, ^{23}\text{Na}(p,\alpha)$,
$^{22}\text{Ne}, ^{25}\text{Mg}(p,\gamma)$
NOT $^{12}\text{C}(p,\gamma)$
(photodissociation!)

S-process distribution at the end of the C shell

Pignatari 2009
Experiment at Notre Dame: $^{17}$O+alpha

$^{3}$He detector system
- thermalization of neutrons
- $^{3}$He(n,p) reaction
  \[ Q = 764 \text{ keV} \]
- 8 tubes in inner ring
- 12 tubes in outer ring

Target: Ta$_2$O$_5$
- enriched water $>$97 %
  (17O: $2000/ml)$
$^{17}\text{O}(\alpha, n)^{20}\text{Ne}$

$Q = 0.59 \text{ MeV}$

$S_\alpha = 7.35 \text{ MeV}$

$S_n = 6.76 \text{ MeV}$

Previous work:

Bair and Haas 1973
1.4-5.3 MeV
Anodized Ta:
$^{17}\text{O}(15\%)/^{18}\text{O}(5\%)$
$^{17}\text{O}$ implanted

Denker PhD Thesis 1994
0.8-2.0 MeV
Gas target
$^{17}\text{O}(50\%)/^{18}\text{O}(29\%)$
Preliminary results  
$^{17}\text{O}(\alpha,n)^{20}\text{Ne}$

Good agreement with Denker  
Correct for $(\alpha,n_1)$!!

Measurement below 900 keV hampered by cosmic/room background

Up to now:  
NO experimental information for $^{17}\text{O}(\alpha,n_1/\gamma)$
Preliminary results
$^{17}\text{O}(\alpha,\text{n}^1\gamma)^{20}\text{Ne}$

PVC neutron "shield"

FIRST measurement
Preliminary results
$^{17}\text{O}(\alpha,\gamma)^{21}\text{Ne}$

$(\alpha,n)/(\alpha,\gamma)$

Fowler: $\sim 10$
Descouvemont $\sim 10000$ (theory)

will be continued with large Ge detector array…
**\(^{22}\text{Ne}(\alpha,n)\), the main neutron source**

Q = -0.48 MeV

**\(^{26}\text{Mg}(\gamma,\gamma')\) to search for state and its spin!**

630 keV J\(^{\pi}\)=1\(^{-}\) resonance ??

Present upper limit: < 50 neV
Experiment at HIGS

High Intensity γ-ray Source (HIγS)

Target: 10 g(!) $^{26}$Mg
Market value $100000 ($10/mg)
On loan for 10% of value per year
Unique spin and parity assignment
But strong ground state transition is required
Results

TABLE III: Summary of width calculations for observed $^{26}$Mg excited states. Intermediate de-excitation level energies taken from [34]. $\gamma$-partial widths are denoted by their final state energy in keV. The final line gives $\Gamma_{thin}$, signifying the width calculated without electronic or nuclear attenuation effects using the thin target approximation (Equation 9).

<table>
<thead>
<tr>
<th>Width [eV]</th>
<th>$J^\pi$</th>
<th>$S_\alpha$</th>
<th>Initial Excite State, $E_{x_i}$ [keV], $J_f^\pi$</th>
<th>$S_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_0$</td>
<td>0$^+$</td>
<td>0.08(2)</td>
<td>10573 $1^-$</td>
<td>1.9(1)</td>
</tr>
<tr>
<td>$\Gamma_{1809}$</td>
<td>2$^+$</td>
<td>4.3(2)</td>
<td>10647 $1^-$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{2938}$</td>
<td>2$^+$</td>
<td>0.15(2)</td>
<td>10806 $1^-$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{3589}$</td>
<td>0$^+$</td>
<td>0.31(2)</td>
<td>10949 $1^-$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{4333}$</td>
<td>2$^+$</td>
<td>0.08(2)</td>
<td>11154 $1^+$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{4972}$</td>
<td>0$^+$</td>
<td>0.07(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{5292}$</td>
<td>2$^+$</td>
<td>0.09(1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{7100}$</td>
<td>2$^+$</td>
<td>0.06(1)</td>
<td></td>
<td></td>
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<tr>
<td>$\Gamma_n$</td>
<td></td>
<td></td>
<td></td>
<td>8.0</td>
</tr>
<tr>
<td>$\Gamma_{thin}$</td>
<td></td>
<td></td>
<td></td>
<td>0.33(3)</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td></td>
<td></td>
<td></td>
<td>0.23(3)</td>
</tr>
</tbody>
</table>

$^a$Not measured, $\Gamma_n/\Gamma = 0.75$ assumed for this state [18].
$^{25}\text{Mg}+n$: Evaluation from Koehler

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>19.880 ± 0.014</td>
<td>19.7 ± 0.2</td>
<td>19.90 a</td>
<td>51 ± 6</td>
<td></td>
<td></td>
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<tr>
<td>62.738 ± 0.023</td>
<td>62.5 ± 0.2</td>
<td>62.88</td>
<td>60 ± 10</td>
<td>62.4</td>
<td></td>
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<tr>
<td>72.674 ± 0.042</td>
<td>73.1 ± 0.5</td>
<td>73.3</td>
<td></td>
<td>72.3</td>
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<tr>
<td>79.30 ± 0.15</td>
<td>79.4 ± 0.2</td>
<td>79.6</td>
<td></td>
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<tr>
<td>81.13 ± 0.14</td>
<td>81.2 ± 0.7</td>
<td>81.35</td>
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<tr>
<td>93.61 ± 0.17</td>
<td>93.6 ± 0.2</td>
<td>93.8</td>
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<tr>
<td>100.007 ± 0.050</td>
<td>99.6 ± 0.2</td>
<td>99.8</td>
<td>102 ± 2</td>
<td></td>
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<tr>
<td>105.5 ± 0.2</td>
<td>105.8</td>
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<tr>
<td>156.169 ± 0.076</td>
<td>156.3 ± 0.2</td>
<td>156.5</td>
<td></td>
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<tr>
<td>188.334 ± 0.081</td>
<td>188.6 ± 0.2</td>
<td>188.9</td>
<td></td>
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<tr>
<td>194.502 ± 0.085</td>
<td>194.0 ± 0.2</td>
<td>194.2</td>
<td></td>
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</tr>
<tr>
<td>200.285 ± 0.097</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>204</td>
</tr>
<tr>
<td>201.062 ± 0.095</td>
<td>201.3 ± 0.3</td>
<td>201.6</td>
<td></td>
<td></td>
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<tr>
<td>203.86 ± 0.44</td>
<td>204.0 ± 0.3</td>
<td>204.3</td>
<td></td>
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</tr>
<tr>
<td>211.20 ± 0.11</td>
<td>209.8 ± 0.5</td>
<td>210</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>226.19 ± 0.50</td>
<td>226.7 ± 0.5</td>
<td>227</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>242.45 ± 0.55</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>244.58 ± 0.12</td>
<td>244.7 ± 0.5</td>
<td>245</td>
<td>235 ± 2</td>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>


Uncertainties from resonances below the detection limit of direct measurement!

Next month: complimentary ($\gamma$,n) reaction at HI$\gamma$S

Last known resonance at 832 keV
Uncertainties in the $^{12}\text{C}+^{12}\text{C}$ fusion rate?

Consequences for:
- Stellar Carbon burning
- Type Ia supernova ignition
- Superburst ignition conditions

Absorption under the barrier - 1973

Hindrance at extreme sub-barrier energies – 2002
Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).

- standard potential model
- hindrance potential model

Caughlan & Fowler ADND 1988
Gasques et al. PRC 2005
Yakovlev et al. PRC 2006
Jiang et al. PRC 2007
Resonance structure in $^{12}$C+$^{12}$C

Stokstad, 1976

Spillane, 2007
$^{12}\text{C}-^{12}\text{C}$ cluster configuration?

Almost of $2^+$ and $4^+$ states

$E_r \approx 1.5$ MeV

$\Gamma_{\text{tot}} \approx 1000$ eV

$\Gamma_{\alpha} \approx 250$ eV

$\Gamma_{p} \approx 750$ eV

$\Gamma_{12\text{C}} \approx 0.0001$ eV?

~1 count per day!
Influence of hypothetical 1.5 MeV resonance

Strong, molecular $^{12}\text{C}+^{12}\text{C}$ resonance causes enormous enhancement of S-factor and reaction rate at stellar burning conditions.

- Standard potential model
- Low energy resonances

<table>
<thead>
<tr>
<th>Temperature [GK]</th>
<th>Reaction rate</th>
</tr>
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<tbody>
<tr>
<td>$1.0E-28$</td>
<td>$10^{-28}$</td>
</tr>
<tr>
<td>$1.0E-20$</td>
<td>$10^{-20}$</td>
</tr>
<tr>
<td>$1.0E-12$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>$1.0E-04$</td>
<td>$10^{-4}$</td>
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<tr>
<td>$1.0E+04$</td>
<td>$10^{4}$</td>
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</tbody>
</table>
Future

Georgina

St.George
Future: 5 MV heavy ion accelerator Santa Ana

Provide intense heavy ion beams for St. George

Provide intense proton and alpha beams for direct experiments
Future: Georgina Ge array

1. Large efficiency up to 12 MeV.
2. Compact design to fit into tight spaces and to allow effective shielding (e.g., with cosmic ray veto detector).
3. Versatility to adopt the array to a wide variety of experimental needs (e.g., in combination with Si-detector arrays or other γ-detectors).
4. Modest granularity; in most experiments of interest the γ-ray multiplicity will be ≤3.

Monte Carlo simulation
sum efficiency:
1.33 MeV  6.7%  (GS 9%)
10.0 MeV  1.0%  1.6% addback
Future: recoil separator St. George

Design goal: alpha capture reactions with $Q \sim 10$ MeV

Recoil separator: Principle

γ detector

(projectiles (heavy)) → target (light) + recoils → separation → recoils, projectiles → detection identification

focusing and charge selection

Drawings from D. Schürmann
layout of St. George

$^{24}\text{Mg}(\alpha,\gamma)^{28}\text{Si}$
Wien filter electrostatic fringe field

Velocity filter: $v \sim E \times B$

- E-field of optimized WF
- Clamped magnetic field
- E-field of standard WF electrodes
It’s Coming!
Plans for St. George

DIRECT
$^{17}$O, $^{22}$Ne$(\alpha,\gamma)$
$^{22}$Ne$(\alpha,n)$(!)
Q<0
sorry, no $^{17}$O$(\alpha,n)$
(Q>0)

INDIRECT
alpha-transfer reactions
at sub-Coulomb energies
- evaluate resonances
too weak for DIRECT
- locate exact energies
of resonances for Direct
(“misuse” St.George as 0 degreee spectrometer)
Future: Underground Accelerator Laboratory

DUSEL Deep Underground Science and Engineering Laboratory at Homestake, SD
Why going underground?

For low Q-value reaction: Local shielding (Pb) is more effective when the muon flux is reduced!
Accelerators for Nuclear Astrophysics is a collaboration between the following institutions:
Laboratory Lay-Out

Approx. Cave Dimensions:
Length: 45 m
Width: 20 m
Max. Height: 20 m
Collaborators

University of Notre Dame
Andreas Best
James deBoer
P.J. LeBlanc
Shawn O'Brien
Antonios Kontos
Qian Li
Rashi Talwar
Ethan Uberseder
Georg Berg
Manoel Couder
Ed Stech
Wanpeng Tan
Michael Wiescher
J.G.

Universität Mainz:
Sascha Falahat
K.L. Kratz
Uli Ott

LUNA
Heide Costantini
Gianluca Imbriani
Mathias Junker
LUNA collaboration

University of North Carolina
Richard Longland
Christian Iliadis

Duke University
Gencho Rusev
Anton Tonchev

University of Victoria
Marco Pignatari