Experimental results of the $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ carbon burning reaction at low energies and (a limit) overview of direct data
Outline of this Presentation

Experimental results of the $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ carbon burning reaction at low energies and (a limit) overview of direct data

• Astrophysical Motivation – Carbon Burning

• The Carbon Fusion - $^{12}\text{C} + ^{12}\text{C}$ - recent experiments
  → experimental issues
  → extrapolation
  → robustness of data

• Recommendations for future experiments
Astrophysical Motivation $^{12}\text{C} + ^{12}\text{C}$ fusion

Results of current Stellar Models suggest:

**$M_{up} \equiv$ minimum mass for carbon ignition**

- **Stars with $M < M_{up}$ (presently $8M_{\odot}$)**
  These stars shed their H-rich envelopes during He burning (AGB phase) and end as CO White Dwarfs.
  → *Impact on the Nucleosynthesis and the chemical evolution of the Universe*

  → *the expected observational rates for Supernovae and Novae depend on the fundamental mass limits $M_{up}$ and $M'_{up} and, thus on the $^{12}\text{C} + ^{12}\text{C}$ reaction rates*

- **Stars with $M > M'_{up}$**
  Ignition of central *carbon burning* followed by Ne, O, and Si burning. The subsequent evolution proceeds in most cases to a core collapse Supernova.

degenerated conditions and after a super AGB phase end as ONeMg White Dwarf.
Wide range of possible heavy ion reactions - at low energies most important:

$^{12}$C + $^{12}$C (lowest Coulomb Barrier)

$^{12}$C($^{12}$C,p)$^{23}$Na Q = 2.240 MeV
$^{12}$C($^{12}$C,α)$^{20}$Ne Q = 4.617 MeV
$^{12}$C($^{12}$C,n)$^{23}$Mg Q = -2.598 MeV

$E_G = 2.42 \times T_9^{2/3} \pm 0.75 \times T_9^{5/6}$

The $^{12}$C+$^{12}$C fusion reactions produce light elements; their abundances stay relatively low and reflect the rate of the reactions destroying them and of $^{12}$C+$^{12}$C.
Summary of previous studies

γ-ray spectroscopy

High and Cujec, Nucl. Phys. A, 1977, $E_{cm} > 2.46$ MeV
Erb et al., Phys. Rev. C, 1980 $E_{cm} > 5.6$ MeV
Kettner et al., Z. Phys. A, 1980, $E_{cm} > 2.45$ MeV $\rightarrow$ large discrepancy with Mazarakis
Barron-Palos et al., Nucl. Phys. A, 2006, $E_{cm} > 2.25$ MeV $\rightarrow$ different energy dependence
Spillane et al., Phys. Rev. Lett., 2007, $E_{cm} > 2.1$ MeV

particle spectroscopy ($\alpha$- and p-detection)

Patterson et al., Astrophys. J., 1969, $E_{cm} > 3.23$ MeV
Mazarakis and Stephens, Phys. Rev. C, 1973 $E_{cm} > 2.45$ MeV
Becker et al., Z. Phys. A, 1981, $E_{cm} > 2.8$ MeV $\rightarrow$ most complete data set at present
Aguilera et al., Phys. Rev. C, 2006, $E_{cm} > 4.42$ MeV $\rightarrow$ higher energy only

common issue: large uncertainties below $E_{cm} = 3$ MeV
Level Scheme - γ-ray spectroscopy
Experimental Setup - $\gamma$-ray spectroscopy

- 1 germanium detector (115%) at 0°
- lead shielding (15 cm)
- active shielding (cosmic muons)
- thick Graphite target (1 mm) – high stability, clean
- target heated with beam (about 700° C)

→ no hydrogen/deuterium contaminations
- differential method – energy steps 12.5 and 25 keV
- observation of $E_\gamma = 440$ keV (p channel) and $E_\gamma = 1634$ keV ($\alpha$ channel)

- covered energy range $E_{cm} = 2.1 – 4.7$ MeV

2 cm Ge detector

$\varepsilon_\gamma = 2\%$ (3.6%)

12 C beam

Graphite

40 pµA

Experimental Setup - $\gamma$-ray spectroscopy
Experimental Results - $\gamma$-ray spectroscopy

$^{12}$C + $^{12}$C

$E_{cm} = 2.85$ MeV

Counts per second

Energy [keV]

Spillane et al., PRL 98, 122501 (2007)
**Experimental Results - γ-ray spectroscopy**

very important feature of this experiment: low hydrogen content in target

comparison of γ-ray spectra with earlier experiments

Baron-Palos et al., NPA 779 (2006) 318
Experimental Results - $\gamma$-ray spectroscopy

Advantages of this approach:
- very easy
- „clear“ signature of $\gamma$-lines

Disadvantage:
- low efficiency
- unknown angular distribution
- not sensitive to ground state transitions
  → could make 50% of cross section
  → no measurement of $\sigma_{tot}$
  → need estimate from old measurement
Experimental Results – total $S$-factor

$S^*_\text{tot}$ [MeV b]

importance of resonances

$E$ [MeV]
natural next step

CIRCE Accelerator

Tandem Accelerator
3 MV

Ion Production and Detection
Electrostatic Components
Magnetic Components
Beam line

Injection Magnet
Magnetic field 15 kV/m amu
m = 0.427 m

Multistep Switcher
E = 100 kV
m = 0.352 m

Electrostatic Analyzer
E = 50 kV
m = 0.801 m

Stable Isotope Measurement

Heavy Isotope
C + C
Reaction
Switching Magnet
B = 1.2 T

Electrostatic Doublet
E = 5.1 MV
m = 3.54 m

TOF-Detector

C Detection

ERMA Separator

Magnetic Quadrupole

C + C

Terminal

Charging chain

gas stripper

E = 176 kV/m amu
m = 1.273 m

Beam profile monitor

Electrostatic Components

Beam line
Level Scheme - particle spectroscopy
Experimental Setup - particle spectroscopy

preliminary tests with single detector:

→ beam induced background too high at lower energies

→ $\Delta E$-$E$ particle detector telescope
Experimental Setup - particle spectroscopy

Completely separate detector volume from target using foils and sheet metal

→ Target sputtering causing large leak currents on silicon detectors
Experimental Results - particle spectroscopy

- only p channel is detected
- $^{12}\text{C}(^{12}\text{C},p_{0,1})^{23}\text{Na}$
- $\Delta E$ detector too thick
- $\alpha$ particles are stopped
- background tests

Background arising from hydrogen contaminations

$E = 3.5 \text{ MeV}$

$E = 1.6 \text{ MeV}$
disadvantage of particle spectroscopy:
    very poor energy resolution
    from kinematics as well as experimental technique

→ background discrimination not as „easy“ as for γ-ray spectroscopy

→ test with various beams and targets (\(^{7}\text{Li},^{9}\text{Be},^{10,11}\text{B},^{13}\text{C}\))
    no impact observed so far

but:
    water, i.e. deuterium, remains as a huge problem
Background considerations

in $\gamma$-ray spectroscopy measurements main source of background

$^{12}\text{C}(d,p\gamma)^{13}\text{C}$ or $d(^{12}\text{C},p\gamma)^{13}\text{C}$

→ Proton from this contaminant reaction lower in energy than signal

but:

→ Elastic scattering under forward angles $d(^{12}\text{C},d)^{12}\text{C}$

→ followed by $^{12}\text{C}(d,p\gamma)^{13}\text{C}$, but then at higher CM energy
Background considerations

\[^{12}\text{C}\text{ beam}\]

\[\text{detector}\]

\[\text{deuterium (water)}\text{ contamination}\]

\[\text{graphite target}\]
Background considerations

In γ-ray spectroscopy measurements main source of background

\[ ^{12}\text{C}(d,p\gamma)^{13}\text{C} \text{ or } d(^{12}\text{C},p\gamma)^{13}\text{C} \]

→ Proton from this contaminant reaction too low in energy

but:

→ Elastic scattering under forward angles \( d(^{12}\text{C},d)^{12}\text{C} \)

→ followed by \( ^{12}\text{C}(d,p\gamma)^{13}\text{C} \), but then at higher CM energy

→ higher proton energy, in the region of \( ^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na} \) (!!!!)

→ checked with \( ^{16}\text{O} \) beam (advantage: contamination can be monitored)
Background considerations

in $\gamma$-ray spectroscopy main source of background $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ or $d(^{12}\text{C}, p\gamma)^{13}\text{C}$

Improvements:

→ all vacuum components in CF – on vacuum level of $10^{-7}$ mbar a build up of water is likely, at $10^{-9}$ mbar sputtering is faster than the build up

→ „radon“ box: experimental setup enclosed in a box flushed with argon suppression of hydrogen and nitrogen (water to a lesser extend)

→ HOPG targets: graphite almost free of hydrogen and oxygen

→ cold trap with liquid nitrogen (suppression of water)
Preliminary New Results

Influence of $^{12}\text{C}(d,p)^{13}\text{C}$ resonances

Gamow window

hydrogen “free” target

a lot need to be done!!

Courtesy Jim Zickefoose
Results $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ - particle spectroscopy

- Zickefoose et al. (in prep.)
- Fit
- non-res. contribution (const. $S^*$-factor)

- narrow, 2.1 MeV resonance (Spillane?)
- broad resonances (no parameters known, weak constraint from the data)

Influence of low-energy resonance cannot be excluded
Results $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$ - particle spectroscopy

transformation of yield into cross section $\sigma(E)$

\[ \sigma(E) = S(E)^* E^{-1} \exp(-87.21 E^{-1/2} - 0.46 E) \]

- low-energy resonance at 2.1 MeV compatible with Spillane et al.
  → however, measurements at lowest energies are difficult and statistic is very limited, an influence of beam-induced background still difficult to evaluate

- discrepancies with respect to Becker et al. needs further investigation

- a low-energy resonance at 1.5 MeV cannot be excluded, present data are consistent with an upper limit from Cooper et al.

- no constraint on non-resonant contribution
  → data are consistent with constant $S^*$-factor, but other energy dependence would also give a proper fit
comparison of the two methods

Becker et al. – proton channel

\[ p_{\text{tot}} \]

\[ p_0 + p_1 \]

→ constant ratio above 3 MeV – similar below?
Comparison of the two methods

At low-energies (below $E \leq 2.7$ MeV)

Particle spectroscopy

$^{24}\text{Mg}$

Unobserved

$\gamma$-ray spectroscopy

Indirectly observed

No $\text{tr} \rightarrow \text{e}$ reported

Situation similar for the $\alpha$-channel

Observed $\sigma_{\alpha0+\alpha1} \approx 0.3 \times (\text{Becker et al., 1981})$

Observed $\sigma_{1634} \equiv 0.55 \times \sigma_{\alpha}$

(Becker et al., 1981)
comparison – total $S^*$-factor

from Becker et al.

calculation of the astrophysical reaction rate is in progress

comparison of $p_0 + p_1$ to total ($\alpha$- and proton-channel)

- $p_0 + p_1$ contribute about 15%
  (on average)
- these values are currently used for extrapolations below 3 MeV
- large fraction of the assumed cross section at low-energy
  is not directly observed in studies

probably uncertainty from direct experiments is larger than currently assumed
Detector development
Summary

Experimental results of the $^{12}\text{C}^{(12}\text{C},p)^{23}\text{Na}$ carbon burning reaction at low energies and (a limited) overview of direct data

- astrophysical implications: stellar evolution, supernovae
- difficult measurement due to beam-induced background
- low energy limit has been moved downward
- extrapolation to astrophysical energies still uncertain
- new measurement of the $\alpha$-channel (particle spec.) is on the way
- but solution of the problem will need both approaches, i.e. $\gamma$-ray and particle spectroscopy
- perspectives for measurements in an underground lab → need larger accelerator
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