Light and Heavy Fragments Mass Correlation in the $^{197}$Au+$^{130}$Te Transfer Reaction

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INFN Laboratori Nazionali di Legnaro

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Motivation

More accurate description of the reaction mechanism leading to the population of neutron-rich heavy nuclei

$$Xe + {}^{208}Pb \text{ (E}_{cm} = 700 \text{ MeV)}$$

Nuclear structure studies in the vicinity of N=126

Investigation of prolate-to-oblate shape transition moving towards the neutron-rich Pt-Os region

Astrophysical r-process

C. H. Dasso, G. Pollarolo, A. Winther, PRL 73 (1994) 1907

P. R. John et al., PRC 90 (2014) 021301(R); PRC 95 (2017) 064321.


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EuNPC 2018 (Bologna, 2-7 September 2018)
Fusion reactions with neutron-rich radioactive beams

Neutron-capture reactions

Fragmentation reactions at relativistic energy
Multinucleon transfer reactions near the Coulomb barrier

low beam intensity from accelerators
low beam intensity from reactors

challenging experiments
reachable $\sigma$ in the $\mu$b - nb range

How to access neutron-rich heavy nuclei?
It is important to understand which is the most suitable mechanism for the production of nuclei close to the $Z = 82$ and $N = 126$ region of the nuclide chart.

Multinucleon transfer is a complementary mechanism to the fragmentation of actinides or lead on light targets for the population of heavy neutron-rich nuclei.

**BUT**

direct identification is very difficult.

$^{136}$Xe+$^{198}$Pt @ 8 AMeV
VAMOS+EXOGAM
$\gamma$-particle coincidences

Y. X. Watanabe et al., PRL 115 (2015) 172503

$^{208}$Pb+Be @ 1 AGeV
Fragment Separator
In-flight separation

T. Kurtukian-Nieto et al., PRC 89 (2014) 024616

Multinucleon transfer is a complementary mechanism to the fragmentation of actinides or lead on light targets for the population of heavy neutron-rich nuclei.

**BUT**

direct identification is very difficult.
Populating neutron-rich nuclei via MNT reactions

C. H. Dasso, G. Pollarolo, A. Winther, PRL 73 (1994) 1907

T. Mijatović et al., PRC 94 (2016) 064616

F. Galtarossa, INFN LNL

EuNPC 2018 (Bologna, 2-7 September 2018)
Production of neutron-rich nuclei near \(N=126\) via \(^{136}\text{Xe}+^{198}\text{Pt}\)

Very neutron-rich nuclei can be populated in transfer with low TKEL. For large TKEL secondary processes play a major role in the final mass distributions.

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Y. X. Watanabe et al., PRL 115 (2015) 172503
A benchmark system at LNL: $^{197}\text{Au} + ^{130}\text{Te} @ 1.07 \text{ GeV}$

Goal: to understand the production mechanism for neutron-rich nuclei in the $A=200$ region and the effect of secondary processes on the final yields.

Via proton pick-up and neutron stripping channels from $^{130}\text{Te}$ one produces neutron-rich nuclei around $A=200$.

We will mainly focus here on neutron transfer channels.
The large-acceptance magnetic spectrometer PRISMA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid angle</td>
<td>80 msr</td>
</tr>
<tr>
<td>Angular acceptance</td>
<td>$\Delta \theta = \pm 6^\circ$ $\Delta \phi = \pm 11^\circ$</td>
</tr>
<tr>
<td>Dipole curvature radius</td>
<td>1.2 m ($60^\circ$)</td>
</tr>
<tr>
<td>Maximum magnetic rigidity</td>
<td>1.2 T·m</td>
</tr>
<tr>
<td>Flight path length</td>
<td>$\sim 6$ m</td>
</tr>
<tr>
<td>Rotation spectrometer</td>
<td>$-20^\circ$/ $+130^\circ$</td>
</tr>
<tr>
<td>Momentum acceptance</td>
<td>$\Delta p/p = \pm 10%$</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>$\Delta E/E \sim 1/1000$</td>
</tr>
</tbody>
</table>

G. Montagnoli et al. NIM A547, 455 20(05)

S. Beghini et al. NIM A551 (2005) 364
NOSE, an ancillary particle detector coupled to PRISMA

Bragg Curve Spectroscopy

E. Fioretto et al., NIM A 899 (2018) 73-79

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The experimental set-up

TLF in PRISMA (master trigger)
- \((x, y)\) at the entrance MCP -> \((\theta, \phi)\)
- \((X, Y)\) at the MWPPAC
- ToF between MCP and MWPPAC
- \(Z\) from E-\(\Delta E\) in the IC

PLF in NOSE
- \((x', y')\) at the entrance PPAC -> \((\theta, \phi)\)
- \(\Delta\text{ToF}\) between PRISMA MCP and NOSE PPAC
- \(Z\) from E-\(\Delta E\) in the IC

In PRISMA: \(\Delta A/A \sim 1/250\)
In NOSE: \(\Delta A/A \sim 1/40\)

EuNPC 2018
In PRISMA (optimized for the light partner) the Z resolution is sufficient to distinguish different proton transfer channels, which nonetheless have very low cross section at this low bombarding energy.

In NOSE (optimized for the heavy partner) the PLF and TLF can be clearly separated but no Z identification is possible due to the very low energy of Au-like ions.
Through an event-by-event trajectory reconstruction in PRISMA the mass distribution of Te ions is obtained. The yields are extracted with a multi-Gaussian fit.

Total kinetic energy loss (TKEL) distributions are obtained for the different transfer channels, showing an increasing contribution of DIC components as more neutrons are transferred.

ΔA/A \sim 1/240

PRISMA alone
PRISMA in coinc. with NOSE
Ground-to-ground-state Q value
Mass reconstruction of the heavy partner

\[ M_B = \frac{p_A}{d} \frac{\sin \theta_b}{\sin(\theta_B + \theta_b)} \]

\( \Delta A/A \sim 1/40 \)

A+a \rightarrow B+b, where A is the heavy projectile (Au) and a the target nucleus (Te). The mass \( M_B \) of the heavy PLF can be deduced from momentum conservation assuming a binary character of the reaction.
The correlation between the masses of the reaction partners allows to separate the heavy partner mass distributions in well defined bands. One can then follow the evolution of the widths and centroids of the heavy partner mass distributions, which are affected by the effect of secondary processes.
The simulations incorporate a successive evaporation of neutrons taking into account the experimental TKEL distributions (to compute evaporation), the cross sections measured in PRISMA and the experimental resolution.

The simulations indicate that the shift of the centroids towards lower masses and the width enlargement is due to evaporation.

F. Galtarossa et al., PRC 97 (2018) 054606
Theoretical models for MNT reactions

- GRAZING

- Langevin-type dynamical equations of motion
  V. Zagrebaev, W. Greiner, PRL 101 (2008) 122701

- Time-Dependent Hartree-Fock (TDHF) theory
  K. Sekizawa, K. Yabana, PRC 88 (2013) 014614

- DiNuclear System (DNS) model

- Improved Quantum Molecular Dynamics (ImQMD)
The GRAZING code calculates distributions in masses, charges, energies and angular momenta of fragments in collisions between heavy nuclei according to a semiclassical model. This model has been successfully applied in the description of transfer reactions and can reproduce the near-barrier fusion excitation functions and extract barrier distributions.

• The trajectory is calculated by solving the system of classical equations for the variables of relative motion and the deformation parameters for the surface modes. The two ions interact via a Coulomb plus nuclear interaction and may exchange nucleons.

• The exchange of many nucleons proceeds via a multi-step mechanism of single nucleons (both, protons and neutrons, via stripping and pick-up processes). The different single-particle states that are participating to the transfer process are described by introducing average single-particle level densities.

• The model includes the low-lying 2+ and 3− states of both projectile and target.

program GRAZING. http://www.to.infn.it/nanni/grazing
Comparison with GRAZING predictions

The cross sections for neutron transfer channels were compared to GRAZING after normalizing to the (1n) channel. GRAZING calculations include the effect of neutron evaporation.

The good agreement between experimental and theoretical cross sections and between experimental and simulated mass distributions of the heavy partner allows us to show the predictions of the same code for the production of Au isotopes.
Conclusions

- We studied MNT processes in the $^{197}$Au+$^{130}$Te system at $E_{\text{lab}} = 1.07$ GeV with a kinematic coincidence where one of the two detectors was a high-resolution large-acceptance magnetic spectrometer;

- We determined the mass of the light partner in PRISMA through an event-by-event trajectory reconstruction and the mass of the heavy partner in NOSE from momentum conservation in a binary collision;

- We correlated the masses of the light and heavy partner in a mass-mass correlation matrix and through the comparison with a simple Monte Carlo simulation we could follow the behavior of the heavy partner and infer about the effect of evaporative processes;

- The measured cross sections for neutron transfer channels of the light partner are in good agreement with GRAZING calculations which take into account the effect of neutron evaporation
Perspectives: towards SPES, a RIB facility @ LNL

![Graphs and diagrams showing atomic trends and cross-sections for the reaction $^{140}Xe + ^{198}Pt, E_{lab}=850$ MeV.]

Cortesey of E. Fioretto

Lol presented to the 3rd Int. Work. of SPES
Collaboration

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PRISMA
Backup slides
Multinucleon transfer reactions at energies around the Coulomb barrier are governed by optimum-Q-value considerations. With a neutron-poor projectile only proton stripping and neutron pick-up channels are open.
New set-ups for $\beta$ and $\gamma$ spectroscopy of heavy nuclei

KEK Isotope Separator System (KISS) for $\beta$-decay spectroscopy of neutron-rich nuclei with $A \sim 200$ and $N \sim 126$

Gas cell and Laser ion & Separation (GaLS) setup for $\beta$ spectroscopy of neutron-rich nuclei at $N \sim 126$
This is done in the **semi-classical approximation** where the relative motion is treated classically and the time evolution of the intrinsic states is described by the system of coupled equations:

\[
\begin{align*}
    i\hbar \dot{c}_\beta(t) &= \sum_\alpha \langle \beta | H_{\text{int}} | \alpha \rangle c_\alpha(t)e^{\frac{i}{\hbar}(E_\beta - E_\alpha)t + i(\delta_\beta - \delta_\alpha)} \\
    i\hbar \dot{\psi}(t) &= (H_0 + H_{\text{int}})\psi(t) \\
    \psi(t) &= \sum_\beta c_\beta(t)\psi_\beta e^{\frac{i}{\hbar}E_\beta t}
\end{align*}
\]

where \( \psi_\alpha \) are the channels wave functions:

\[
\psi_\alpha(t) = \psi^a(t)\psi^A(t)e^{i\phi(R)}
\]

It uses a microscopic approach. Ingredients:

- **surface modes**
- low and high lying states
- **transfer channels** (form factor for transfer)

The intrinsic Hamiltonian and the interaction are:

\[
\begin{align*}
    \hat{H}_0 &= \sum_i^{(a)} \epsilon_i a_i^\dagger a_i + \sum_{\lambda \mu}^{(a)} \hbar \omega_{\lambda \mu} a_{\lambda \mu}^\dagger a_{\lambda \mu} + (A) \\
    \hat{V}_{\text{int}}(t) &= \hat{V}_{tr}(t) + \hat{V}_{in}(t) + \Delta U_{\alpha A}(t)
\end{align*}
\]

\( V_{\text{int}} \) contains the well known **form-factors** for **inelastic excitation** and for **one-particle transfer** (both protons and neutrons).

The **time dependence** of the matrix elements is obtained by solving the Newtonian equations for the relative motion in the nuclear plus Coulomb field. For the nuclear potential we use the **Akyüz-Winther parametrization** that describes quite well elastic scattering data for several projectile and target combinations.

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**GRAZING code** (www.to.infn.it/~nanni)

Independent particle transfer

+ pair transfer modes

+ evap

EXP: $^{58}\text{Ni}^{+}\text{208Pb}$

L. Corradi et al., PRC 66 (2002) 024606
GRAZING or CWKB, G. Pollarolo

$$P_{\beta\delta}(\ell) = \left| \frac{i}{\hbar} \int_{-\infty}^{+\infty} dt \, e^{i\hbar\mu t} \sum_{\beta\delta} \langle 0, r | H_{\ell}(E_{\beta} - E_{\alpha}) + (\delta_{\beta} - \delta_{\delta}) | 0, r \rangle \right|^2$$

Time Dependent Hartree-Fock theory
K. Sekizawa, K. Yabana, PRC 88 (2013) 014614

$$P_n = \int dx_1 \cdots \int dx_N \psi_1^* (x_1) \cdots \psi_N^* (x_N) \hat{P}_n \det \{ \psi_i (x_j) \}$$

Langevin-type dynamical equations of motion
V. Zagrebaev, W. Greiner, PRL 101 (2008) 122701

$$\frac{d\eta_N}{dt} = -\frac{2}{N_{CN}} D_N^{(1)} + \frac{2}{N_{CN}} \sqrt{D_N^{(2)}} \Gamma_N(t)$$
Proton transfer channels

The (-1p) channel is very well reproduced by the calculations. A modest theoretical under prediction for the (-2p) channel with growing differences showing-up as more protons are stripped. On the proton pick-up side these differences become more pronounced as more protons are added.

Experimental mass integrated cross sections - extracted via a multi-gaussian fit of the nuclear charge distribution - vs GRAZING calculations.

Same normalization constant as for the (-1n) transfer channel (129Te)

These results have been also emphasized in the very few systems studied so far where proton pick-up channels have been identified in high resolution measurements.
Exploring the neutron-rich heavy region via MNT

High-resolution but low-efficiency measurements, tagging the light partner with high-resolution spectrometers with the possibility to detect coincident Doppler-corrected $\gamma$ rays of the heavy partner

High-efficiency but low-resolution kinematic coincidences between binary partners (direct or inverse kinematics)

Y. X. Watanabe et al., PRL 115 (2015) 172503

E. M. Kozulin et al., PRC 86 (2012) 044611

F. Galtarossa, INFN LNL

EuNPC 2018 (Bologna, 2-7 September 2018)
In fragmentation reactions on light targets one could produce neutron rich nuclei with measurable cross sections down to ~ nb level. However, σ drop off very quickly with neutron number.

Fragmentation reactions of $^{208}$Pb at 1 GeV/A on Be target

T. Kurtukian-Nieto et al., PRC 89 (2014) 024616

T. Kurtukian-Nieto et al., INFN LNL

F. Galtarossa, INFN LNL

EuNPC 2018 (Bologna, 2-7 September 2018)
Production of neutron-rich nuclei near N=126 via $^{136}$Xe+$^{198}$Pt

That very neutron-rich nuclei are populated only in transfer with low TKEL is confirmed in multidimensional dynamical model of nucleus-nucleus collisions based on Langevin equations.

A. V. Karpov and V. V. Saiko, PRC 96 (2017) 024618
The effect of large TKEL is confirmed with calculations performed within the Improved Quantum Molecular Dynamics model ImQMD with GEMINI code for the treatment of secondary processes.

Production of neutron-rich nuclei near $N=126$ via $^{136}$Xe+$^{198}$Pt

new very neutron rich nuclei are predicted at the level of $10^{-3} - 10^{-6}$ mb

C. Li et al., PLB 776 (2018) 278