SOFIA
Fission studies at GSI

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for the SOFIA collaboration

CEA, DAM, DIF

Perspective on Nuclear Data for the Next Decade - Oct. 2014
1 Intro

2 Experimental setup
   Secondary beam
   Fission fragments
   Electromagnetic fission

3 SOFIA 1
   Yields
   Neutron multiplicity
   TKE
   SOFIA-1

4 SOFIA 2

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• Fission yields,
  Total kinetic energy,
  (and total prompt neutron multiplicity)
• Fully and simultaneously identify both fission fragments
• For a wide variety of fissioning systems
- At GSI, Darmstadt, Germany
- Primary beam $^{238}U$
- Secondary beam, of fissile nuclei
- Identification of the fissile nucleus
- Fission and identification of both fission fragments

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Identification of the ions

\[ B \rho \propto \gamma v \frac{A}{Z} \]

\( Z \) Charge,  
\[ \rightarrow \Delta E \text{ in an ionization chamber} \]

\( \rho \) Ion’s trajectory curvature in a dipole  
\[ \rightarrow \text{Dipoles and positions} \]

\( \gamma v \) Lorentz factor and velocity  
\[ \rightarrow \text{Time of flight} \]

\( A \) Mass

\[ (Z, \rho, \gamma v) \rightarrow A \]

Three measurements for a full identification
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Secondary beam

Primary beam $^{238}$U, 1A GeV

Fragmentation

FRS - Setting the secondary beam

Secondary beam

Cave C

238 target

Dipoles

Scintillators

Degrador

TPC

MUSIC

Secondary beam

START

LoF 135m

STOP

From FRS

START

Z Charge Ionization chamber

$\rho$ Positions

$\gamma$ Velocity ToF
Secondary beam

Primary beam $^{238}\text{U}$, 1A.GeV

FRS - Setting the secondary beam

Cave C

Fragmentation

$Z$

$\rho$

$\gamma V$

$(Z, B\rho, \gamma V) \rightarrow A$

STOP

From FRS

START

LoF 135m

Be target
Dipoles
Scintillators
Degrador
TPC
MUSIC
Secondary beam identification map

A/Z

Z

94
93
92
91
90
89

2.54
2.55
2.56

A/Z
Fission fragments

GSI facility, Darmstadt, Germany
Court. GSI

LINAC
Synchrotron
FRS
Cave C
ALADIN was there. All the detectors developed and built by the SOFIA collab.
Setup SOFIA en Cave-C

SOFIA setup in Cave-C

Active Target Fission
Setup SOFIA in Cave-C

Secondary beam Fission

from FRS

SOFIA setup in Cave-C ALADIN

Active Target Fission Twin-MUSIC Charges
Setup SOFIA en Cave-C

SOFIA setup in Cave-C

Secondary beam
Fission
from
FRS

ALADIN

Active Target Fission
Twin-MUSIC Charges
MWPCs Positions
Setup SOFIA en Cave-C

Active Target  Fission
Twin-MUSIC  Charges
MWPCs  Positions
ToF  Velocity
Active Target Fission
Twin-MUSIC Charges $Z$
MWPCs Positions $\rho$
ToF Velocity $\gamma \nu$

$(Z, B_{\rho}, \gamma \nu) \rightarrow A$
EM fission

\[ v/c \sim 0.8 \]

- Actinide
- Target

\( E^* \text{[MeV]} \)

\[ \gamma \]

\( \sigma \)
EM fission

- Actinide
- Target
- Photon

Excitation function at fission,
\[ \frac{d\sigma}{dE} \] (MeV)

\[ \langle E^* \rangle = 12 \text{ MeV} \]

\[ \approx 6 \text{ MeV} \] neutron

\[ ^{238}\text{U} \text{(EM, f)} \approx ^{237}\text{Np} \text{(n, f)} \]
EM fission

Excitation function at fission,

\[ E^* \text{ [MeV]} \]

\[ / \text{dE} \text{ [mb/MeV]}, f) \gamma (\sigma_d) \]

\[ U \text{ secondary beam} \]

\[ 235 \text{U} \]

Excitation energy distribution after EM excitations

Same as photofission

\[ <E^*> = 12 \text{ MeV} \Leftrightarrow 6 \text{ MeV} \text{ neutron} \]

\[ 238 \text{Np} (\text{EM}, f) \approx 237 \text{Np} (\text{n}, f) \]

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EM fission

Excitation function at fission, $\gamma_\sigma (E^*, dE/f)$

\[
\frac{\text{d}E}{\text{d}E} = \text{mb/MeV} \\
E^* = \text{MeV}
\]

Same as photofission

$E^* = 12\text{ MeV} \implies E^* \approx 6\text{ MeV}$

$^{238}\text{Np} (EM, f) \approx ^{237}\text{Np} (n, f)$
EM fission

Excitation energy distribution after EM excitations

Same as photofission

\[ \langle E^* \rangle = 12 \text{MeV} \iff 6 \text{MeV neutron} \]

\[ ^{238}\text{Np}(EM, f) \approx ^{237}\text{Np}(n_{6 \text{ MeV}}, f) \]
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Results

SOFIA-1: 6 days in 2012

SOFIA (08/2012)
Recorded fission events
- >10^5 - 10^6
- >10^3 - 10^5
- >10^1 - 10^3

Review results, example is $^{235}U(\text{coulex}, f)$
Complete disentanglement of charges
Landmarks: e-0 staggering and $Z = 54$
Complete disentanglement of charges
Landmarks: e-o staggering and $Z = 54$

Such reliability on charge yields is reachable exclusively at GSI
Complete disentanglement of charges
Landmarks: e-o staggering and $Z = 54$
• Width of gaussians 0.58 – 0.75 u FWHM
• Statistical uncertainty: ranging from 1.6% to 3%
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- Statistical uncertainty: ranging from 1.6% to 3%
- Width of gaussians $0.58 - 0.75 \text{ u FWHM}$
- Statistical uncertainty: ranging from 1.6% to 3%
$N = A - Z$

- Landmarks: e-o staggering and $N = 82$
$N = A - Z$

- Landmarks: e-o staggering and $N = 82$
Very high resolution

Heavy fragments are more demanding
Very high resolution

Heavy fragments are more demanding
Neutron multiplicity

\[ \nu_n \]

- Indirect neutron multiplicity measurement:
\[ \nu_n = A - (A_L + A_H) \]
- Made possible by excellent resolution on mass
Neutron multiplicity

$^{235}\text{U (coulex, f)}$

$V_{\text{tot}}$
Neutron multiplicity

$^{235}$U (coulex, f)

$\bar{V}_{\text{tot}}$

Z

Scission config., Court. N. Dubray
Total kinetic energy

Measured TKE - $^{235}\text{U}$ (coulex, f)
Total kinetic energy

Measured TKE - $^{235}$U (coulex, f)

Scission config., Court. N. Dubray

TKE [MeV]

30 35 40 45 50 55 60

145 150 155 160 165 170 175

U (coulex, f)

PND2-2 - Oct. 2014 J.-F. Martin

Z
Total kinetic energy
SOFIA-1, August 2012

- SOFIA-1 has been a success
- For the very first time, both fission fragments fully identified, simultaneously
- Z, A, N and isotopic yields
- Prompt neutron multiplicity and total kinetic energy
- 80 fissioning systems, some measured for the first time

But...

- We missed $^{236}U \approx ^{235}U + n$
SOFIA-1, August 2012

- SOFIA-1 has been a success
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But...

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SOFIA-2 is planned for now!
Beam 22-24th October, 2014
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SOFIA-2

SOFIA setup in Cave-C

Secondary beam
from FRS

START
STOP
Fission

1.5 m
60 cm

ALADIN

ToF 7.5 m

TPC (court. FRS)
MUSIC (court. FRS)
Scintillator
Stripper
Active Target
He pipe
Twin-MUSIC
MWPC
ALADIN
Fragment's flightpath

SOFIA-2 setup in Cave-C

Secondary beam
from FRS

Fission

1.80 m
45 cm

ALADIN

ToF 8. m

Triple MUSIC
Scintillator
Active Target
He pipe
Twin-MUSIC
MWPC
ALADIN
Fragment's flightpath
- All the same, but all improved!
- Efficiency was 75%, it becomes 95%
- Max count rate was 2kHz, it becomes 4 – 5kHz
- $^{236}\text{U}$ is to be measured with high statistics
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Within 5 years, SOFIA at R3B
The experimental area Cave C is to be upgraded, to R3B = Reactions with Relativistic Radioactives Beams
Outlook, 5 years

GLAD  New dipole, more powerful -> better resolution on mass measurement

CALIFA  Calorimeter -> fission $\gamma$, multiplicity and total energy

NeuLAND  Neutron detector -> assign prompt neutron to each fragment

Also, considering $^{242}$Pu as primary beam. Access fission of heavier actinides: Am, Pu, Np...
Outlook, a long time

SOFIA at ELISE = fELISE
Complete revolution as compared to first steps of SOFIA

- $^{238}U$ primary beam accelerated through LINAC, SIS
- Fragmentation reaction to produce secondary beam
- Selection of ions of interest through SuperFRS
- Injection of pure $2\gamma$ beam into storage ring NESR
Outlook, a long time

SOFIA at ELISE = fELISE
Complete revolution as compared to first steps of SOFIA

- Electron ion scattering
- Excitation of ion known on an event-by-event basis
- De-excitation through fission
- Identification of the fragments
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## Conclusion

### SOFIA-1

- **SOFIA-1 in Aug. 2012**
- Fission observables are Z, A, N and isotopic yields, and TKE and **total** prompt neutron multiplicity
- For the very first time, both fragments are fully and simultaneously identified
- With unprecedented resolution
  - Paramount for the applications...
  - But we missed $^{236}U \approx^{235}U + n$!
- **Over 80 nuclei**
  - Overview on the nuclear landscape
Conclusion

SOFIA-1

SOFIA-2

- SOFIA-2 in Oct. 2014 (now !)
- The principle stays the same, but the whole setup is improved
- Higher geometrical acceptance, higher counting rate
- We are ready for $^{236}U$!
Conclusion

SOFIA-1

SOFIA-2

And then?

- First step: SOFIA at R3B
  - evolution of the setup
  - Horizon 2017
  - Better mass resolution
  - New observables: prompt neutron multiplicity per fragment, prompt γ emission

- Further down the line: SOFIA @ FAIR/ELISε
  - (r)evolution of the setup
  - fission induced by electron-ion scattering
  - excitation energy known on an event-by-event basis