Title: Light-ion production from O, Si, Fe and Bi induced by 175 MeV quasi-monoenergetic neutrons

Author(s): Bevilacqua, Riccardo
Pomp, Stephan
Jansson, Kaj
Gustavsson, Cecilia
Osterlund, Michael
Simutkin, Vasily
Hayashi, Masateru
Hirayama, Shusuke
Naitou, Yuuki
Watanabe, Yukinobu
Hjalmarssson, Anders
Prokofiev, Alexander
Tippawan, Udomrat
Lecolley, Francois-Rene
Marie, Nathalie
Leray, Sylvie
David, Jean-Christophe
Mashnik, Stepan G

Intended for: 2013 International Conference on Nuclear Data for Science & Technology (ND2013), 2013-03-04/2013-03-08 (New York, New York, United States)

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher’s right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.
Light-ion production from O, Si, Fe and Bi induced by 175 MeV quasi-monoenergetic neutrons

Riccardo Bevilacqua*, S. Pomp, K. Jansson, C. Gustavsson, M. Osterlund, V. Simutkin
Department of Physics and Astronomy, Uppsala University, Sweden

M. Hayashi, S. Hirayama, Y. Naitou, Y. Watanabe
Department of Advanced Energy Engineering Science, Kyushu University, Fukuoka, Japan

A. Hjalmarsson, A. Prokofiev
The Svedberg Laboratory, Uppsala University, Sweden

U. Tippawan
Chiang Mai University, 50200 Chiang Mai, Thailand

F.-R. Lecolley, N. Marie
LPC, Universite de Caen, 14050 Caen, France

S. Leray, J.-C. David
Commissariat a l’Energie Atomique, CEA/Saclay, France

S. Mashnik
Los Alamos National Laboratory, Los Alamos NM, USA

* Present address: European Commission – Joint Research Centre
Institute for Reference Materials and Measurements
2440 Geel, Belgium
A good model can advance fashion by ten years.

(Yves Saint-Laurent, 1936-2008)
A good model can advance fashion by ten years.

(Yves Saint-Laurent, 1936-2008)

to have a good model, we need good experimental data
Outline

- The Medley spectrometer
- Double differential cross sections at 175 MeV QMN composite charged particles production from O, Si, Fe, Bi (C and U measured, not presented here) in comparison with model calculations:
  - MCNP6
  - Quantum Molecular Dynamics (QMD) with PHITS
  - Modified QMD with PHITS
  - INCL4.5-Abla07
  - TALYS-1.2
  - Modified TALYS-1.2
- Angle integrated cross sections for Fe and Bi
- Conclusions
Cyclotron: 180 MeV protons

Pulsed neutron beam line: 
$^7$Li(p,n) reaction

Quasi-monoenergetic neutrons with energies up to 175 MeV
Medley Spectrometer
@ The Svedberg Laboratory

- Eight three-elements $\Delta E-\Delta E-E$ telescopes
- Detects: protons, deuterons, tritons, $^3$He, $\alpha$ particles
- Low particle identification threshold (2 MeV for protons)
- Wide dynamic range (up to 170 MeV)
Medley Spectrometer
@ The Svedberg Laboratory

- Bending magnet
- Li target
- Iron collimator
- Medley
- New iron wall
- Proton beam dump
- Neutron beam dump
Outline

- The Medley spectrometer
- Double differential cross sections at 175 MeV QMN composite charged particles production from O, Si, Fe, Bi (C and U measured, not presented here) in comparison with model calculations:
  - MCNP6
  - Quantum Molecular Dynamics (QMD) with PHITS
  - Modified QMD with PHITS
  - INCL4.5-Abla07
  - TALYS-1.2
  - Modified TALYS-1.2
- Angle integrated cross sections for Fe and Bi
- Conclusions
MCNP6
Event generator: Cascade-Exciton Model (CEM03.03)

Leslie M. Kerby “Preequilibrium Emission of Light Fragments in Spallation Reactions”
Central Park West, now (unfortunately!)

Calculations by Stepan Mashnik
Quantum Molecular Dynamics

PHITS calculations
- pre-equilibrium: QMD
- statistical decay: generalized evaporation model (GEM)

Calculations by Y. Watanabe
Quantum Molecular Dynamics
Modified with a Surface Coalescence Model

Calculations by Y. Watanabe
INCL4.5-Abla07

- Intranuclear cascade model
- Abla de-excitation model

Fe(n,xd)  Fe(n,xt)  Bi(n,x^3He)  Bi(n,x\alpha)

\[ \sigma(E,\theta) \text{ (mb/MeV sr)} \]

\[ \text{Deuteron Energy (MeV)} \quad \text{Triton Energy (MeV)} \quad \text{^3He Energy (MeV)} \quad \text{\alpha Energy (MeV)} \]

Riccardo Bevilacqua

Calculations by Jean-Cristophe David

International Conference on Nuclear Data for Science and Technology
Riccardo Bevilacqua
International Conference on Nuclear Data for Science and Technology

Pre-equilibrium:
- two component exciton model (EM)
- composite particles direct-like mechanisms (Kalbach systematics)
- nucleon transfer (pick-up)
- knock-out for $\alpha$ particles

TALYS-1.2

![Graphs showing cross-sections for Fe(n,xd) and Bi(n,x\alpha) reactions.](image)
Modified TALYS-1.2

Scaling down the nucleon transfer mechanism

Calculations folded with QMN spectrum:
energy dependence in the scaling factor
Outline

- The Medley spectrometer
- Double differential cross sections at 175 MeV QMN composite charged particles production from O, Si, Fe, Bi (C and U measured, not presented here) in comparison with model calculations:
  - MCNP6
  - Quantum Molecular Dynamics (QMD) with PHITS
  - Modified QMD with PHITS
  - INCL4.5-Abla07
  - TALYS-1.2
  - Modified TALYS-1.2
- Angle integrated cross sections for Fe and Bi
- Conclusions
Light-ion production from Fe
Energy differential cross sections

TALYS-1.2
modified TALYS-1.2
MCNP6
INCL4.5-Abla07
MQMD (PHITS)
exp. data

angular integration by Kaj Jansson
Light-ion production from Bi
Energy differential cross sections

```
<table>
<thead>
<tr>
<th></th>
<th>TALYS-1.2</th>
<th>modified TALYS-1.2</th>
<th>MCNP6</th>
<th>INCL4.5-Abla07</th>
<th>MQMD (PHITS)</th>
<th>exp. data</th>
</tr>
</thead>
</table>
```

Angular integration by Kaj Jansson
Conclusions

- We have measured light ion production at 175 MeV QMN for O, Si, Fe, Bi (also C and U, not shown in this talk).

- Double differential cross sections for O, Si, Fe, Bi and

- Energy differential cross sections for Fe and Bi.

- Compared with model calculations.

- Pre-equilibrium emission of composite light-ions is the most critical issue at these energies.

- More work is required to fully reproduce all experimental results.
Thank you for your attention!

Riccardo.BEVILACQUA@ec.europa.eu

Present address:
European Commission – Joint Research Centre
Institute for Reference Materials and Measurements
2440 Geel, Belgium

I could participate in this conference thanks to the financial support of:

European Nuclear Education Network
ENEN PhD Prize 2011

Department of Physics and Astronomy
Division of Applied Nuclear Physics
A general scheme of CEM/LAQGSM calculation

1. **Input**
   - **IntraNuclear Cascade (INC)**
     - **A > 13?**
       - yes ➔ **Fission, if Z>64**
         - yes ➔ **Evaporation from fission fragments**
           - yes ➔ **Output**
           - no ➔ **Evaporation**
             - yes ➔ **Output**
             - no ➔ **Preequilibrium**
               - yes ➔ **Output**
               - no ➔ **Coalescence**

2. **Coalescence**
   - **d, t, ^3He, ^4He**

Slide courtesy of Stepan Mashnik
Pre-equilibrium emission: Exciton Model

Time evolution of the occupation probability of n-exciton state in the energy space
exciton = particle-hole pair

Projectile energy gradually redistributed among nucleons

Allows emission of particles
Preequilibrium reactions with complex particle channels

C. Kalbach

*Physics Department, Duke University, Durham, North Carolina 27708-0305*

(Received 10 November 2004; published 22 March 2005)

Investigations of nucleon induced reactions at incident energies of 14–90 MeV resulting in the emission of complex particles ($A = 2–4$) have provided insights which complement those previously obtained from $(N, xN)$ reactions. The description of the preequilibrium energy spectra required modifications to an earlier phenomenological model for direct pickup reactions. This model supplements the usual exciton preequilibrium model. Work on complex particle induced reactions confirms some of these results, extends them to include stripping and exchange reactions, and provides evidence for a projectile dependence of the average effective matrix elements for the residual interactions in the exciton model. A full description of reactions with complex projectiles will require the inclusion of a realistic breakup component and the resulting reduction of the cross section available for the exciton model calculations. Reactions with complex particles in the entrance and/or exit channels have provided indirect evidence for the amount of surface peaking of the initial target-projectile interaction. A summary of additional data needed to help resolve remaining questions is presented.

DOI: 10.1103/PhysRevC.71.034606

PACS number(s): 24.60.Gv, 24.10.Pa
TALYS pre-equilibrium

Direct-like reactions not included in the Exciton Model:

nucleon transfer (NT): pick-up and stripping knock-out (KO) of performed clusters

Kalbach phenomenological model
pre-equilibrium reactions with complex particle channels


\[
\frac{d\sigma_{k}^{PE}}{dE_k} = \frac{d\sigma_{k}^{EM}}{dE_k} + \frac{d\sigma_{k}^{NT}}{dE_k} + \frac{d\sigma_{k}^{KO}}{dE_k}
\]
Energy dependence scaling of Nucleon Transfer in TALYS

\[ c_{strip} = \begin{cases} 
1.0 & \text{if } E \leq 90 \text{ MeV} \\
1.9 - \frac{E}{100 \text{ MeV}} & \text{if } 90 \text{ MeV} \leq E \leq 180 \text{ MeV} \\
0.1 & \text{if } 180 \text{ MeV} \leq E 
\end{cases} \]
Absolute double-differential cross-sections $\sigma_x$, for a reaction target $x$ and a given light-ion, are obtained from net counts $N_x$, applying the following expression:

$$\frac{\sigma_x}{N_x} = \frac{\sigma_H}{I_H} \frac{2A_x}{A_{CH_2}} \frac{m_{CH_2}}{m_x} \frac{\Phi_{CH_2}}{\Phi_x} \frac{\Omega_{CH_2}}{\Omega_x} \frac{1}{\Delta E}$$

(3.5)

where $A_x$ and $A_{CH_x}$ are respectively the atomic weight of the reaction target and of the CH$_2$ target, $m_x$ and $m_{CH_2}$ are the target masses, $\Phi_X$ and $\Phi_{CH_2}$ are the neutron fluences measured with one of the neutron monitors, $\Omega_{CH_2}/\Omega_x$ is the ratio between the solid angle seen by the telescope at 20 degrees and the telescope used for the measurement, and $\Delta E$ is the energy bin width.