RECENT RESULTS OF EXPERIMENTS WITH MASSIVE URANIUM TARGET SETUP QUINTA AT NUCLotron.

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ISINN-20, Alushta, May 21-25, 2012
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INTRODUCTION

- As it was reported at previous ISINN-19 the ADS project “Energy and Transmutation RAW” (E&T RAW) continued to run at JINR.

- The project is aimed at study of possibilities to use deep subcritical natural (depleted) uranium or thorium active core (AC) with very hard neutron spectrum inside for effective burning of the core material together with spent nuclear fuel (SNF).
• To preserve maximally hard neutron spectrum it is necessary to use high temperature helium cooling in primary circuit and large volume (“quasi-infinite”) AC loaded by small size encupsulated fuel elements including these made from SNF without its preliminary radiochemical reprocessing

• The essential point of this ADS is direct use of the core load as a target for smeared incident beam with energy up to 10 GeV.
• The new approach to ADS outlined above is called the **Relativistic Nuclear Technology (RNT)** for utilization of spent nuclear fuel and energy production.

• At present very challenging problem of any ADS is a creation of powerful (~ 10-50 MWt) accelerator with good enough duty cycle.

• But creation of such accelerator as well as all RNT engineering problems are so far out of the current JINR project.
The objectives of project “E&T RAW” are to study during 2011-2013 the basic features of model ADS with quasi-infinite deep-subcritical AC irradiating by deuteron (proton) beam from JINR NUCLOTRON in incident energy range 1-10 GeV.
JINR PROJECT “Energy&Transmutation RAW”

• For realization of “E&T RAW” project there are two target assemblies at JINR:
  - semi-infinite (~20 tones) depleted uranium AC BURAN
  - and smaller (~500kg) nat. U target assembly QUINTA modeling the central part of the larger AC
**Quasi-infinite depleted uranium target (BURAN) with replacement central zone**

| Mass of uranium | – 19.5 т. |
| Diameter        | – 1,2 м. |
| Length          | – 1 м.  |
| Materials of central zone | – U, Th, Pb. |
| Diameter of central zone | – 0,2 м. |

**Front view**
- Input beam window
- Steel case
- Central zone (U, Th, Pb)
- Frame

**Rear view**
- Detector channels

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Quasi-infinite depleted uranium target (BURAN) with replacement central zone

Longitudinal section of the BURAN together with central zone and detector sets

Input beam window

Central zone (U, Th, Pb)

Detector assemblies

Front view photo

Rear view photo

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Target assembly “Quinta” at the irradiation position (March 2011)

- Displacement of SSTD and threshold activation detectors on surface of “Quinta” setup

Bedplate (700x400x16)

Activation detector plates

Pad with a Pb foil monitor and SSTD

Platform

Beam window

Rails

d

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“Quinta” at the irradiation position
(June 2009, December 2011, March 2012)

\[
m_U = 315 \text{ kg} \\
m_{Pb} = 1780 \text{ kg} \\
m_\Sigma = 2125 \text{ kg}
\]
JINR PROJECT “Energy & Transmutation RAW”

- In present talk it’ll be discussed mainly the results of experiments carried out with target assembly QUINTA during 2011-2012 aimed at study basic physics of RNT.
- Really these experiments are preparatory stage to future measurements with quasi-infinite AC planned for 2013.
• It is appropriate to note that quasi-infinite subcritical AC from natural or depleted uranium were studied earlier:

- R.Vassil’kov et al. ~7 tons nat. U+660 MeV protons (1978)
- C. Rubbia et al. ~3.6 tons nat.U+0.6-2.7GeVprotons (1995)

• Only in three first experiments there was realized hard neutron spectrum
• In the fourth FEAT experiment U rods were embedded into light water moderator so real neutron spectrum was close to thermal one and neutron multiplicity coefficient $k_{eff}$ of this system was near 0.9.
• In experiment by Vasil’kov-Goldansky group on Dubna synchrocyclotron it was not used any moderator and was applied a special geometry so their 3.5 tons target was equivalent ~ 7 tones setup with rather small (<10%) neutron leakage.

• In this case of “quasi-infinite” AC maximally hard neutron spectrum has been realized with rather low $k_{\text{eff}} \sim 0.4$

• They obtained integral number of fission events $N_f \sim 20$ and produced $^{239}\text{Pu}$ nuclei $N_{n\gamma} \sim 45$ per incident proton.

• It leads to the beam power gain (BPG) $\sim 7$ for 0.66 GeV protons at rather small $k_{\text{eff}} \sim 0.4$
So it is very important to realize the experiment with quasi-infinite AC such as BURAN for more high energy (up to 10 GeV).

The measurements with QUINTA target assembly allow us to test experimental technique planned to use for study of the AC BURAN properties and to clear out the basic characteristics of the central “neutron tube-like source” of this AC investigated in 2009 - 2012.
Scheme of experiment with “Quinta” setup, March 2011 run

- Beam output
- Scintillation monitor telescope
- Profilometer
- Activation foil
- Ionization chamber
- «Quinta» target assembly
- Bedplate axis shifted for 2° respective beam direction
- Borated polyethylene shielding
- Stilbene and $^3$He detectors
- ISOMER-M
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Upgraded target assembly “Quinta” (front view)
QUINTA at the irradiation position (front view)
General view of the experimental setup

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Beam position into input window (front view)

$E_d = 2 \text{ GeV}$

A – SSTD

Beam shift in X: 7.8 mm (to the right in the beam direction)
FWHM: 13 mm
Beam shift in Y: -6.4 mm (down)
FWHM: 16 mm

B – Activation method

Beam shift in X: 12 mm (to the right in the beam direction)
FWHM: 20 mm
Beam shift in Y: -5 mm (down)
FWHM: 28 mm

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Mica SSTD

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**Preliminary results of March 2011 experiments**

Spatial distributions of fission rates (in $\text{cm}^3$/one deuteron) for QUINTA setup irradiated by deuteron beam

*Measurements by solid state track detectors (SSTD)*

$E_d = 2 \text{ GeV}$

$E_d = 4 \text{ GeV}$

$E_d = 6 \text{ GeV}$
“Quinta” at the irradiation position (June 2009 and March 2012)

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Fission rates
f/1nucleus/deuteron
Measurements by solid state track detectors (SSTD)
In March 2012

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Distributions numbers of fissions integrated over Z axis - left over X axis - right
Total numbers of fissions from QUINTA per one deuteron and 1 GeV from SSTD

![Graph showing total numbers of fissions from QUINTA per one deuteron and 1 GeV from SSTD]
Plutonium production

$^{238}\text{U}(n,\gamma)^{239}\text{U}\ (23,54\ \text{min})\ \beta^-\rightarrow^{239}\text{Np} \ (2,36\ \text{days})\ \beta^-\rightarrow^{239}\text{Pu}$

$277.6\ \text{keV}\ \gamma$-line from $^{239}\text{Np}$

$\gamma$- detector calibrated with $^{60}\text{Co}, ^{54}\text{Mn}, ^{57}\text{Co}, ^{88}\text{Y}, ^{109}\text{Cd}, ^{113}\text{Sn}, ^{133}\text{Ba}, ^{137}\text{Cs}, ^{139}\text{Ce}, ^{152}\text{Eu}, ^{228}\text{Th}, ^{226}\text{Ra}$ standard sources.

Number of fissions defines by averaging of following fission product yields:

$^{97}\text{Zr}\ (5.42\%),\ ^{131}\text{I}\ (3.64\%),\ ^{133}\text{I}\ (6.39\%),\ ^{143}\text{Ce}\ (4.26\%)$

In brackets there are mean cumulative FP yields

For more details see M. Artwushmanko’s report later in this session
Total numbers (per 1 GeV) of produced nuclei $^{239}$Pu ($N_{Pu}$) and fissions ($N_f$) of $^\text{nat}U$ into target assembly QUINTA

<table>
<thead>
<tr>
<th>Run</th>
<th>$E_d$ GeV</th>
<th>$N_{Pu}$</th>
<th>$N_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 2011</td>
<td>2</td>
<td>(7.0 ± 0.3) ± 0.8</td>
<td>(8.8± 0.4) ± 1.0</td>
</tr>
<tr>
<td>(without Pb blanket)</td>
<td>4</td>
<td>(7.2± 0.4) ± 0.8</td>
<td>(8.8± 0.4) ± 1.0</td>
</tr>
<tr>
<td>March 2011</td>
<td>6</td>
<td>(6.9± 0.3) ± 0.7</td>
<td>(8.3± 0.4) ± 0.9</td>
</tr>
<tr>
<td>Dec. 2011</td>
<td>1</td>
<td>(11.6± 0.6) ± 1.2</td>
<td>(10.2± 0.5) ± 1.1</td>
</tr>
<tr>
<td>(with Pb blanket)</td>
<td>4</td>
<td>(10.9± 0.5) ± 1.1</td>
<td>(8.7± 0.4) ± 1.0</td>
</tr>
<tr>
<td>March 2012</td>
<td>1</td>
<td>(11.2± 0.6) ± 1.2</td>
<td>(9.6± 0.5) ± 1.1</td>
</tr>
<tr>
<td>(with Pb blanket)</td>
<td>4</td>
<td>(10.8± 0.5) ± 1.1</td>
<td>(8.8± 0.4) ± 1.0</td>
</tr>
<tr>
<td>March 2012</td>
<td>8</td>
<td>(10.5± 0.5) ± 1.1</td>
<td>(9.8± 0.5) ± 1.1</td>
</tr>
</tbody>
</table>
Comparison of DN and fission data

- It is interesting to note that similar result was obtained in CERN experiment by C. Rubbia group for ~ 6 tons $^{nat}U$ target with fully thermalized neutron spectrum and $k_{eff} \sim 0.9$
Main result of the FEAT experiment
(S. Andriamonje et al., CERN/AT/94-45(ET))
The time dependence of the neutron yield from the geometrically identical lead and uranium targets. 1 - (Pb+d) for $E_d = 4$ GeV; 2 and 3 (U+d) for $E_d = 1$ and 4 GeV.
Neutron time spectrum

\( E_d = 6 \text{ GeV}, (T = 11 \text{ s}, \Delta T = 0.25 \text{ s}), \) total DN yield \( I = (7.8 \pm 0.6) \cdot 10^{-9}/\text{d} \)
Comparison of DN and fission data

<table>
<thead>
<tr>
<th>Run</th>
<th>1 Gev</th>
<th>2 GeV</th>
<th>4 GeV</th>
<th>6 GeV</th>
<th>8 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSTD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03.12</td>
<td>8.8 ±1.5</td>
<td>8.4 ±1.5</td>
<td>9.3 ±1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>03.11</td>
<td>11 ±1.9</td>
<td>9.4 ±1.7</td>
<td>9.6 ±1.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activ.M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03.12</td>
<td>9.6 ±1.6</td>
<td>8.8 ±1.3</td>
<td>9.8 ±1.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03.12</td>
<td>11 ±0.7</td>
<td>10.3 ±0.7</td>
<td>14 ±1.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

V.G ~ 30

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Comparison of DN and fission data

• The DN time spectra were obtained for three target assemblies irradiated by deuterons with energy 1, 2, 4, 6 and 8 GeV.
• In parallel it was measured the spatial distributions of fission rates inside of uranium targets.
• If total fission numbers (per one deuteron and 1 Gev) are constant in limits of experimental errors so similar relative DN total yields shows in contrast a slight increase. An essential increase of this yield observed in June 2009 could be caused by deficiency in monitoring of deuteron fluxes as it became clear now.
• Difference in incident energy dependence of DN relative yields and total fission numbers is the subject for further experimental and theoretical study.
Group analysis of DN time spectra

\( ^{238} \text{U} + 4 \text{GeV d} \)

- DN group 5
  - \( T_{1/2} = 0.62 \text{ s} \)
- DN group 4
  - \( T_{1/2} = 2.75 \text{ s} \)

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The time dependence of neutron yields from different target assemblies for $E_d = 4$ GeV.

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Results of DN spectra analysis of June and November 2009 data

Comparison of neutron energy dependence of the weight ratios of 5-th to (4+3-th) DN groups from $^{238}$U(n,f)-reaction and similar values extracted from DN time spectra measured in present work.

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Analysis of DN time spectra

• “Mean neutron energy” $<\text{En}>$ inducing fission of $^{238}\text{U}$ that extracted from analysis of DN time spectra shows essential growth with increase of incident deuteron energy.

• $<\text{En}> = (13 \pm 3) \text{ MeV}$ at $Ed = 1 \text{ GeV}$
• $<\text{En}> = \sim 40 \text{ MeV}$ at $Ed = 8 \text{ GeV}$
• *Reason for this should be studied more*
Neutron energy spectra obtained in June 2009
Neutron energy spectra obtained in June 2009
Neutron energy spectra

• Obtained data for spatial distribution of neutron spectra and fluxes as well as main features of leakage neutrons should be a subject of subsequent analysis

• It is planned to carry out of theoretical analysis of whole set of the obtained data aimed at verification and modification INC models in MC transport codes.
<table>
<thead>
<tr>
<th>$E_{sh}$ MeV r cm</th>
<th>$E_d = 1$ GeV</th>
<th>$E_d = 4$ GeV</th>
<th>$E_d = 8$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>59.2</td>
<td>97</td>
<td>73</td>
</tr>
<tr>
<td>12</td>
<td>214</td>
<td>453</td>
<td>201</td>
</tr>
<tr>
<td>34</td>
<td>678</td>
<td>687</td>
<td>292</td>
</tr>
<tr>
<td>11.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>33</td>
<td>24</td>
<td>29</td>
</tr>
<tr>
<td>12</td>
<td>46</td>
<td>45</td>
<td>40</td>
</tr>
<tr>
<td>34</td>
<td>52</td>
<td>57</td>
<td>59</td>
</tr>
<tr>
<td>54.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>12</td>
<td>12</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>34</td>
<td>14</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>
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Thanks for your attention
#### Discussion of results

**Number per one deuteron**

<table>
<thead>
<tr>
<th>$Ed$</th>
<th>0.66 GeV ($Vassil’kov et al$)</th>
<th>2 GeV</th>
<th>4 GeV</th>
<th>6 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}$Pu production</td>
<td>46 4</td>
<td>17 1.7</td>
<td>30 3.0</td>
<td>45 4.5</td>
</tr>
<tr>
<td>$^{238}$U(n,f)</td>
<td>18.5 1.7</td>
<td>21 3.6</td>
<td>36 3.6</td>
<td>54 5.4</td>
</tr>
<tr>
<td>$^{238}$U(n,f)</td>
<td>20.4 3.8 2</td>
<td>32 6 3.2</td>
<td>44 7 4.4</td>
<td></td>
</tr>
<tr>
<td>DN relative yield normalized to fission data at 2 GeV</td>
<td>$20 \pm 1.4$</td>
<td>$69 \pm 4.9$</td>
<td>$120 \pm 8.4$</td>
<td></td>
</tr>
</tbody>
</table>
Analysis of neutron energy spectra

• The comparison of these total neutron spectra demonstrates the pronounced contribution of prompt fission neutrons for the uranium target in the energy range $(1 – 10) \text{ MeV}$
• Role of these neutrons is more important for the central zone of the target than for peripheral regions of the target
• This effect becomes more pronounced with increasing incident deuteron energy
• More detailed analysis of obtained neutron spectra is a subject of following work
Results from threshold activation detectors (March 2011)

R=4 cm

\[ F, \frac{1}{dx cm^2} \]

\[ E_n, MeV \]

1 GeV
2 GeV
3 GeV

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Results from threshold activation detectors (March 2011)

$R=12 \text{ cm}$

$E_n, \text{ MeV}$

$F, 1/\text{ dxcms}^2$

1 GeV

2 GeV

3 GeV

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Плотность делений 238U на 1 дейтрон на 1 ГэВ на 1 г natU
Радиальные распределения по блоку Z =245

Плотность делений 238U на 1 дейтрон на 1 ГэВ на 1 г natU
Радиальные распределения по блоку Z =122.5

Плотность делений 238U на 1 дейтрон на 1 ГэВ на 1 г natU
Радиальные распределения по блоку Z =0

Плотность наработки 239Pu на 1 дейтрон на 1 ГэВ на 1 г natU
Радиальные распределения по блоку Z =122.5

Плотность наработки 239Pu на 1 дейтрон на 1 ГэВ на 1 г natU
Радиальные распределения по блоку Z =245

Плотность наработки 239Pu на 1 дейтрон на 1 ГэВ на 1 г natU
Радиальные распределения по блоку Z =0

Спектральные индексы в зависимости от координаты R для различных энергий.

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Preliminary results on DN yields (per deuteron and 1 GeV) from QUINTA target assembly

<table>
<thead>
<tr>
<th>Number per one deuteron</th>
<th>E&lt;sub&gt;d&lt;/sub&gt; 1 GeV</th>
<th>E&lt;sub&gt;d&lt;/sub&gt; 2 GeV</th>
<th>E&lt;sub&gt;d&lt;/sub&gt; 4 GeV</th>
<th>E&lt;sub&gt;d&lt;/sub&gt; 6 GeV</th>
<th>E&lt;sub&gt;d&lt;/sub&gt; 8 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>DN total yield</td>
<td>March 2011</td>
<td>20 (7%)</td>
<td>69 (7%)</td>
<td>94 (7%)</td>
<td></td>
</tr>
<tr>
<td>arbitrary units</td>
<td>March 2012</td>
<td>11 (6%)</td>
<td>41 (6%)</td>
<td></td>
<td>111 (6%)</td>
</tr>
</tbody>
</table>