Search for muonic analog of neutrinoless double beta decay in titanium

Stable-ion beam experiments for nuclear astrophysics

ERAWAST-II workshop
PSI, 30.08.-02.09.2011

Daniel Bemmerer
Stable-ion beam experiments for nuclear astrophysics

- Why stable-ion beam experiments?

- The Sun
  - The $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction
  - The $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction

- Nucleosynthesis around $^{44}\text{Ti}$: contributions by stable-ion beam work
  - $^{44}\text{Ti}(\alpha,p)^{47}\text{V}$ (Tariq Al-Abdullah, this morning)
  - $^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$ (Konrad Schmidt, Friday morning)

- Science case for future underground accelerators
- LUNA-upgrade and Felsenkeller-accelerator projects
The origin of the chemical elements: Overview

Charged-particle induced reactions
Nuclear reaction cross section $\sigma$ for low-energy charged particles

- Typical Coulomb barrier height: $\sim$ MeV
- Typical temperature $k_B \cdot T \sim$ keV
  - The energy dependence of the cross section is dominated by the tunneling probability.

Tunneling probability (for relative angular momentum $l=0$):

$$\propto \exp \left[ -Z_1 Z_2 \alpha \left( \frac{\mu}{E} \right)^{0.5} \right]$$

Thermal neutron capture: $\sim 1$ barn

Charged-particle capture at astrophysical energies: $\sigma \sim 1$ nanobarn
At which energy do we have to know the cross section?

Answer: Inside the Gamow peak

Tunneling probability (for zero relative angular momentum):

\[ \alpha \exp \left[ -Z_1Z_2\alpha \left( \frac{\mu}{E} \right)^{0.5} \right] \]
The Gamow peak, some examples

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Reaction</th>
<th>(E_G) [keV]</th>
<th>(\sigma) [barn]</th>
<th>Detected events/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun (16 MK)</td>
<td>(^3)He((\alpha,\gamma))^7Be</td>
<td>23</td>
<td>(10^{-17})</td>
<td>(10^{-9})</td>
</tr>
<tr>
<td></td>
<td>(^{14})N(p,(\gamma))^15O</td>
<td>28</td>
<td>(10^{-19})</td>
<td>(10^{-11})</td>
</tr>
<tr>
<td>AGB stars (80 MK)</td>
<td>(^{14})N(p,(\gamma))^15O</td>
<td>81</td>
<td>(10^{-12})</td>
<td>(10^{-4})</td>
</tr>
<tr>
<td>Big bang (300 MK)</td>
<td>(^3)He((\alpha,\gamma))^7Be</td>
<td>160</td>
<td>(10^{-9})</td>
<td>(10^{-1})</td>
</tr>
<tr>
<td></td>
<td>(^2)H((\alpha,\gamma))^6Li</td>
<td>96</td>
<td>(10^{-11})</td>
<td>(10^{-3})</td>
</tr>
</tbody>
</table>

Assume \(10^{16} \text{ s}^{-1}\) beam
\(10^{18}\) at/cm\(^2\) target
\(10^{-2}\) detection efficiency

➔ Need high-intensity, low-background stable-ion beam
➔ A challenging task! But is it worthwhile?
Structure of the Sun: Observable

- Corona
- Chromosphere
- Photosphere
  - Fraunhofer lines
- Convection zone
  - p-modes (helioseismology)
- Radiation zone
- Core
  - Neutrinos
Data on the Sun (1): Helioseismology

Satellite “SoHo”
(Solar and Heliospheric Observatory)

Fourier transformed spectrum from GOLF instrument on SoHo

Simulated standing waves, p-mode $\sim 3$ mHz
Data on the Sun (2): Elemental abundances from the model-based interpretation of the Fraunhofer lines

1D model - observation

3D model - observation

3-dimensional models of the photosphere lead to lower derived abundances:

1D: 2.29% (by mass) of the Sun are “metals” (Li...U)

3D: 1.78% (by mass) of the Sun are “metals” (Li...U)
Problem: Contradiction between helioseismology and solar model predictions

Difference between model and data: Density $\rho$ of the Sun

($\delta\rho/\rho$ Deviation of model from data)

Further contradictions:
- Depth of the convective zone
- Helium-Abundance

This may be called the “solar abundance problem”!

Haxton and Serenelli (2008)
Serenelli et al. (2009)
Neutrino fluxes predicted by the standard solar model

A. Serenelli et al. (2009): Two versions of standard solar model: GS98 and AGSS09ph

- **GS98**
  - Old (<2005) elemental abundances
  - Consistent with helioseismology
  - $\Phi(^8B) = 5.88$  
  - $\Phi(^{15}O) = 2.09$

- **AGSS09ph**
  - New (>2005) elemental abundances
  - Not consistent with helioseismology
  - $\Phi(^8B) = 5.22$  
  - $\Phi(^{15}O) = 1.55$

- **Experiment (SNO, Super-Kamiokande)**
  - $\Phi(^8B) = 5.09 \pm 0.16$
  - $\Phi(^{15}O) ...$ Borexino/SNO+ detectors

Neutrino fluxes can be used to measure the elemental abundances in the center of the Sun, if the nuclear physics input is precise enough.

(Haxton and Serenelli 2008)
The $^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction at the LUNA 0.4 MV accelerator

LUNA = Laboratory Underground for Nuclear Astrophysics
Gran Sasso national underground lab / Italy

LUNA approach:
Measure at or near Gamow peak, using
- high beam intensity
- low background
- great patience
\(^3\text{He}(\alpha,\gamma)^7\text{Be}\) at LUNA (activation and prompt-\(\gamma\) technique)

- Windowless \(^3\text{He}\) gas target, with \(^3\text{He}\) recirculation
- Water-cooled collimators, \(d=15\), and 7mm
- \(4\times10^{-4}\text{ mbar}^3\text{He}\)
- Roots pump, 2000 m\(^3\)/h
- 0.7 mbar \(^3\text{He}\)
- \(^{135}\text{HPGe detector}\)
- \(^3\text{He}\) gas inlet
- \(^7\text{Be}\) catcher
- Copper shield
- Lead shield
- Lead
- Calorimeter
$^3\text{He}(\alpha,\gamma)^7\text{Be}$ at LUNA, $^7\text{Be}$ activation spectra

Detected $^7\text{Be}$ activities: 0.8 - 600 mBq

Home-made $^7\text{Be}$ calibration sources: 100 Bq
$^3\text{He}(\alpha,\gamma)^7\text{Be}$ reaction, S-factor results from LUNA and others
Impact of the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ data: More precise inputs for solar $^7\text{Be}$, $^8\text{B}$ neutrinos

Impact of cross section $\sigma$ on neutrino flux $\Phi_B$ from model:

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\frac{\partial \Phi_B}{\partial \sigma}$</th>
<th>$\Delta \Phi_B/\Phi_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}(^3\text{He},2p)^4\text{He}$</td>
<td>-0.43</td>
<td>1.8%</td>
</tr>
<tr>
<td>$^3\text{He}(\alpha,\gamma)^7\text{Be}$</td>
<td>0.85</td>
<td>7.5%</td>
</tr>
<tr>
<td>$^7\text{Be}(p,\gamma)^8\text{B}$</td>
<td>1.00</td>
<td>7.5%</td>
</tr>
</tbody>
</table>

4.2%
Carbon-nitrogen-oxygen (Bethe-Weizsäcker) cycle: $^{14}\text{N}(p,\gamma)^{15}\text{O}$

Postulated in 1938

- Slowest reaction: $^{14}\text{N}(p,\gamma)^{15}\text{O}$
- Some of the oldest observed stars burn mainly by CNO
- ~0.8% contribution in our Sun $\rightarrow$ CNO neutrinos as a probe of the concentration of carbon and nitrogen in the solar core
Study of $^{14}$N(p,γ)$^{15}$O over a wide energy range

Important levels in $^{15}$O
- $E = -0.504$ MeV, $^{15}$O*(6.79)
- $E = 0.259$ MeV
- $E = 0.987$ MeV
- $E = 2.187$ MeV
- “background pole”

Curves: R-matrix extrapolations

LUNA 2004
Münster 1987
TUNL 2005
HZDR 2008-
Experimental setup at the HZDR 3.3 MV Tandetron, Dresden
Detectors and targets

Side View

Lead Shield
Proton Beam
Target
Det1
Det2
BGO

Top View

Proton Beam
Target
Det1
Det2
Det3
BGO

15 cm

Target
Lead Shield

1 cm

Collimator (watercooled)
Pressure 10^{-7} mbar
Cu pipe
Secondary electrons Suppression
Turbo Pump

Resonance strengths $\omega_\gamma$ in the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ and $^{15}\text{N}(p,\alpha\gamma)^{12}\text{C}$ reactions

278 keV reference point:

$\omega_\gamma = (13.1 \pm 0.6) \text{ meV}$

(Solar Fusion II recommendation)

$$Y = \frac{\lambda^2}{2} S P_{\text{eff}} \omega_\gamma$$

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Literature [23, 52]</th>
<th>Present</th>
<th>Literature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}\text{N}(p,\gamma)^{15}\text{O}$</td>
<td>$E_p$ [keV] $\Gamma_{\text{lab}}$ [keV] $\omega_\gamma/n/\omega_\gamma 278$</td>
<td>$\omega_\gamma$ [eV]</td>
<td>$\omega_\gamma$ [eV]</td>
</tr>
<tr>
<td>278</td>
<td>1.12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>$\omega_\gamma/n/\omega_\gamma 278$</td>
<td>$\omega_\gamma$ [eV]</td>
</tr>
<tr>
<td>1058</td>
<td>3.8&lt;sup&gt;c&lt;/sup&gt;</td>
<td>27.8±0.9</td>
<td>0.364±0.020</td>
</tr>
<tr>
<td>430</td>
<td>0.1</td>
<td>$(1.73\pm0.07)\cdot10^3$</td>
<td>22.7±1.4 &amp; 21.1±1.4 [46]</td>
</tr>
<tr>
<td>897</td>
<td>1.57</td>
<td>$(2.77\pm0.08)\cdot10^4$</td>
<td>362±20</td>
</tr>
</tbody>
</table>

High-energy data on the $^{14}$N($p,\gamma$)$^{15}$O reaction

- Also high-energy data influence the R-matrix extrapolation to low energy
- Plot includes preliminary data from the Dresden 3.3 MV Tandetron
Doppler shift study of the lifetime of the 6.792 MeV level in $^{15}\text{O}$

\[ \Delta E_\gamma(6792) = \frac{\hbar}{\tau(6792)} \]
\[ 0.9 \text{ eV} = \frac{\hbar}{0.7 \text{ fs}} \]

- Subthreshold level populated in $^{14}\text{N}(d,n)^{15}\text{O}$ reaction
- Difficult analysis, expected lifetime $\sim 1$ fs
- R. Depalo et al. (INFN Padua)
Higher-energy accelerator underground: Science case (1)

Helium burning
- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
- $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}$
- $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$
- $^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$

Carbon burning
- $^{12}\text{C}(^{12}\text{C},\alpha)^{20}\text{Ne}$

Neutron sources for the s-process
- $^{13}\text{C}(\alpha,n)^{16}\text{O}$
- $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$
Higher-energy accelerator underground: Science case (2)

Solar composition problem
- $^3\text{He}(\alpha,\gamma)^7\text{Be}, E>0.4 \text{ MeV}$
- $^{14}\text{N}(p,\gamma)^{15}\text{O}, E>0.4 \text{ MeV}$

Radionuclides seen in space based observatories
- $^{26}\text{Al}, ^{44}\text{Ti}, ^{60}\text{Fe}$

Applied physics
- $^1\text{H}^{(15}\text{N},\alpha\gamma)^{12}\text{C}$, hydrogen depth profiling

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**Graphs and Data:**
- Plot showing $\rho/p$ vs $R/R_\odot$ with multiple lines representing different models.
- Energy spectrum plot with intensity (10^6 photons cm^-2 s^-1 rad^-1 keV^-1) vs energy (keV) showing peaks at specific energies with error bars.

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[Graphs and Data Image Descriptions and Analysis]
Gran Sasso / Italy: LUNA-upgrade 4 MV accelerator, site identified

Idea: 4 MV single-ended accelerator, with ECR ion source.

Courtesy A. Guglielmetti
Dresden underground laboratory: Felsenkeller, below 47 m of rock

- $\gamma$-counting facility for analytics, established 1982
  founding member of CELLAR collaboration

- 10 HPGe detectors

- Since 2009, contract enabling scientific use of Felsenkeller by HZDR and TU Dresden

- Several active Masters+PhD theses using Felsenkeller

- 5 km from TU Dresden, 25 km from HZDR campus
Photoactivation study at Felsenkeller: $^{144}\text{Sm}(\gamma,\alpha)^{140}\text{Nd}(\text{EC})^{140}\text{Pr}$

Activation study of $^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$, $\gamma$-counting in Felsenkeller

Counts/(keV*hour)

Energy [keV]

$^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$

Konrad Schmidt, talk on Friday

$^{44}\text{Ti}$ calibration sources (100 Bq) from ERAWAST
The issues are:

- Interaction of cosmic-ray nucleons in the detector → 10m rock
- Energy loss of passing/stopping muons in the detector → active shield
- Neutrons generated by \((\alpha,n)\) reactions from natural radioactivity in the walls → Pb/Fe shield
- Neutrons generated by muons in the passive shield → 1000m rock
\( \gamma \)-background comparison in a “traveling” HPGe detector, combining rock overburden with active shield (muon veto)

CLOVER HPGe detector, with BGO anticompton shield

+ at LUNA

+ at Felsenkeller

\[ {^{14}N(p, \gamma)^{15}O} \]
\[ {^{12}C(\alpha, \gamma)^{16}O} \]
γ-background comparison in a “traveling” LaBr$_3$ detector, combining rock overburden with active shield (muon veto)

$\gamma$-background comparison in a “traveling” LaBr$_3$ detector, combining rock overburden with active shield (muon veto)

LaBr$_3$ detector, inside BGO active shield

2010 at LNGS and at Felsenkeller
Felsenkeller, possible site for an accelerator

• Tunnels exist since the 1850’s, currently used for storing sausage skins, truck parking, etc.

• Inside Dresden city limits, trucks can drive in, technicians available at HZDR

• Startup possible with a used accelerator (ideally 3 MV, 0.1 mA \(\alpha\)-beam, ion source on HV terminal)

• Open to international users
The European perspective

- 1\textsuperscript{st} Workshop on “Underground nuclear-reaction experiments for astrophysics and applications”, Dresden/Germany April 2010: 30 participants from 8 countries, all projects represented
  
  http://www.hzdr.de/felsenkeller

  "Due to the extensive science programme, the long running time per experiment, and the number of researchers involved (...), most participants see it necessary to call for at least two European underground facilities to be realized. (...) A consensus emerged that all facilities should be as open as possible to the community (...). The observational and computational astrophysicists should be included at the earliest stage, helping drive and define the science agenda and creating the added value of multidisciplinarity (...)."

- NuPECC Long Range Plan 2010, released on 8 December 2010:
  
  http://www.nupecc.org

  “An immediate, pressing issue is to select and construct the next generation of underground accelerator facilities. Europe was a pioneer in this field, but risks a loss of leadership to new initiatives in the USA. Providing an underground multi-MV accelerator facility is a high priority. There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible.”

- “Round Table LUNA-Megavolt at Gran Sasso”, Gran Sasso/Italy 10.-11.02.2011

- 3\textsuperscript{rd} workshop on “Underground nuclear-reaction experiments for astrophysics and applications” Canfranc/Spain, April 2012
Dresden, Germany

- 505,000 people, capital of Saxony region
- Semiconductor industry, “Dresdner Stollen” cake
- City center destroyed in 1945, now largely rebuilt (Zwinger Castle 1950’s, Church of Our Lady 2005, Royal Castle almost done)
- Technical University (founded 1961), 36,000 students
- HZDR = Helmholtz-Zentrum Dresden-Rossendorf (formerly FZD)
  - One of 16 national laboratories (GSI, DESY, KIT...)
  - 800 staff
  - 60 M€ budget + 20 M€ projects
  1. Research with Photons, Neutrons, and Ions
  2. New Materials
  3. Cancer Research
  4. Nuclear Safety Research
HZDR campus in Dresden-Rossendorf

6 MV Tandetron (AMS)
3 MV Tandetron
40+200+500 kV implanters
2 MV van de Graaff

ELBE 40 MeV e⁻ linac
DRACO 150 TW laser
D+T neutron generator

50 M€ upgrade underway
Summary

- Stable-ion beam experiments are still necessary to fill nuclear astrophysics data needs
- Low-background settings underground greatly enhance sensitivity
- Rich science case for future underground accelerators
  - recommendation from NuPECC for “one or more projects” to be started “as soon as possible”
  - Successful workshops in Dresden in April 2010 and at Gran Sasso in February 2011
  - Next follow-up: 2012 at Canfranc/Spain (L. Fraile), 2013 Boulby/UK (M. Aliotta)
- Stable-ion beam work sometimes requires radioactive samples for calibration or as target (\(^7\)Be, \(^{44}\)Ti)
Felsenkeller, cross section

- Height: 47 m
- Length: 45 m
- Features: Workshop, MK 2, Office, MK 1
$E_\gamma < 3 \text{ MeV}$, HPGe laboratory $\gamma$-ray background, without active shield.

Without active shield: an intermediate solution between surface and Gran Sasso.