New Developments on the Recoil-Distance Doppler-Shift Method

C. Fransen, A. Dewald, A. Blazhev, T. Braunroth, M. Hackstein, J. Jolie, T. Pissulla, W. Rother

Institute for Nuclear Physics
University of Cologne, Germany

AGATA Physics Workshop 2010, Istanbul, Turkey
• Fusion, direct reaction or Coulex with radioactive beams in inverse kinematics: lifetimes determination with RDDS

• RDDS after Coulex in inverse kinematics: example $^{128}$Xe

• The new Cologne plunger for radioactive ion beams

• Recent experiments at NSCL

• Outlook: planned experiments at GSI, Darmstadt
The recoil distance Doppler-shift method (RDDS)

\[ E_{obs} = E_0 \cdot \left( \frac{v}{c} \cos(\theta) \right) \]

\[ \tau(t_k) = \frac{I^{us}(t_k)}{d/dt I^{sh}(t_k)} \]

- \( I^{us} \) = Intensity of the unshifted \( \gamma \)-ray line
- \( I^{sh} \) = Intensity of the Doppler-shifted component

Differential Plunger

Use degrader instead of stopper to allow identification of recoils
Inverse Kinematics Coulomb Excitation: Example: $^{128}\text{Xe}$ measured at Jyväskylä

Gating on target recoils: do not observe Coulex on degrader!

$$E_{\text{obs}} = E_0 \cdot \left( \frac{v}{c} \cos(\theta) \right)$$

Fe target 1mg/cm$^2$  
Nb degrader 5mg/cm$^2$  
Au beam stopper 19 mg/cm$^2$

Measure target like recoils protect detector from beam
Deorientation

Hyperfine interaction:
Original spin alignment diminished as function of interaction time

Decay described by attenuation function
\[
\omega(d) = 1 + pe^{-d/T_D}
\]

\(T_D\) relaxation time

After projectile leaves foil, angular distribution decays into isotropy

Intensities of fast and slow components:
\[
\tilde{R}_{i,f}^s = \omega(d) R_{i,f}^s
\]

Integrate from 0 to \(d\) (target – degrader) for \((f)\) and from \(d\) to infinity (behind degrader) for \((s)\)

\(128\text{Xe}, 4^+_1 \rightarrow 2^+_1\)

Sum of components not constant!
A new plunger device for radioactive beams at NSCL, MSU

target/ degrader diameter: 4 cm
target/ degrader separations: 0-2.5 cm
precision: ~ 1 μm
target/ degrader thickness: ~ 1μm - 1mm
Plunger for radioactive ion beams: NSCL coupled cyclotron facility + A1900; MSU

$^{124}\text{Sn} @ 120 \text{ MeV/u}$

A1900: mass separation
Identification of incoming beam:
TOF between K1200 and Diamond

$^9\text{Be} \text{ production target}$

Mass and charge of reaction products:
from TOF and energy loss.
TOF between Diamond and scintillator in S800 focal plane
energy loss with ionization chamber in S800 focal plane
Plunger lifetime measurements using secondary knock-out reactions or coulomb excitation

**Knock-out reaction**

**Investigation of the N=Z nucleus $^{64}$Ge (and $^{62}$Zn) at NSCL**


**beam:** ~5% $^{65}$Ge, ~25% $^{64}$Ga, ~70% $^{63}$Zn, ~2% $^{62}$Cu

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Beam energy distribution:
- $E \sim 100$ MeV/u
- $E' \sim 90$ MeV/u
- $E'' \sim 60$ MeV/u

**Diamond detector for TOF**

- $^{65}$Ge
- $\beta = 0.42$

- $^{12}$C, 500 $\mu$m

**Target**

- 93Nb, 250 $\mu$m

**Deexcitation lines:**
- $E'_{\gamma}$
- $E''_{\gamma}$

**Knockout or fragmentation:** access of states beyond the $2^+_1$ relativistic Coulex: practically only $2^+_1$
$^{62}\text{Zn} : (2^+ \rightarrow 0^+)$ transition measured at different target – degrader separations

- Stopping power fixed by using velocities measured after the target and after the degrader
- Relativistic effects were considered
- Parameter: degrader excitation (40%) width of the velocity distribution
- Free parameter: lifetime, normalisation factor

Lifetime determined for $2_1^+$ in $^{62}\text{Zn}$:
$\tau = 4.2(7) \text{ ps}$ including lineshape analysis

90% of intensity of $2^+$ decay in $^{62}\text{Zn}$ from fast feeding.
Knockout reaction excellent tool for lifetime measurements!

Nucl. Data Sheets 91(2000)
$\tau = 4.2(3) \text{ ps}$
Plunger technique at intermediate-energy for $^{110}\text{Pd}$ and $^{114}\text{Pd}$ with coulex

Diamond detector for TOF

$^{114}\text{Pd}$

$\beta = 0.354$

$^{93}\text{Nb} 100 \, \mu\text{m}$

$^{12}\text{C} 500 \, \mu\text{m}$

$E\sim 70 \, \text{MeV/u}$

$E'\sim 60 \, \text{MeV/u}$

$E''\sim 44 \, \text{MeV/u}$

$\beta' = 0.343$

$\beta'' = 0.298$

$\gamma$-ray detector (SeGA)

New data for neutron rich Pd isotopes

$^{114}\text{Pd}$:

$\tau = 118 \, (20) \, \text{ps}$

$^{110}\text{Pd}$:

$\tau = 67 \, (8) \, \text{ps}$

New data

A. Dewald et al, Phys. Rev C 78, 051302(R), 2008
Investigation of n-rich Fe isotopes @ NSCL, MSU

RDDS after Coulex in inverse kinematics

<table>
<thead>
<tr>
<th>A</th>
<th>Beta</th>
<th>Energy [MeV/u]</th>
<th>pps</th>
<th>Au –Target</th>
<th>Nb-Degradar</th>
</tr>
</thead>
<tbody>
<tr>
<td>62</td>
<td>0.43</td>
<td>100</td>
<td>36k</td>
<td>0.3 mm</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>64</td>
<td>0.42</td>
<td>95</td>
<td>6k</td>
<td>0.3 mm</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>66</td>
<td>0.40</td>
<td>85</td>
<td>1k</td>
<td>0.3 mm</td>
<td>0.3 mm</td>
</tr>
</tbody>
</table>

Example: lineshape analysis $^{66}$Fe

$^{66}$Fe, $2_1^+ \rightarrow 0_1^+$

forward angle

Wolfram Rother, IKP Cologne
B(E2, 2_1^+ -> 0_1^+) systematics for Fe isotopes

Fe: N=26 – 34 from Nuclear Data Sheets
N=36,38,40 Wolfram Rother, new data

Calculations in pfgd and pf shells:
Plunger at GSI: PRESPEC/LYCCA -> HISPEC
Plunger for radioactive beam experiments @ MSU

Required for GSI plunger:
- larger target/degrader diameter 70 – 80 mm  ✓
- larger beam pipe diameter 6" = 152.4 mm  ✓
- two piezo motors necessary  ✓
- less material in front of target (beam halo)  ×
A dedicated plunger for deep inelastic reactions: PRISMA @ LNL, VAMOS @ GANIL

Modifications for use at PRESPEC:
- Construction not stable enough for large ($\varnothing = \sim 80$ mm) and heavy targets ($\sim 1$ g/cm$^2$)
  - fundamental changes to mechanics needed.
- two inchworm motors necessary
- large target chamber needed.
Advantage of construction: nearly no material in front of target
Outlook: Investigation of neutron rich Cd isotopes at GSI with RDDS and the new AGATA array at PRESPEC

1. Commissioning experiment on $^{122}$Cd with new Cologne differential plunger

Aim: application of Cologne differential plunger for lifetime measurements at HISPEC/PRESPEC with Coulex in inverse kinematics

Measure $B(E2, 0_1^+ \rightarrow 2_1^+)$ in $^{122}$Cd:
Determine from lifetimes measured with plunger
Compare to $B(E2, 2_1^+ \rightarrow 0_1^+)$ from Coulex

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime $\tau$ [ps]</td>
<td>14.4</td>
</tr>
<tr>
<td>Doppler-shifted $\gamma$-ray energy after plunger-target at 15° [keV]</td>
<td>914.2</td>
</tr>
<tr>
<td>PRESPEC $\gamma$-ray energy resolution [%]</td>
<td>4</td>
</tr>
<tr>
<td>Averaged cross section for Coulex in target [mb]</td>
<td>300</td>
</tr>
<tr>
<td>Cross section for Coulex in degrader [mb]</td>
<td>140</td>
</tr>
<tr>
<td>Number of detected good PRESPEC-LYCCA coincidences/h</td>
<td>172</td>
</tr>
<tr>
<td>Shifts per single target-degrader data point</td>
<td>1</td>
</tr>
<tr>
<td>Estimated number of shifts</td>
<td>3</td>
</tr>
</tbody>
</table>

Approved parasitic experiment 21 parasitic shifts (Spring 2011)
Outlook: Investigation of neutron rich Cd isotopes at GSI with RDDS and the new AGATA array at PRESPEC

2. Letter of Intent:
measurement of B(E2) in $^{124,126}$Cd in inverse kinematics Coulex with differential plunger

- Investigate collectivity when approaching N=82
- B(E2, $2^+_1 \rightarrow 0^+_1$) related to nuclear quadrupole deformation
- Milestone in understanding properties of these nuclei
- Anomalous behavior of $2^+_1$ in n-rich Cd

Need precise data on B(E2, $2^+_1 \rightarrow 0^+_1$)
Conclusion

Differential plunger is a very profitable instrument for lifetime measurements in inverse kinematics:

- New results on stable $^{128}$Xe from JYFL
- Examples for measurements with radioactive ion beams at NSCL/MSU
- Outlook: Experiments planned at FRS/GSI with radioactive beams and AGATA
Collaboration:

Institut für Kernphysik, Universität zu Köln
C. Fransen, A. Dewald, M. Hackstein, W. Rother, T. Pissulla,
J. Jolie, K. O. Zell

Michigan State University/NSCL
K. Starosta, A. Chester, P. Adrich, D. Bazin, M. Bowen,
A. Gade, T. Glasmacher, D. Miller, V. Moeller, A. Stolz, C. Vaman,
P. Voss, D. Weisshaar

INRNE, Bulgaria
P. Petkov

GSI, Darmstadt, Germany
M. Gorska and the PRESPEC Collaboration

Athens, Greece
S. Harrisoupulos, T. Konstaninopulos
Example: experiment on $^{128}\text{Xe}$ at Jyväskylä

- $^{128}\text{Xe}$ candidate for E(5) critical point in transition from vibrator to gamma-soft
- Experiment performed in Coulex in inverse kinematics with differential plunger
- Experimental method, data analysis, setup

W. Rother, Diploma thesis University of Cologne 2009
Bateman equations: correct for deorientation

\[ \omega (d) = 1 + p e^{-d/D} \]

\[ \overline{R}_{ik}^f (d) = \int_0^d dd' \omega (d') \dot{R}_{ik}^f (d') \]

\[ \overline{R}_{ik}^s (d) = \omega (d) \int_{d}^{\infty} dd' \dot{R}_{ik}^s (d') \]

\[ 6_{1}^{+} \rightarrow 4_{1}^{+} \]

\[ \tau_{6_{1}^{+}} \approx 1.95(1) \text{ps} \]

\[ \frac{\nu}{c} = 3.24(1) \]

\[ \tau_{4_{1}^{+}} \approx 4.7(2) \text{ps} \]

\[ 4_{1}^{+} \rightarrow 2_{1}^{+} \]
A New Application of the Recoil Distance Method
Probing Exotic, Particle-Decay Isotopes

P. Voss\textsuperscript{1,2}, P. Adrich\textsuperscript{1}, T. Baumann\textsuperscript{1}, D. Bazin\textsuperscript{1}, A. Dewald\textsuperscript{3}, D. Enderich\textsuperscript{1,2}, H. Iwasaki\textsuperscript{3}, D. Miller\textsuperscript{1,2}, R. P. Norris\textsuperscript{1,2}, S. Progovac\textsuperscript{1,2}, A. Ratkiewicz\textsuperscript{1,2}, A. Spyrou\textsuperscript{1}, K. Starosta\textsuperscript{1,2}, M. Thoennessen\textsuperscript{1,2}, C. Vaman\textsuperscript{1}
NSCL/MSU ; IKP Köln

Plunger with a 500\textmu m carbon target and a double sided, 16x16 strip, 300\textmu m silicon detector on a ceramic mount from Micron Semiconductor.
### Table 1: Experimental details

<table>
<thead>
<tr>
<th></th>
<th>$^{122}$Cd</th>
<th>$^{124}$Cd</th>
<th>$^{126}$Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary beam</td>
<td>$^{136}$Xe</td>
<td>$^{136}$Xe</td>
<td>$^{136}$Xe</td>
</tr>
<tr>
<td>Energy [MeV/u]</td>
<td>700</td>
<td>675</td>
<td>675</td>
</tr>
<tr>
<td>Intensity [pps]</td>
<td>$1 \cdot 10^9$</td>
<td>$1 \cdot 10^9$</td>
<td>$1 \cdot 10^9$</td>
</tr>
<tr>
<td>$^9$Be target [mg/cm$^2$]</td>
<td>1622</td>
<td>1622</td>
<td>1622</td>
</tr>
<tr>
<td>S1 wedge Al [mg/cm$^2$]</td>
<td>2000</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>S2 wedge Al [mg/cm$^2$]</td>
<td>5000</td>
<td>6400</td>
<td>5500</td>
</tr>
<tr>
<td>Secondary beam</td>
<td>$^{122}$Cd</td>
<td>$^{124}$Cd</td>
<td>$^{126}$Cd</td>
</tr>
<tr>
<td>Purity [%]</td>
<td>93</td>
<td>93</td>
<td>96</td>
</tr>
<tr>
<td>S2 intensity</td>
<td>$9.80 \cdot 10^4$</td>
<td>$4.50 \cdot 10^4$</td>
<td>$1.30 \cdot 10^4$</td>
</tr>
</tbody>
</table>

### Table 2: Continuation of Tab. 1

<table>
<thead>
<tr>
<th></th>
<th>$^{122}$Cd</th>
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<th>$^{126}$Cd</th>
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</thead>
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<tr>
<td>Averaged cross section for Coulex in target [mb]</td>
<td>300</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>Cross section for Coulex on degrader [mb]</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>Number of Coulomb excitations on target [1/s]</td>
<td>1.19</td>
<td>0.24</td>
<td>0.14</td>
</tr>
<tr>
<td>Number of excitations on degrader [1/s]</td>
<td>0.15</td>
<td>0.05</td>
<td>0.008</td>
</tr>
<tr>
<td>Photopeak efficiency for three rings of PRESPEC at forward angles [%]</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Number of detected good PRESPEC-LYCCA coincidences [1/s]</td>
<td>0.0477</td>
<td>0.0096</td>
<td>0.0056</td>
</tr>
<tr>
<td>Number of detected good PRESPEC-LYCCA coincidences per hour</td>
<td>172</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>Number of shifts per single target-degrader data point</td>
<td>1</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Estimated number of shifts to complete the measurement</td>
<td>3</td>
<td>9</td>
<td>18</td>
</tr>
</tbody>
</table>

**Transmission through FRS for nucleus of interest**

- $15.86\%$
- $22.09\%$
- $23.98\%$

**Beamspot size at plunger-target X-plane [mm]**

- $\pm 20$
- $\pm 20$
- $\pm 15$

**Incoming beam energy on plunger-target [MeV/u]**

- 220
- 220
- 280

**Incoming velocity on plunger-target [c]**

- 0.59
- 0.59
- 0.64

**Total/$^{122}$Xe incoming beam intensity on plunger target [pps]**

- 770/727
- 230/209
- 34/31

**Number of particles registered by LYCCA [pps]**

- 700/651
- 200/186
- 30/27

**Thickness Au plunger target [g/cm$^2$]**

- 2.0
- 2.0
- 3.5

**Outgoing beam energy plunger target [MeV/u]**

- 120
- 120
- 130

**Outgoing velocity plunger target [c]**

- 0.464
- 0.464
- 0.480

**Thickness plunger-degrader (Nb) [μm]**

- 300
- 300
- 300

**Outgoing beam energy plunger-degrader [MeV/u]**

- 100
- 100
- 110

**Outgoing beam velocity plunger-degrader [c]**

- 0.430
- 0.430
- 0.447

**Change in beam velocity plunger-degrader [c]**

- 0.034
- 0.034
- 0.033

**State of interest**

- $2^+_1$
- $2^+_1$
- $2^+_1$

**Transition of interest**

- $2^+_1 \rightarrow 0^+_1$
- $2^+_1 \rightarrow 0^+_1$
- $2^+_1 \rightarrow 0^+_1$

**$\gamma$-ray energy of interest [keV]**

- 562
- 612
- 652

**Assumed lifetime $\tau$ [ps]**

- 14.4
- 16.4
- 16.4

**Flight-path corresponding to $\tau$ [mm]**

- 2.1
- 2.4
- 2.4

**Doppler-shifted $\gamma$-ray energy of interest after plunger-target at 30° [keV]**

- 843.4
- 907.5
- 979.0

**Doppler-shifted $\gamma$-ray energy of interest after plunger-target at 15° [keV]**

- 914.2
- 983.7
- 1066.5

**Doppler-shifted $\gamma$-ray energy of interest after plunger-degrader at 30° [keV]**

- 819.2
- 881.5
- 951.6

**Doppler-shifted $\gamma$-ray energy of interest after plunger-degrader at 15° [keV]**

- 879.4
- 946.4
- 1026.4

**Change in Doppler-shifted energy at 30° [keV]**

- 24.2
- 26.0
- 26.6

**Change in Doppler-shifted energy at 15° [keV]**

- 34.8
- 37.4
- 40.1

**PRESPEC $\gamma$-ray energy resolution [%]**

- 4
- 4
- 4
114Pd: \((2^+ \rightarrow 0^+)\) transition measured at different target – degrader separations

Emission only up to 5cm downstream of the degrader considered

Emission up to 15cm downstream of the degrader considered

Assumption of a longer lifetime
Motivation

Present nuclear physics:
focus on nuclei far from stability

Crucial information:
level scheme
absolute transition strengths

Evolution of collectivity
critical point symmetries
nuclear shapes
...

Lifetimes in ps range from
recoil distance Doppler-shift (RDDS):
Advantage:
does not depend on reaction mechanism!
Inverse Kinematics Coulomb Excitation

beam → coulex on target

beam → coulex on degrader

v1, v2

gate on target recoils

Measure target like recoils protect detector from beam

Protection foil
The recoil distance Doppler-shift method (RDDS)

\[ E_{\text{obs}} = E_0 \cdot \left( \frac{v}{c} \cos(\theta) \right) \]

\[ \tau(t_k) = \frac{I^\text{us}(t_k)}{d/dt I^\text{sh}(t_k)} \]

\[ I^\text{us} = \text{Intensity of the unshifted } \gamma\text{-ray line} \]

\[ I^\text{sh} = \text{Intensity of the Doppler-shifted component} \]

\[ ^{92}\text{Mo}({}^{10}\text{B,3np})^{98}\text{Pd} \]
Gamma-ray singles gated on target recoils @ 30µm

$2^+_2 \rightarrow 2^+_1$

$4^+_1 \rightarrow 2^+_1$

degraded flight

degraded flight

Gruppe A

Gruppe B

510 520 530 540 550 560 570 580 590

0 50 100 150 200 250 300 350
E(5): exact solution of Bohr hamiltonian at critical point of shape phase transition from spherical vibrator to gamma-soft nuclei

B(E2)-Systematics for Pd Isotopes and Neighbours: old

Old data: strong deviation of neutron rich Pd isotopes from Grodzins rule

Grodzins rule:

\[ E(2^+) \cdot B(E2, 2^+ \rightarrow 0_1^+) = \frac{Z^2}{A} (24.6 \pm 8.2) \text{MeV}e^2\text{fm}^4 \]
$e_\pi = 12 \text{ fm}^2$

$e_\nu = 10 \text{ fm}^2$