Experimental techniques to measure ion-induced cross sections and applications to the p process


Institut für Kernphysik, Universität zu Köln

supported by DFG (ZI 510/5-1 and INST 216/544-1)
Ion-induced cross sections on heavy nuclei

Interesting energy range usually way below the Coulomb barrier

Typical cross sections in \( \mu b \) range

• Maximize number of reactions
• Find efficient detection techniques
Maximize beam current

Low cross sections can partly be compensated by high beam currents, but the target has to withstand it.

In activation and AMS experiments one can separate reaction site and counting site.

A dedicated, high current, few MeV accelerator for protons and α’s with excellent energy definition should be set up! (see ECOS/NuPECC report)
Find efficient detection techniques:

**Two-step experiments**

**Step 1:** Induce the reaction of interest, e.g.

\[(p,\gamma), (\alpha,\gamma), (\alpha,\text{n}), \ldots\]

**Step 2:** Take the irradiated sample and analyze it

- using $\gamma$ spectroscopy after $\beta$ decay
- using fingerprints from other decay paths
- using Accelerator Mass Spectrometry (AMS)
Find efficient detection techniques: 
One-step (in-beam) experiments

Detect the ejectile in-beam after the reaction of interest, e.g. radiative capture \((p,\gamma)\) or \((\alpha,\gamma)\), or the reaction product (recoiling compound nucleus)

- using \(4\pi\) NaI summing crystals
- using high resolution HPGe arrays
- using recoil separators
Find efficient detection techniques: Experiments with radioactive ion beams

- Experiment is carried out in inverse kinematics
  
  \[ ^{92}\text{Mo}(p,\gamma)^{93}\text{Tc} \rightarrow p(^{92}\text{Mo},^{93}\text{Tc})\gamma \]

- typically very low beam currents
- H or He gas (jet) target, plastic target
- in-beam oder two-step experiments (implantation)
Find efficient detection techniques: 
**Two-step experiments**

**Step 1**: Induce the reaction of interest, e.g. 
$(p,\gamma)\), (\alpha,\gamma), (\alpha,n), \ldots$

**Step 2**: Take the irradiated sample and analyze it

- using $\gamma$ spectroscopy after $\beta$ decay
- using fingerprints from other decay paths
- using Accelerator Mass Spectrometry (AMS)
Activation followed by $\gamma$ spectroscopy

I. Irradiation

- $\alpha, p$ projectile
- $\gamma, n, p$ ejectile
- HPGe detector
- Shielding target

II. Counting

$^{141}\text{Pr}(\alpha, n)^{144}\text{Pm}$

$E_1 = 696$ keV

$T_{1/2} = 1 \text{ a}$

$E_2 = 618$ keV

$E_3 = 477$ keV

$^{144}\text{Nd}$

$E_1 = 696$ keV

$E_2 = 1314$ keV

$E_3 = 1791$ keV
Activation followed by $\gamma$ spectroscopy

**Irradiation @ PTB Braunschweig**

He++ ions from TCC-CV28 cyclotron, energies between 11 and 15 MeV, ion current in $\mu$A range

**Counting @ IKP Köln:**

Two 100% Clover (4 detectors each) plus addback, shielded by BGO and passive shielding
\( ^{141}\text{Pr}(\alpha,n)^{144}\text{Pm} \): Single spectrum after activation

\[ E_{\alpha} = 13.8 \text{ MeV} \text{ @ PTB} \]

\( ^{141}\text{Pr}(\alpha,n)^{144}\text{Pm} \)

\( ^{144}\text{Pm} \)

\( ^{144}\text{Nd} \)

\( T_{1/2} = 1 \text{ a} \)

\( E_1 = 696 \text{ keV} \)

\( E_2 = 618 \text{ keV} \)

\( E_3 = 477 \text{ keV} \)

\( E_{\gamma} \text{ [keV]} \)

\( \text{events / keV} \)

\( 618 \text{ keV} \)

\( 696 \text{ keV} \)

\( 477 \text{ keV} \)
$^{141}\text{Pr}(\alpha,n)^{144}\text{Pm}$: Single spectrum after activation

$^{141}\text{Pr}(\alpha,n)^{144}\text{Pm}$

$^{144}\text{Pm}$

$^{144}\text{Nd}$

$E_{1} = 696 \text{ keV}$

$E_{2} = 618 \text{ keV}$

$E_{3} = 477 \text{ keV}$

$T_{1/2} = 1 \text{ a}$

$E_{\alpha} = 11.0 \text{ MeV @ PTB}$

Coincidence between two Clover segments

\[ ^{141}\text{Pr}(\alpha,n)^{144}\text{Pm} \]

\[ E_1 = 696 \text{ keV} \]

\[ E_2 = 618 \text{ keV} \]

\[ E_3 = 477 \text{ keV} \]

\[ E_\alpha = 11.0 \text{ MeV} \]

\[ T_{1/2} = 1 \text{ a} \]

\[ \varepsilon = 1791 \]

Talks by LARS NETTERDON and ANNE SAUERWEIN this afternoon

Limitations of γ spectroscopy after irradiation

 Activation and subsequent γ spectroscopy is limited by:

• stable reaction products
• very long half-life of reaction products
• weak γ intensities of radioactive decays
Find efficient detection techniques:

**Two-step experiments**

**Step 1:** Induce the reaction of interest, e.g. 
(p,γ), (α,γ), (α,n), ...

**Step 2:** Take the irradiated sample and analyze it

- using γ spectroscopy after β decay
- using fingerprints from other decay paths
- using Accelerator Mass Spectrometry (AMS)
Accelerator Mass Spectrometry

Identify the compound nuclei in the target after irradiation

Very high sensitivity: isotope ratio up to $10^{-15}$
Accelerator Mass Spectrometry

Typical application:
Detection of smallest amounts of $^{14}\text{C}$ and/or of other cosmogenic nuclides (e.g. $^{10}\text{Be}$, $^{26}\text{Al}$, $^{36}\text{Cl}$, $^{41}\text{Ca}$, $^{129}\text{I}$)

Turin shroud

Oetzi
But as well: Detection of nuclides produced in the laboratory

Problem: Each isotope to be measured needs development time for sample preparation and detection

$^{26}\text{Mg}(p,n)^{26}\text{Al}$: M. Paul et al., PLB 94 (1980) 303 ($^{26}\text{Al}$ is a cosmogenic nuclide)

$^{40}\text{Ca}(\alpha,\gamma)^{44}\text{Ti}$: H. Nassar et al., PRL 96 (2006) 041102

Talk by MICHAEL PAUL this afternoon
A new AMS facility at the IKP, University of Cologne

- Tandetron with 6 MV terminal voltage (no moving parts)
- Standard isotopes: $^{10}$Be, $^{14}$C, $^{26}$Al, $^{36}$Cl, $^{41}$Ca, $^{129}$I (geosciences, prehistory, protohistory)

- SFB 806: Our way to Europe
- SPP 1158: Coordinated Antarctica research

- Ample beam time for development and nuclear physics applications
CologneAMS – a new option to measure small reaction cross sections

Ion source wheel, up to 200 probes
CologneAMS – a new option to measure small reaction cross sections

• First $^{14}$C test measurement: February 2011 (all specifications fulfilled)
• Start of standard operation: fall 2011
Find efficient detection techniques: One-step (in-beam) experiments

Detect the ejectile in-beam after the reaction of interest, e.g. radiative capture \((p,\gamma)\) or \((\alpha,\gamma)\) or the reaction product (recoiling compound nucleus)

- using 4\(\pi\) NaI summing crystals
- using high resolution HPGe arrays
- using recoil separators
The HORUS array at IKP Köln

- 14 HPGe $\gamma$ detectors in close geometry
- Photopeak efficiency at 1332 keV: up to 5%
- Installed at 10 MV Tandem

- High energy resolution to observe single transitions
- Adequate efficiency to study low cross sections
- Determination of angular distributions possible
- Coincidence technique to suppress background
Experiments to study capture reactions

\[ ^{92}\text{Mo}(p,\gamma)^{93}\text{Tc} \]

- \( Q = 4086 \text{ keV} \)
- \( p + ^{92}\text{Mo} \)
- Entry state
- \( T_{1/2} = 2.7 \text{ h} \)
- \( T_{1/2} = 43.5 \text{ m} \)
- 398 keV
- 0 keV
Radiative proton capture on $^{92}$Mo

$^{92}$Mo($p,\gamma$)$^{93}$Tc

$E_p = 3300$ keV
$Q = 4087$ keV

Deexcitation of compound state

Partial cross sections
Radiative proton capture on $^{92}\text{Mo}$

$^{92}\text{Mo}(p,\gamma)^{93}\text{Tc}$

$E_p = 3300$ keV

$Q = 4087$ keV

Transitions to ground state
Radiative proton capture on $^{92}$Mo

$^{92}$Mo(p,γ)$^{93}$Tc

$E_p = 3300$ keV
$Q = 4087$ keV

Transitions to 1$^{st}$ excited state

Production of 1$^{st}$ excited state
Background reduction using $\gamma$-$\gamma$ coincidence techniques

$^{92}\text{Mo}(\alpha,\gamma)^{96}\text{Ru}$

No coincidence
Background reduction using $\gamma$-$\gamma$ coincidence techniques

$^{92}\text{Mo}(\alpha,\gamma)^{96}\text{Ru}$

No coincidence

Coincidence with $E_\gamma=833$ keV
Yields a wealth of information on

- partial and total cross sections
- gamma ray strength function
- structure of compound system
Find efficient detection techniques: Experiments with radioactive ion beams

• Experiment is carried out in inverse kinematics
  → typically very low beam currents

• H or He gas (jet) target

• In-beam oder two-step experiments (implantation)
Experiment with radioactive ion beams @ ESR

- radioactive ion beam injected in storage ring
- deceleration and cooling possible
- internal H or He gas jet target
- detection of ions with in-ring silicon strip detectors

ESR@GSI

Courtesy: M. Heil
Pilot experiment with stable beam: $^{96}\text{Ru}(p,\gamma)^{97}\text{Rh}$

Without $(p,n)$ component – resulting in an upper limit for $(p,\gamma)$

$\sigma_{PG} < 4.0$ mb

Non-smoker: 3.5 mb

Courtesy: M. Heil
Experimental techniques to measure ion-induced cross sections and applications to the p process


Institut für Kernphysik, Universität zu Köln

V. Foteinou, A. Lagoyannis, S. Harissopulos

INP Demokritos, Athens, Greece

H.W. Becker, D. Rogalla

Ruhruniversität Bochum

U. Giesen

PTB Braunschweig

supported by DFG (ZI 510/5-1 and INST 216/544-1)
Gamma-ray strength functions used in TALYS code

- Brink-Axel standard Lorentzian
- Generalized Lorentzian Kopecky-Uhl for E1 radiation
- Hartree-Fock BCS tables for E1 radiation
- Hartree-Fock-Bogolyubov tables for E1 radiation

*TALYS 1.2:*
A. Koning, S. Hilaire, M. Duijvestijn
Partial cross sections for $^{92}\text{Mo}(p,\gamma)$
Population of levels in $^{92}$Mo($p,\gamma$)
Radiative $\alpha$ capture: $^{92}\text{Mo}(\alpha,\gamma)$

E$_\alpha$ = 9300 keV
Q = 1692 keV

$\sigma$(experiment) = 382 ± 100 µb

$\sigma$(TALYS) = 422 µb

$^{96}\text{Ru}^*$ $\rightarrow$ $^{96}\text{Ru}$
Beamtime distribution at CologneAMS

- **Development**
  - Geosciences
  - Environmental Research
  - Astrophysics
  - Medicine
  - Others
  - > 25% Users from Cologne and Potsdam
  - < 20% special applications
  - Ion implantation

- **Maintenance**
  - Nuclear Physics
    - Geography
    - Pre- and Protohistory
    - Nuclear Chemistry
    - Geology
    - Others
    - > 20%

- **External Users**
  - 20%
CologneAMS – a new option to measure small reaction cross sections

Inauguration: October 1st, 2010
CologneAMS – a new option to measure small reaction cross sections

Inside the Tandetron