The status and prospects of nuclear physics research at IPPE

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State scientific center of the Russian Federation – Institute for physics and power engineering named after A. I. Leypunsky
IPPE in nuclear data community

IPPE was established in 31 May 1946!

Neutron nuclear data important for nuclear reactor is one of the first tasks of IPPE.

G.Smirenkin   Yu.Grigoryev
B.Kuzminov    D.Tambovchev
D.Shpak        L.Kozlovsky
A.Soldatov    V.Malinovsky
B.Maksutenko   V.Piksaykin
G.Lovchikova  A.Goverdovski
B.Fursov      V.Tolstikov
N.Kornilov    A.Sergachev
S.Simakov     B.Zhuravlev
V.Kononov    et al.

Fission cross section, fission fragments yield, prompt neutron spectra, prompt neutron multiplicity, elastic and inelastic neutron scattering, neutron capture, ternary fission, \((n,\alpha)\) reaction, benchmark, neutron capture, delay neutron, cold fission, angular distribution of fission fragments, level density, et alia.
IPPE Accelerators

IPPE accelerator complex

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Energy Region (p⁻)</th>
<th>Current</th>
<th>Ion Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>KG-2,5</td>
<td>0.1...13 MeV</td>
<td>-0.01...2000 μA</td>
<td>-1...100 a.m.u.</td>
</tr>
<tr>
<td>EGP-15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EG-1</td>
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<tr>
<td>EG-2,5</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EG-0,3</td>
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</table>

Nuclear physics
Radiation materials science
Nuclear microanalysis
## Accelerators parameters

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Ions energy (MeV)</th>
<th>Ions</th>
<th>Operating mode</th>
<th>Current parameters</th>
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</thead>
<tbody>
<tr>
<td>EG-2,5</td>
<td>0,2 – 2,7</td>
<td>H, D, He, N, Ar, O</td>
<td>DC</td>
<td>0,1 – 30,0 μA</td>
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<td></td>
<td></td>
<td>0,01 – 10,0 μA</td>
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<tr>
<td>EG-1</td>
<td>0,9 – 4,5</td>
<td>H, D</td>
<td>DC</td>
<td>1,0 – 20,0 μA</td>
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<tr>
<td></td>
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<td></td>
<td>Pulsed</td>
<td>Amplitude 2 -3 mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pulse duration 1 – 2 ns</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Frequency 1 – 5 MHz</td>
</tr>
<tr>
<td>EGP-10M</td>
<td>3,5 – 9,0</td>
<td>H, D</td>
<td>DC</td>
<td>1,0 – 10,0 μA</td>
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<td>Pulsed</td>
<td>Amplitude 0,4 mA</td>
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<td>Pulse duration 1 – 2 ns</td>
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<td></td>
<td></td>
<td>Frequency 1 – 5 MHz</td>
</tr>
<tr>
<td>KG-2,5</td>
<td>0,3 – 2,2</td>
<td>H, D</td>
<td>DC</td>
<td>0,1 – 2,0 mA</td>
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<td></td>
<td></td>
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<td>0,01 – 2,0 mA</td>
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<tr>
<td>KG-0,3</td>
<td>0,05 – 0,3</td>
<td>H, D</td>
<td>DC</td>
<td>0,01 – 5,0 μA</td>
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<tr>
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<td></td>
<td>Pulsed</td>
<td>Amplitude 0,3 -0,5 mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Pulse duration 1 – 3 ns</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>Frequency 1,0 – 5 MHz</td>
</tr>
<tr>
<td>EGP-15</td>
<td>4,0 – 12,0 (p, d)</td>
<td>H, D</td>
<td>DC</td>
<td>0,01 – 1,0 μA</td>
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<tr>
<td></td>
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<td></td>
<td>Pulsed</td>
<td>Amplitude 0,3 -0,5 mA</td>
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<tr>
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<td></td>
<td>Pulse duration 1 – 3 ns</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Frequency 1,0 – 5 MHz</td>
</tr>
</tbody>
</table>

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F, C, O, Al, Si, Cl, Ni, Fe, Zr
Fission fragments spectrometer

Ionization chamber: \(d=120\ \text{mm}\), height – 90 mm.

Working gas: \(\text{Ar}+10\%\text{CH}_4\), Pressure – 0.75 atm.

Digitizer: LeCroy 2262, 40 MHz, Time scale – 7 mks.

\(^{238}\text{U}\) sample sizes: Diameter - 60 mm. Thickness 250 mkg/cm\(^2\).

Energy resolution 40 keV for 6 MeV \(\alpha\)-particles.

Angular resolution - 0.065 (in \(\cos(\theta)\) unit).

Mass resolution \(\sim 1\ \text{a.m.u.}\)
$^{232}\text{Th}(n,f)$, $E_n=1, 2$ and 5 MeV

![Graph showing $^{232}\text{Th}(n,f)$ cross-sections for different $E_n$ values.](image)
Fission fragments yield

N

- IPPE
- IRMM

169.8 MeV

TKE, MeV

0 120 140 160 180 200 220

0 500 1000 1500 2000 2500
TKE distributions for mass 140 a.m.u.

- $E_n = 6.5$ MeV
- $E_n = 5$ MeV

$M = 140$ a.m.u.
TKE distributions for mass 140 a.m.u.

- En=5 MeV
- En=6.5 MeV

M=140 a.e.m.

M=130 a.m.u.
TKE and TKE dispersion for $^{238}\text{U}(n,f)$ by 5 and 6.5 MeV neutron
True cold fragmentation observation for $^{238}\text{U}$ fission by 5 MeV neutrons

Fission fragments yields dependence from TKE value. (□) – mass 130 a.m.u., (●) – mass 140 a.m.u.
$^{238}\text{U(n,f), En}=5\ \text{MeV}$
Maximal available TKE for different mass

\[ Q_{-TKE_{Max}} \text{ MeV} \]

- 5 MeV
- 6.5 MeV

Mass, a.m.u.

9.8 MeV
3.34 MeV
$^{252}\text{Cf}$ and $^{233}\text{Th}$ ternary fission
Energy dependence of ternary fission probability for $^{232}\text{Th}(n,f)$

![Graph showing energy dependence of ternary fission probability for $^{232}\text{Th}(n,f)$]
Classical spectrometer events classification

1. Target
2. Full absorption
3. Electrodes
4. Gas α-particles
5. Protons
6. Wall effect
Scheme of the IPPE experimental setup

PA – preamplifier, TFA – timing filter amplifier,
D – discriminator,
SA – spectroscopy amplifier, DLA – delay line amplifier,
WFD – waveform digitizer, PC – personal computer.
Amplitude of anode pulse vs electron drift time

\[ \Delta \tau \text{ window} \]

\[ \text{Rn area} \]

\[ \text{Po area} \]
α-particle directionality determination

![Graph showing the change in $Q_A$ channel over time](image)

- Time, $\mu$s
- $Q_A$, channel

![Diagram illustrating the cathode and anode with QF and QB](image)

- Anode
- Cathode
- QF
- QB
α-particle directionality determination

\[
\frac{dQ_\alpha(t)}{dt} \big|_{\text{begin}} = \left( \frac{dE}{dx} \right)_{\text{begin}} \\
\frac{dQ_\alpha(t)}{dt} \big|_{\text{end}} = \left( \frac{dE}{dx} \right)_{\text{end}}
\]

\[G = \frac{\frac{dQ_\alpha(t)}{dt} \big|_{\text{begin}}}{\frac{dQ_\alpha(t)}{dt} \big|_{\text{end}}} = \frac{\left( \frac{dE}{dx} \right)_{\text{begin}}}{\left( \frac{dE}{dx} \right)_{\text{end}}}
\]
Particle position and type of particle determination

\[ \alpha \text{ particles} \]

\[ ^{16}\text{O}(n,\alpha)^{13}\text{C}, \text{En}=7.1 \text{ MeV} \]

\[ \text{detector gas Kr(97\%)CO}_2(3\%) \]

\[ \Delta T_d \]

\[ \text{Anode pulse amplitude (channel)} \]

\[ \text{Drift time of origin or end of particle track} \]

\[ \text{End of particle} \]

\[ \text{Cathode} \]
Energy spectrum of $\alpha$-particles

- GIC mode, background contribution (BC 19%)
- TPC mode, rise time suppression (BC 2.5%)
- TPC mode, rise time suppression and additionally drift time suppression (BC 1.2%)

Counts/channel

${}^{16}\text{O}(n,\alpha){}^{13}\text{C}$

$\Delta P_\alpha$

Anode pulse amplitude (channel)
Evaluations for $^{16}\text{O}(n,\alpha)$ reaction
Result for $^{16}\text{O}(n,\alpha)^{13}\text{C}$

IPPE 2009

- Convoluted ENDF B VII
- ENDF B VII
- Davis

Cross section, barn

En, MeV
Spectrometer response function for gaseous and solid targets

Solid target:
I – $^{10}\text{B}(n,\alpha_0)$;
II – $^{10}\text{B}(n,\alpha_1)$;
III – $^{10}\text{B}(n,t)$;
VI – $^7\text{Li}$;
V – $^7\text{Li}+\alpha$

Gaseous target:
1 – $^{10}\text{B}(n,\alpha_0)$;
2 – $^{10}\text{B}(n,\alpha_1)$;
3 – $^{10}\text{B}(n,t)$
Result for $^{10}\text{B}(n,2\alpha)t$ reaction

![Graph showing the cross section for the $^{10}\text{B}(n,2\alpha)t$ reaction as a function of neutron energy. The graph compares data from various sources including IPPE 2012, Qaim, Suhaimi, Davis, Lippincott, Frye Jr, Wyman, Woelfe, ENDF/B VII, and JENDL-4.0.](image-url)
New data for:

1) $^{10}$B(n,t),
2) $^{10}$B(n,$\alpha_0$)/$^{10}$B(n,$\alpha_1$),
3) $^{12}$C(n,$\alpha$),
4) $^{14}$N(n,$\alpha_0$), $^{14}$N(n,$\alpha_1$), $^{14}$N(n,$\alpha_2$),
5) $^{14}$N(n,t$_0$),
6) $^{16}$O(n,$\alpha_0$),
7) $^{19}$F(n,$\alpha$),
8) $^{20}$Ne(n,$\alpha_0$), $^{20}$Ne(n,$\alpha_1$), $^{20}$Ne(n,$\alpha_2$), $^{20}$Ne(n,$\alpha_3$),
9) $^{36}$Ar(n,$\alpha_0$), $^{36}$Ar(n,$\alpha_1$), $^{36}$Ar(n,$\alpha_2$),
10) $^{40}$Ar(n,$\alpha_0$)

was measured
Some of structural material isotopes properties

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Natural abundance, %</th>
<th>(n,(\alpha)) reaction Q-value, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{50}\text{Cr},\ T_{1/2}&gt;1,8*10^{17}\ \text{y},\ EC)</td>
<td>4,345</td>
<td>+0,3213</td>
</tr>
<tr>
<td>(^{52}\text{Cr},\ \text{stable})</td>
<td>83,489</td>
<td>-1,2097</td>
</tr>
<tr>
<td>(^{53}\text{Cr},\ \text{stable})</td>
<td>9,501</td>
<td>+1,7903</td>
</tr>
<tr>
<td>(^{54}\text{Cr},\ \text{stable})</td>
<td>2,365</td>
<td>-1,5466</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Residual nuclear</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{50}\text{Cr})</td>
<td>(^{47}\text{Ti})</td>
<td>Stable</td>
</tr>
<tr>
<td>(^{52}\text{Cr})</td>
<td>(^{49}\text{Ti})</td>
<td>Stable</td>
</tr>
<tr>
<td>(^{53}\text{Cr})</td>
<td>(^{50}\text{Ti})</td>
<td>Stable</td>
</tr>
<tr>
<td>(^{54}\text{Cr})</td>
<td>(^{51}\text{Ti}) (T_{1/2}=5,76\ \text{min})</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Residual nuclear</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{54}\text{Fe})</td>
<td>(^{51}\text{Cr}) (T_{1/2}=27,7\ \text{d},\ ec)</td>
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</tr>
<tr>
<td>(^{56}\text{Fe})</td>
<td>(^{53}\text{Cr})</td>
<td>Stable</td>
</tr>
<tr>
<td>(^{57}\text{Fe})</td>
<td>(^{54}\text{Cr})</td>
<td>Stable</td>
</tr>
<tr>
<td>(^{58}\text{Fe})</td>
<td>(^{55}\text{Cr}) (T_{1/2}=3,55\ \text{min})</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Residual nuclear</th>
<th>Stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{58}\text{Ni})</td>
<td>(^{55}\text{Fe}) (T_{1/2}=2,7\ \text{y},\ ec)</td>
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<tr>
<td>(^{60}\text{Ni})</td>
<td>(^{57}\text{Fe})</td>
<td>Stable</td>
</tr>
<tr>
<td>(^{61}\text{Ni})</td>
<td>(^{58}\text{Fe})</td>
<td>Stable</td>
</tr>
<tr>
<td>(^{62}\text{Ni})</td>
<td>(^{59}\text{Fe}) (T_{1/2}=44,5\ \text{d})</td>
<td></td>
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</table>
Present status of experimental data and evaluation for chromium isotopes
Motivations for removing solid target from cathode surface

1) Target surface 10 times less than cathode surface; Probability of gaseous particle absorption is proportional to the surface area.
2) Target material – gold. Low probability for charge particle emission;
New chamber design

1) Cr target;
2) $^{238}$U target;
3) Anode;
4) Anode signal connector;
5) Frisch grid;
6) Guard electrodes;
7) Resistor.
8) Golden threads
Background (neutron beam off)

Anode pulse amplitude, channel

Drift time, channel

- Cathode
- Cr target
- Gas
Own α - activity of the detector

- Target: $E_\alpha = 4.8$ MeV, $0.0043$ Bk
- Cathode: $0.0011$ Bk
- Working gas: $0.00025$ Bk
Drift time selection for $\alpha$-particles only
Result for $^{54}$Fe(n,$\alpha$)$^{51}$Cr reaction cross section

Neutron energy, MeV vs Cross section, mb
Result for $^{50}\text{Cr}$

- ENDF/B VII.1
- JENDL - 4.0
- JEFF - 3.1A
- BROND - 3A
- EAF - 2010
- IPPE 2011
- Matsuyama
- JENDL - 3.3
Result for $^{52}\text{Cr}(n,\alpha)^{49}\text{Ti}$ reaction cross section

![Graph showing the cross section for $^{52}\text{Cr}(n,\alpha)^{49}\text{Ti}$ reaction at various neutron energies. The graph includes data from ENDF/B VII.1, JEFF - 3.1A, JENDL - 4.0, BROND - 3A, EAF - 2010, and IPPE 2014. The cross section is plotted in barns against neutron energy in MeV.]
Result for $^{64}$Zn(n,α) and $^{60}$Ni (n,α) reaction cross section

![Graph showing the cross section for $^{64}$Zn(n,α) and $^{60}$Ni (n,α) reaction as a function of neutron energy.](image)
New data for:

1) $^{50}\text{Cr}(n, \alpha)$,
2) $^{52}\text{Cr}(n, \alpha)$,
3) $^{53}\text{Cr}(n, \alpha)$,
4) $^{54}\text{Fe}(n, \alpha)$,
5) $^{57}\text{Fe}(n, \alpha)$,
6) $^{60}\text{Ni}(n, \alpha)$,
7) $^{64}\text{Zn}(n, \alpha)$,

was measured
Parameters of the Tandem accelerator 3MV Tandetron 4130 HC

Voltage: 0.2 - 3.3 MV
Voltage stability: ± 300 V
Vacuum: 4 x 10^{-7} Torr (oil free)

**Pulse regime (hydrogen):**
- Ion energy: - 0.5 - 4 MeV;
- Pulse width: - 2 ns;
- Pulse rate: - 125 kHz - 4 MHz
- Average current: - 4.8 μA (4 MHz)

<table>
<thead>
<tr>
<th>Ion</th>
<th>Current, μA</th>
<th>Max. energy, MeV</th>
<th>Ion</th>
<th>Current, μA</th>
<th>Max. energy, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>^1H(+)</td>
<td>20</td>
<td>6</td>
<td>^31P(3+)</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>^2D(+)</td>
<td>15</td>
<td>6</td>
<td>^28Si(3+)</td>
<td>48</td>
<td>12</td>
</tr>
<tr>
<td>^4He(2+)</td>
<td>4</td>
<td>9</td>
<td>^58Ni(3+)</td>
<td>20</td>
<td>12</td>
</tr>
<tr>
<td>^7Li(2+)</td>
<td>2</td>
<td>9</td>
<td>^56Fe(3+)</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>^11B(3+)</td>
<td>12</td>
<td>12</td>
<td>^63Cu(2+)</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>^12C(3+)</td>
<td>40</td>
<td>12</td>
<td>^75As(2+)</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>^16O(3+)</td>
<td>40</td>
<td>12</td>
<td>^197Au(2+)</td>
<td>20</td>
<td>9</td>
</tr>
</tbody>
</table>
Expected neutron flux

Current 20 μA. Target thickness – 2 mg. Distance from neutron target – 10 cm.
Plane of future investigations.

- Experiments with gaseous targets ($^{16}$O(n,α), $^{14}$N(n,α), $^{14}$N(n,t) и $^{10}$B(n,α)) for neutron energy range from threshold to 9 MeV.
- Prompt neutron spectra for $^{235}$U fission by thermal neutrons (fully digital experiment).
- (n,α) reaction cross section for structural material nuclear (up to 9 MeV).
- Benchmarks. Liking neutron spectra from sphere for californium source and 14 MeV source.
- Fission fragment yield for fast neutrons.
- Ternary fission by fast neutron.
- Elastic and inelastic neutron scattering cross section for structural materials.
Thank you for attention!