Stellar Production and Destruction Rates of $^{60}$Fe

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• Astrophysical Motivation

• Experimental Setup

• First Results

• Future Plans & Summary
INTEGRAL (INTErnational Gamma RAY Laboratory) observed characteristic $^{60}\text{Co}$ decay lines at 1173 & 1332 keV produced by $\beta$-decay from $^{60}\text{Fe}$

- scaled characteristic distribution of $^{60}\text{Fe}$ along the galactic plane based on $^{60}\text{Fe}/^{26}\text{Al}$ measurements
Nucleosynthesis of the Elements

- Fusion up to iron
- rp-process
- s-process
- p-process
- r-process

proton number

neutron number

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s-process

- slow neutron capture process
- seed isotopes: $^{56}\text{Fe}, ^{57}\text{Fe}, ^{58}\text{Fe}$
- neutron capture and $\beta^-$ decay
- neutron capture rate is small relative to the beta decay rate
- about 50% of the element abundances beyond iron are produced via s-process
- synthesizing elements between iron & bismuth
Provided we know about the nuclear reaction rates for production and destruction we will get information on:

- temperature & density

\[
\begin{array}{ccc}
\text{protons} & \text{neutrons} \\
\text{stable isotope} & \beta^{-} \text{ unstable isotope} & (n, \gamma) \text{ capture} & \beta^{-} \text{ decay} \\
\hline
56\text{Fe} & 57\text{Fe} & 58\text{Fe} \\
91.754 & 2.119 & 0.282 \\
\end{array}
\]
s-process

- s-process:
  - main component & weak component

- main component:
  - He shell burning phase in AGB stars
  - nuclei with $A = 90 - 209$ are mainly produced
  - $^{13}$C($\alpha$,n):
    $\rho_n = 10^7 \text{ cm}^{-3}$ at $kT = 5 \text{ keV}$
    \[
    \frac{(n,\gamma) - \text{ratio}}{\beta^- - \text{ratio}} \approx 10^{-4}
    \]
    \[\Rightarrow\]
    no $^{60}$Fe production

  - $^{22}$Ne($\alpha$,n):
    $\rho_n = 10^{11} \text{ cm}^{-3}$ at $kT = 30 \text{ keV}$
    \[
    \frac{(n,\gamma) - \text{ratio}}{\beta^- - \text{ratio}} \approx 2
    \]
    \[\Rightarrow\]
    $^{60}$Fe production
• weak component
  • massive stars (20-25 M$_\odot$)
  • mainly nuclei A = 56 - 90 are produced

• there are two phases:
  • 1$^{\text{st}}$ phase: He core burning
    $\rho_n = 10^6 \text{ cm}^{-3}$ at kT= 25 keV
    \[
    \frac{(n,\gamma) - \text{ratio}}{\beta^- - \text{ratio}} \approx 10^{-5}
    \]
    \[\Rightarrow \text{no } ^{60}\text{Fe production} \]

  • 2$^{\text{nd}}$ phase: C shell burning
    $\rho_n = 10^{12} \text{ cm}^{-3}$ at kT= 90 keV
    \[
    \frac{(n,\gamma) - \text{ratio}}{\beta^- - \text{ratio}} \approx 10
    \]
    \[\Rightarrow ^{60}\text{Fe production} \]
Production and Destruction of $^{60}$Fe

$^{60}$Fe($\beta^-$):
in progress, new measurements: e.g. talks by
G. Rugel
W. Kutschera et al.
R. Dressler et al.

$^{59}$Fe(n,\gamma):
extremely difficult

$^{60}$Fe(\gamma,n):
coulomb dissociation, experiment performed

(n,\gamma)$^{61}$Fe:
activation experiments
kT = 25 meV
kT = 25 keV
kT = 90 keV
R. Reifarth et al.
next talk
UNIversaLACcelerator:
- length: 120m
- energy of particles: 20% speed of light
  ⇒ 11.4 AMeV
“SchwerIonen“ (heavy ion)-Synchrotron

- pulse duration varies from 1 to 400 µs
- to get higher beam intensity several pulses are injected into SIS
- 90% speed of light \( \Rightarrow \) 1000 AMeV
- this energy can be reached for protons as well as for uranium
FRagment Separator:
- separates the isotopes of interest
- energy of particles: 535 AMeV
- intensities of $10^7$ particles/s
- reduction after FRS: $10^4$-$10^5$ particles/s

primary beam: 660 AMeV $^{64}$Ni

4 g/cm² Be target
R³B/LAND Setup

Production target

Incoming beam

64Ni

64Ni

60Fe

production target

Land

ALADIN

scintillators (TOF,A/Z)

silicon pin diode (ΔE,Z)

Nal crystal ball

ALADIN

fber detector 1 & 2

drift chamber 1 & 2

protons

scintillator walls
reaction of interest: $^{59}\text{Fe} + n \rightarrow ^{60}\text{Fe} + \gamma$

idea: measure time-reversed process:

$^{60}\text{Fe} + \gamma \rightarrow ^{59}\text{Fe} + n$

Beam Energy: 535 AMeV
Advantages:

experiments with radioactive nuclei are possible

Disadvantages:

• indirect method
  ⇒ needs theoretical input
  ⇒ data for verification

• nuclear interaction must be subtracted

• bad energy resolution which is needed for the \((\gamma,n)\leftrightarrow(n,\gamma)\)

• multipole admixtures must be determined
$^{60}\text{Fe}(\gamma, n)^{59}\text{Fe}$ at $\text{R}^3\text{B/LAND}$ Setup

incoming $^{60}\text{Fe}$

Pb target

ALADIN

neutrons

outgoing $^{59}\text{Fe}$

scintillator walls

incoming identification

iron identification

incoming $^{60}\text{Fe}$

$^{60}\text{Fe} + \gamma \rightarrow ^{59}\text{Fe} + n$

$S_n: 8820 \text{ keV}$

$^{60}\text{Fe}^*$

$^{59}\text{Fe}^*$

$^{60}\text{Fe}$

$^{59}\text{Fe}$

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Incoming Identification

**Experimental Astrophysics**

**Goethe-Universität Frankfurt am Main**

- **Incoming** $^{60}\text{Fe}$
  - Pb target
  - $^{60}\text{Fe}$, $^{59}\text{Fe}$, $^{58}\text{Mn}$

**Pb target**

**ALADIN**

- Neutrons
- $^{59}\text{Fe}$
- Fiber detector 1 & 2
- Scintillator walls

**Pos**

- $t_u, \epsilon_u$
- $t_d, \epsilon_d$
- $t_I, \epsilon_I$
- $t_r, \epsilon_r$

**Scintillator $^8$**
- Plastic scintillator
- 2 photomultipliers
- Time measurement

**Position Sensitive Silicon Pin Diode**
- 2D position
- Charge $Z$ of a passing heavy ion can be obtained via $\Delta E$ (Bethe-Bloch formula)

**POS**

- Quadratic plastic scintillator
- 4 photomultipliers
- Time measurement

**PSP**

- Neutrons
- Outgoing $^{59}\text{Fe}$
- Scintillator $^8$
- Plastic scintillator
- 2 photomultipliers
- Time measurement

**LAND**

- Neutrons
- Outgoing $^{59}\text{Fe}$
- Scintillator walls

- Neutrons
- Outgoing $^{59}\text{Fe}$
- Scintillator walls

**S8**

- $t_u, \epsilon_u$
- $t_d, \epsilon_d$

**POS**

- $t_I, \epsilon_I$
- $t_r, \epsilon_r$

**PSP**

- Neutrons
- Outgoing $^{59}\text{Fe}$
- Scintillator walls

**LAND**

- Neutrons
- Outgoing $^{59}\text{Fe}$
- Scintillator walls

**S8**

- Plastic scintillator
- 2 photomultipliers
- Time measurement

**POS**

- Quadratic plastic scintillator
- 4 photomultipliers
- Time measurement

**PSP**

- Neutrons
- Outgoing $^{59}\text{Fe}$
- Scintillator walls

**LAND**

- Neutrons
- Outgoing $^{59}\text{Fe}$
- Scintillator walls

**INCOMING $^{60}\text{Fe}$**

- Scintillators (TOF, A/Z)
- Silicon pin diode ($\Delta E, Z$)

**ALADIN**

- Nal crystal ball

**Fiber detector 1 & 2**

**Scintillator walls**

**59Fe 57Mn**

**58Mn 60Fe**
Incoming Particle Identification

Incoming $^{60}\text{Fe}$

Pb target

ALADIN

Neutrons

Outgoing $^{59}\text{Fe}$

Fiber detector 1 & 2

Scintillator walls

Incoming Z

Outgoing $^{59}\text{Fe}$

$^{57}\text{Mn}$

$^{58}\text{Mn}$

$^{60}\text{Fe}$

Incoming $A/Z$
Outgoing Z Identification

- Outgoing Z
- Identification

**Incoming** $^{60}\text{Fe}$

- Scintillators (TOF, A/Z)
- Silicon pin diode ($\Delta E, Z$)
- Pb target
- Nal crystal ball
- ALADIN
- Neutrons
- Outgoing $^{59}\text{Fe}$

**TFW** & **NTF**

- 18 paddles
- 14 paddles
- 8 paddles

**LAND**

- Scintillator walls

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**Time of Flight Wall & New Time of Flight Wall**

- Ion detector with plastic scintillator and photo-multiplier tubes
- TFW & NTF identify the position, the outgoing Z and the TOF of reaction products
Z \propto \sqrt{E}

Fe Identification TFW included Incoming Cut

mean = 26.0
sigma = 0.2847

Fe Identification NTF included Incoming Cut

mean = 26.0
sigma = 0.2455
Large Area Neutron Detector
- sandwich detector of active & passive material
- 10 planes and every plane contains 20 modules
- 2 x 2 m with a depth of 1 m
- conversion of neutrons into protons via reactions in iron and the secondary protons are detected with plastic scintillators
- good position & time resolution and high efficiency
**Neutron Identification**

- **Pb target**
- **ALADIN**
- **scintillator walls**

**Position of Neutrons**

**Neutron Identification**

- **incoming** $^{60}\text{Fe}$
- **scintillators (TOF, A/Z)**
- **silicon pin diode ($\Delta E, Z$)**
- **Nal crystal ball**

- **neutrons**
- **outgoing** $^{59}\text{Fe}$
- **fiber detector 1 & 2**

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First Results

Experimental Astrophysics

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incoming $^{60}$Fe

Pb target

ALADIN

neutrons

outgoing $^{59}$Fe

scintillator walls

number of breakup events $\approx 70$
a complete measurement is ensured by the determination of:

• mass determination of outgoing particle
  \[ \frac{A}{Z} \] values: \(^{59}\text{Fe} \) & \(^{60}\text{Fe} \)

• identification and momentum vector of each ion before reaction

• identification and momentum vector of each ion after reaction

• for energy dependent cross section, the excitation energy needs to be precisely known
  \[ \Rightarrow \text{require precise momentum vectors and angles} \]
**Doubled Silicon Strip Detector:**

- Si sensor size: 72 mm x 40 mm
- thickness: 0.3 mm
- x-plane: 640 strips & y-plane: 384 strips
- measures position of fragments with a resolution of ≈ 110 μm
**Grand FIbre detector:**
- 480 fibres
- read out by a mask and PSPM
- position resolution ~ 1mm
- used for the reconstruction of the particle trajectory
event 8

deflection angle_{ALADIN} \propto \frac{A}{Z}

ALADIN

Pb target

GFI 1

GFI 2

TFW

2 DSSD’s
• $R^3B/LAND$ setup:
  \[ \Rightarrow \text{many observables can be measured e.g.: TOF, position and } \Delta E \]
  \[ \Rightarrow \text{other quantities like the excitation energy are only accessible via an event-by-event reconstruction} \]

• the invariant masses of the excited incoming and outgoing systems are given by the following expressions:

\[
M_{\text{inv}}^{\text{incoming}} = m_{\text{projectile}} + E^* \\
M_{\text{inv}}^{\text{outgoing}} = \sqrt{\left( \sum_i E_i \right)^2 + \left( \sum_i p_i \right)^2} \quad i:= \text{fragments in the outgoing channel}
\]
Due to the conservation of the invariant mass, the excitation energy is expressed by:

$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j \cos \vartheta_{ij}) + E_\gamma - m_{\text{proj}}}$$

⇒ the reconstruction of the excitation energy relies on the identification and tracking of all outgoing species and on the rest mass of the incoming ion
Beams Energy: 535 AMeV

Total virtual photon numbers produced by a 500 AMeV beam impinging on a Pb (Z=82) target
$^{60}\text{Fe}$ Excitation energy spectrum

Virtual photon theory

$$\frac{d\sigma_{CD}}{dE_\gamma} = \frac{1}{E_\gamma} n\sigma(\gamma,n)$$

detailed balance

$$\sigma_{(\gamma,n)} = \frac{m_{60\text{Fe}} m_\gamma E_{60\text{Fe},n}}{m_{59\text{Fe}} m_n E_{59\text{Fe},n}} \frac{(2J_{60\text{Fe}} + 1)(2J_\gamma + 1)}{(2J_{59\text{Fe}} + 1)(2J_n + 1)} \sigma_{(n,\gamma)}$$
• steps of the analysis:
  • energy-dependent information about the dissociation cross section $^{60}\text{Fe}(\gamma,n)^{59}\text{Fe}$
  • determination of $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$ cross section by the principle of detailed balance

• nucleosynthesis simulations of the late stages of massive stars

• experiment $^{60}\text{Fe}(\gamma,n)^{59}\text{Fe}$ at GSI successfully performed
• analysis in progress
Production and Destruction of $^{60}$Fe

$^{60}$Fe($\beta^-$):
in progress, new measurements: e.g.
S. Söllradl
G. Rugel
W. Kutschera et al.
R. Dressler et al.

$^{59}$Fe(n,\gamma): extremely difficult

$^{60}$Fe(\gamma,n):
ocoulomb dissociation, experiment performed

(n,\gamma)$^{61}$Fe:
activation experiment
kT = 25 meV
kT = 25 keV
kT = 90 keV
R. Reifarth et al.

next talk

this talk
Thank you for your attention!