Measurements of proton-induced reactions on ruthenium-96 in the Experimental Storage Ring(ESR) at GSI

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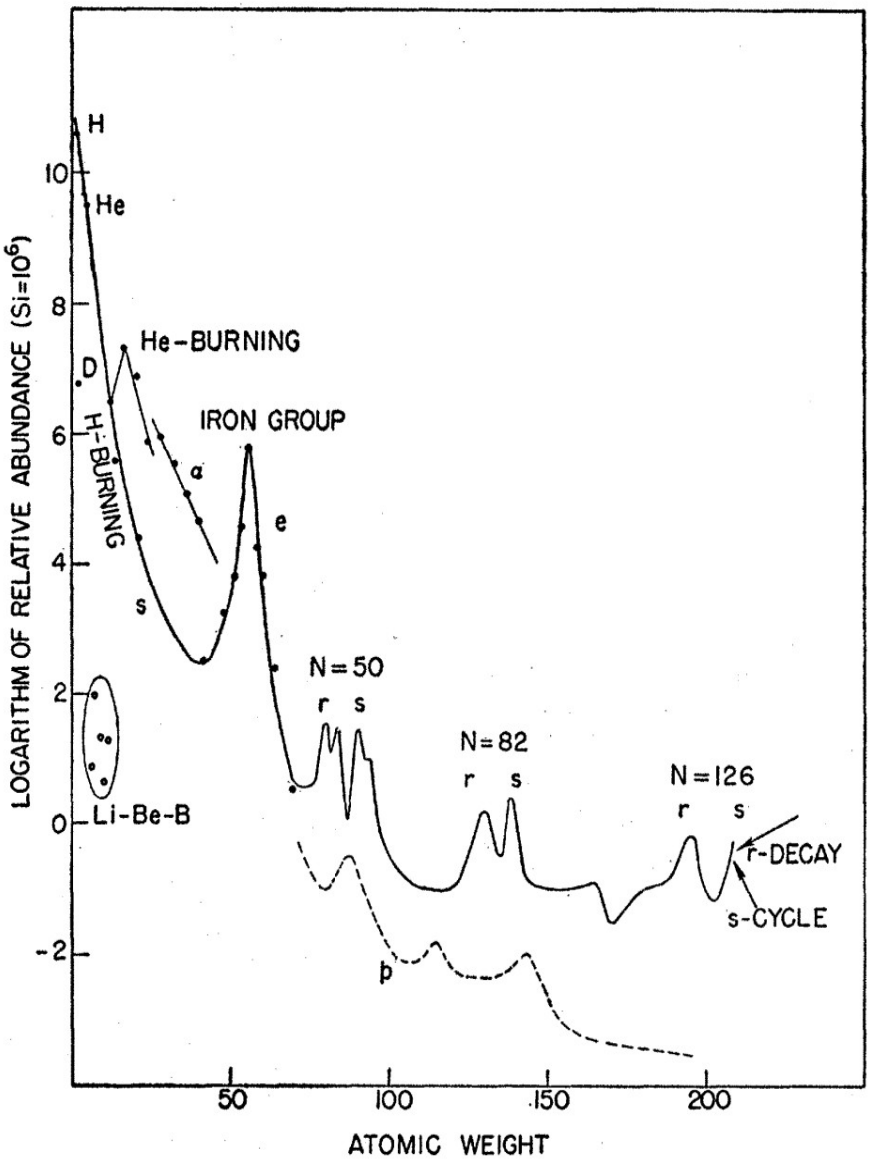
Outlook

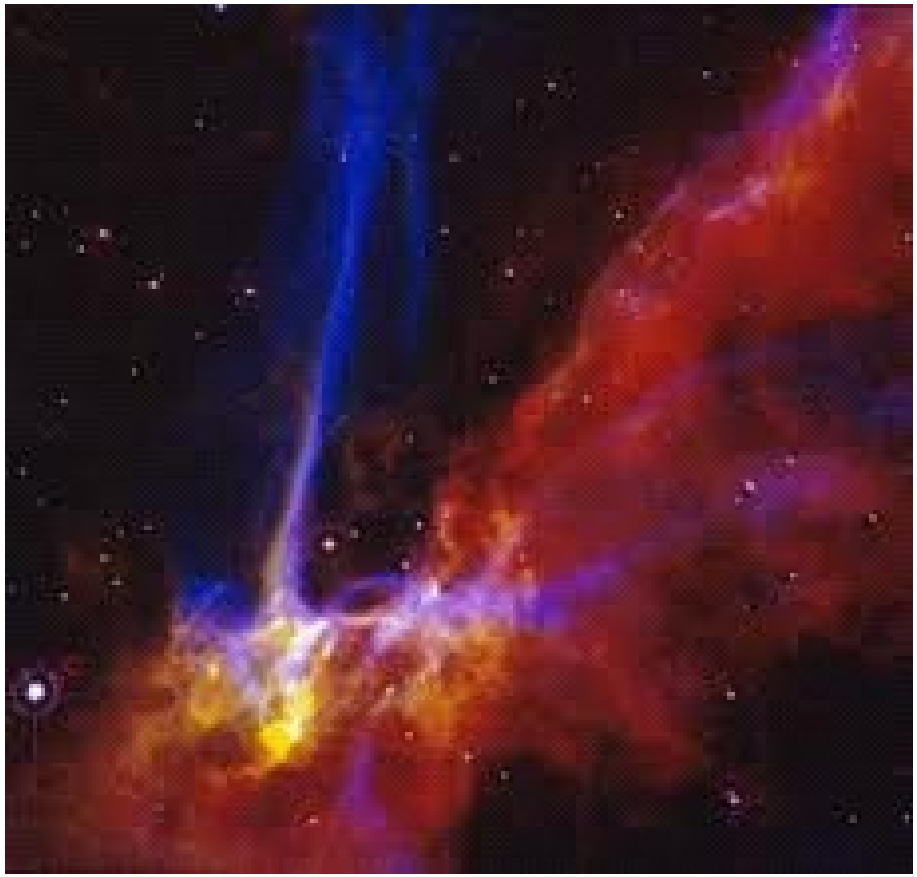
- p-process
- Experimental setup
- Monte-Carlo simulations with Geant4 code
- Analysis results
- Summary

Introduction



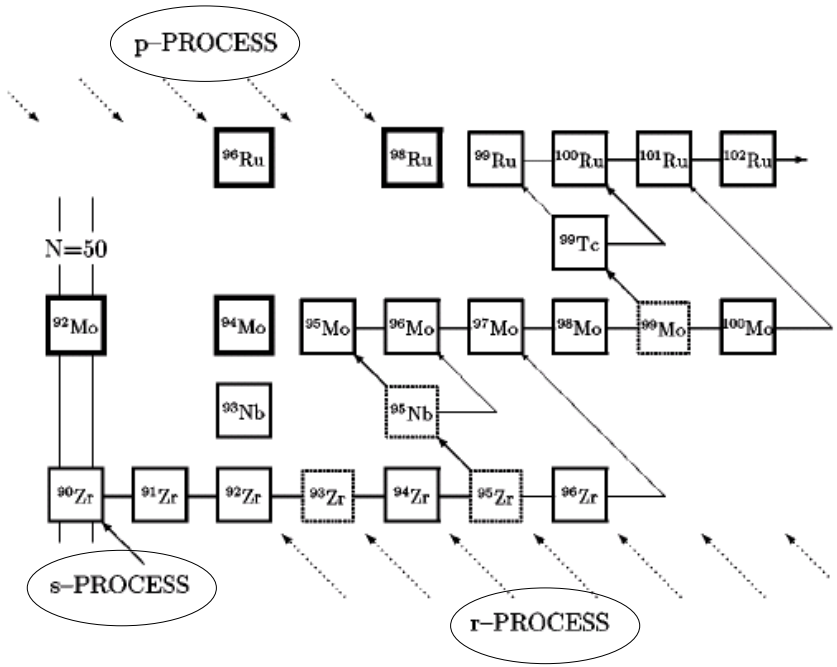
- most of the elements heavier than iron are built in stars via neutron capture in s- or r-processes;
- s(slow)-process with neutron densities in the order of $10^6 \div 10^{11} cm^{-3}$, neutron capture rates slower than β-decay rates;
- r(rapid)-process with neutron density $> 10^{20}$ cm^{-3}, stable nuclides reached through beta decay chains after the neutron capture;
- 35 nuclei from the proton-rich side of the valley of stability are produced by a combination of the (p,γ), (γ, n), (γ,p) and (γ,α) reactions on existing s- or r-nuclei at very high temperatures.

p-process



- to adequately describe p-process need reliable information on the thousands of reaction rates involved;
- the reaction rates based on detailed balance theorem to predict a scenario of p-process;
- p-process appears in supernovae, where (p,γ) and (γ,n) reactions on s- and r-nuclei occurred at high temperatures.

p-process for ruthenium-96

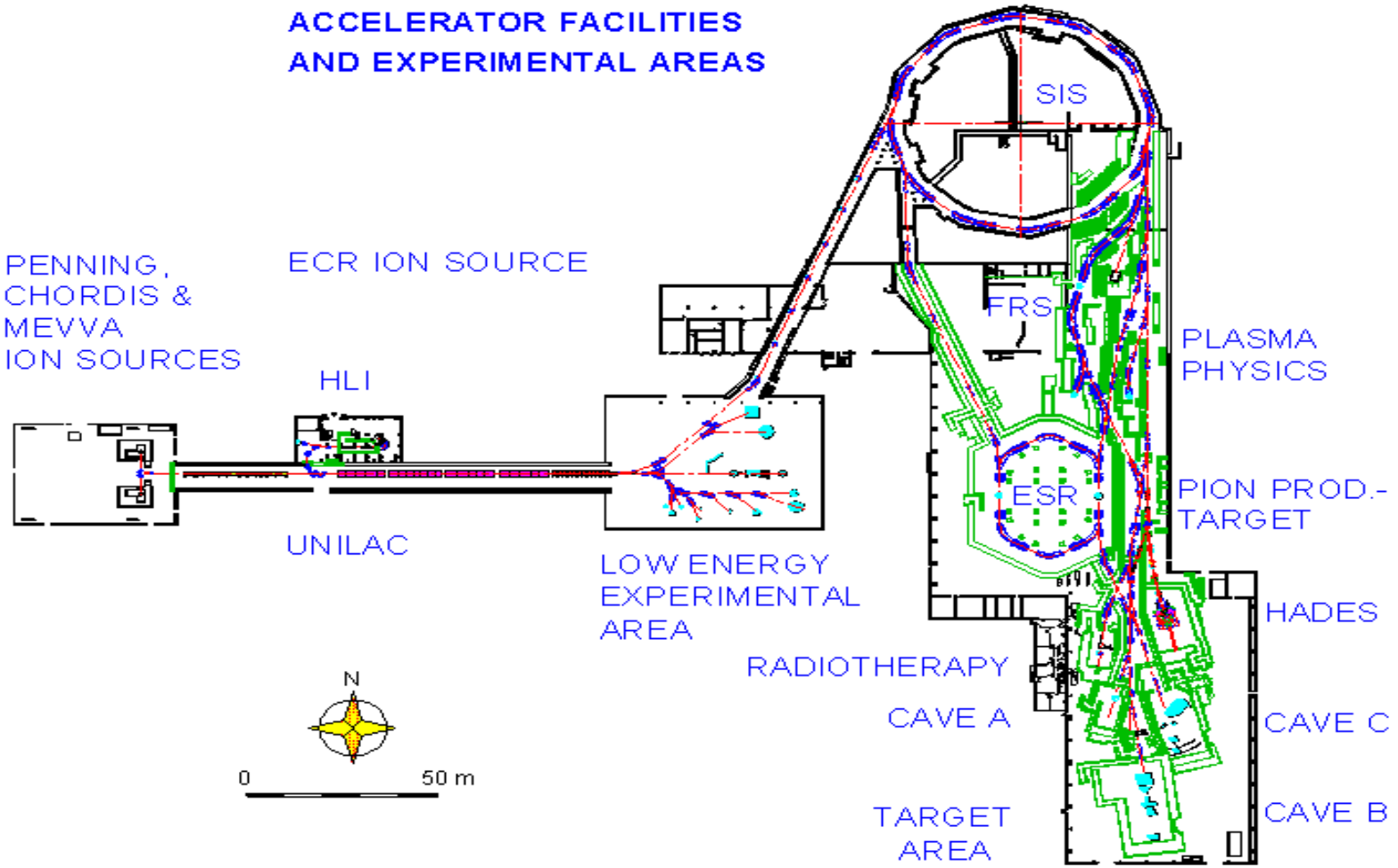


- most p-process nuclides are not known with optimum accuracy;
- the light p-nuclei ^{96}Ru are underproduced in supernovae within a factor of 10, but have rather large isotopic abundance 5.52%.

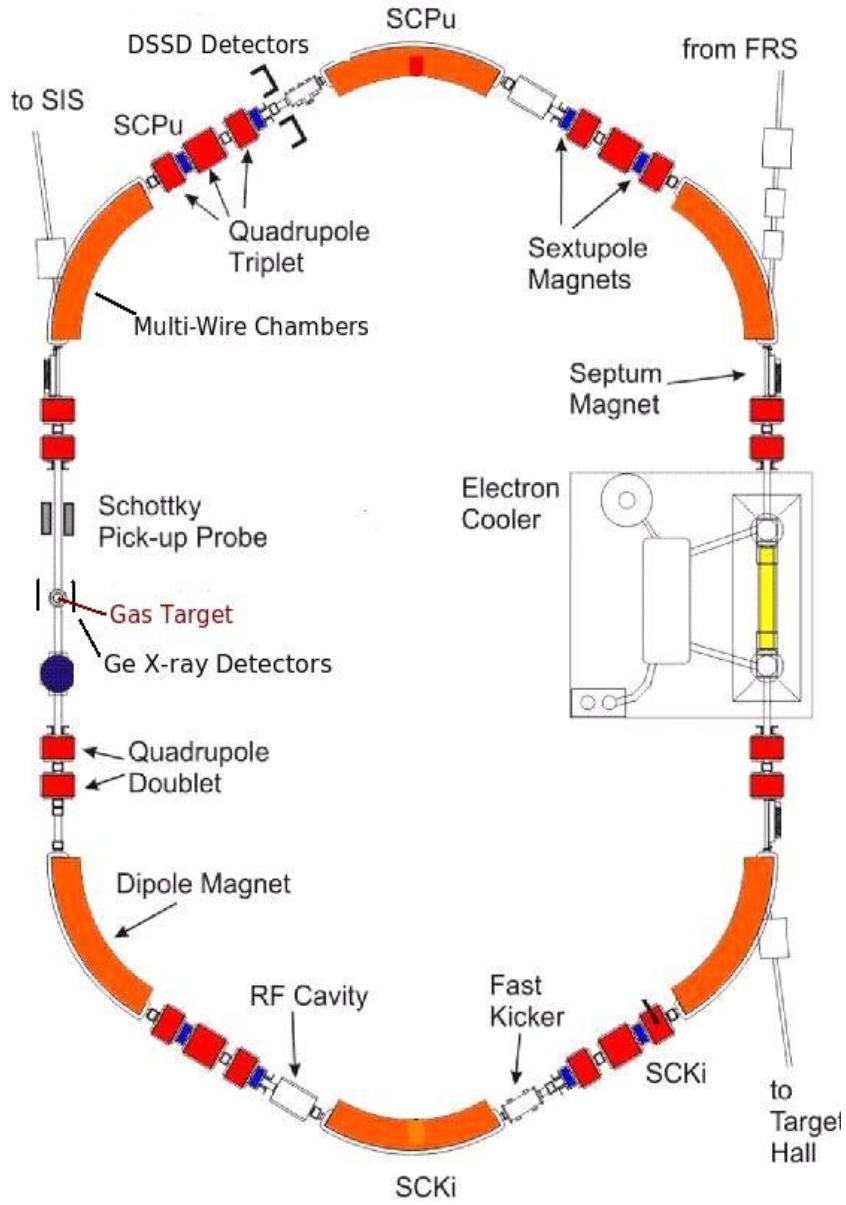
Motivation

- Only a few measurements of the cross-sections are perfomed, mostly in activation experiments.
- Limitation of activation method: need radioactive reaction products and stable samples.
- New experiments in the Experimental Storage Ring (ESR) with circulating heavy ion beams.
- Not limited as experiments using an activation technique.
- The purpose is to compare results measured with activation method and to explore the possibilities of a new method for measuring the same reactions with a short-lived isotopes and stable reaction products.
- Test case: $^{96}Ru(p,\gamma)^{97}Rh$.

Experimental setup at GSI

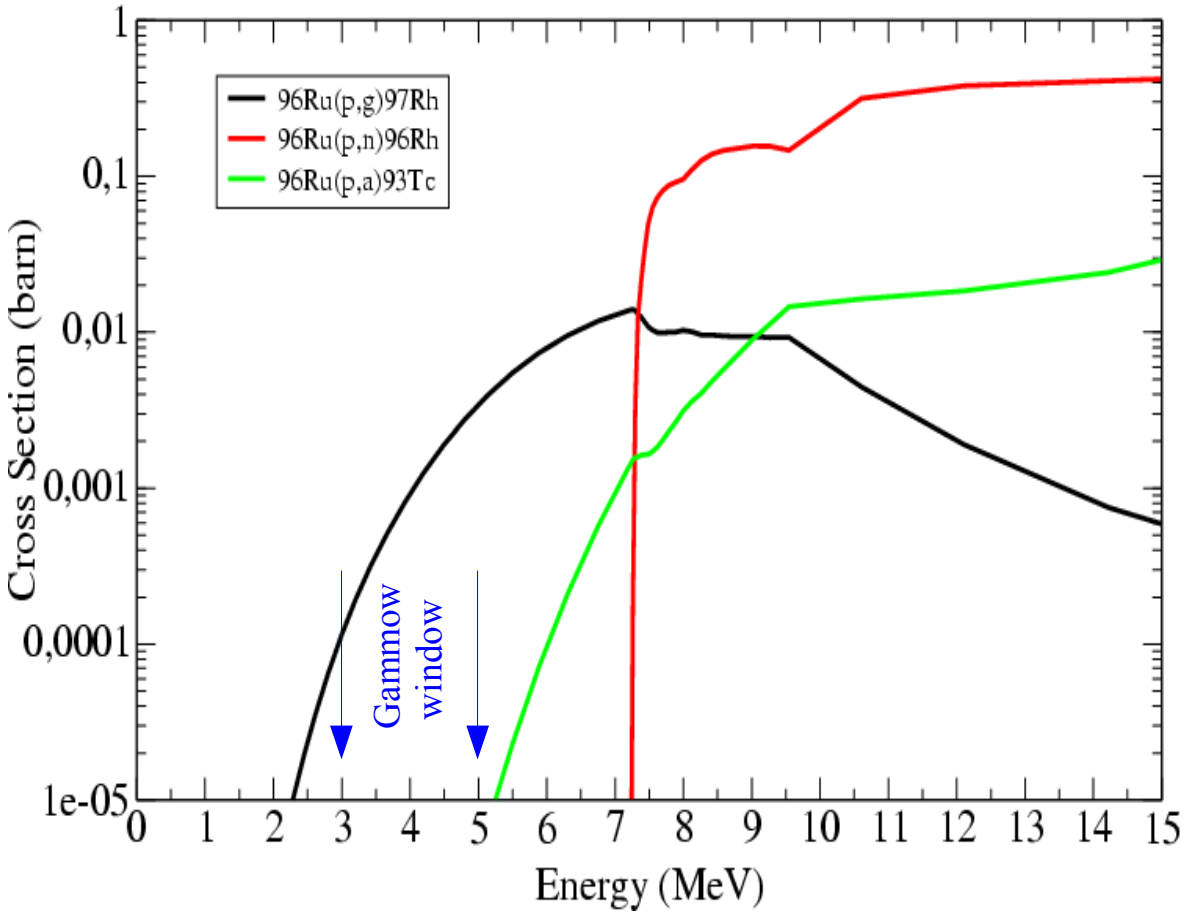


Electron Storage Ring at GSI



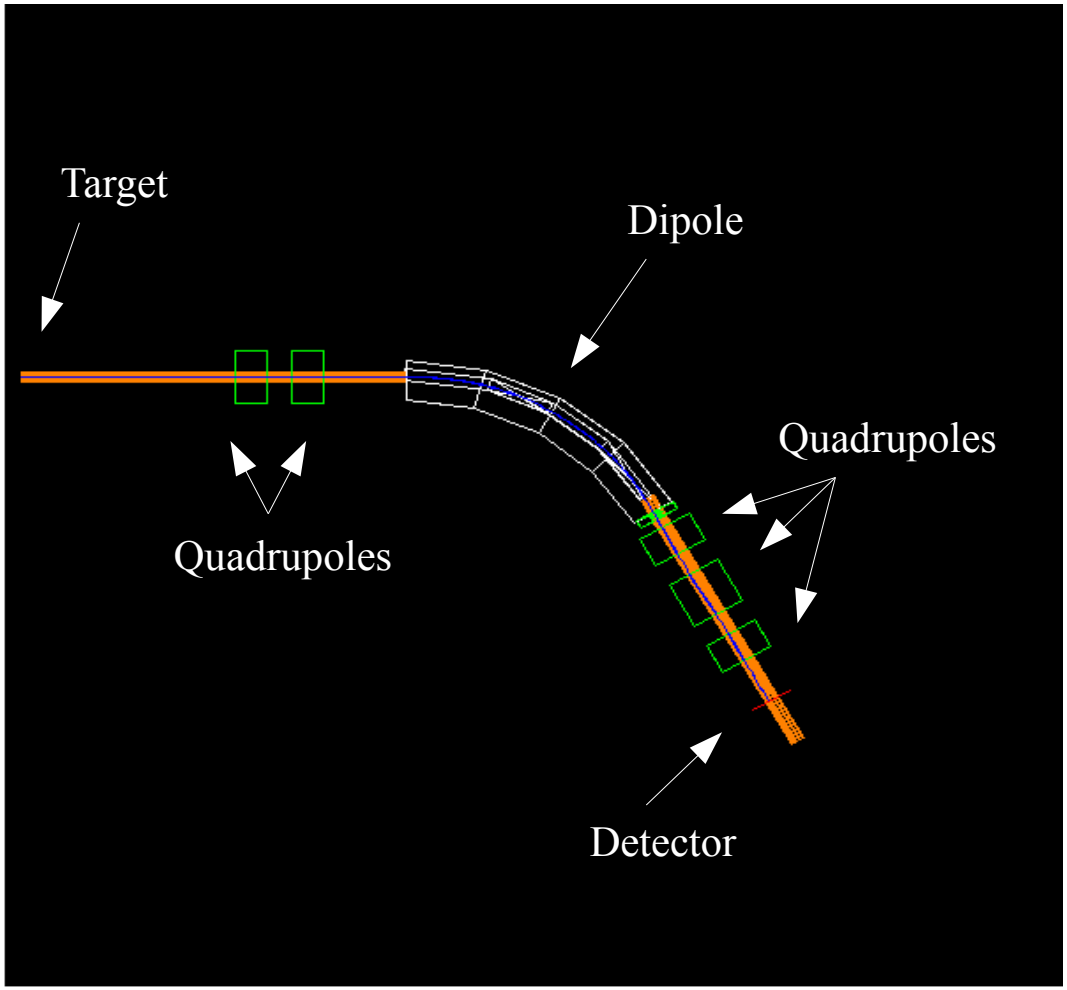
- experiment with ^{96}Ru beam at 9-11 MeV and a hydrogen target;
- products of the ^{96}Ru(p,γ) reaction were detected by 2 Double Sided Silicon Strip Detectors (DSSD);
- Multiwire Proportional Chamber detected electron pick-up reaction;
- X-ray detectors detected the emitted X-rays.

Theoretical cross-section



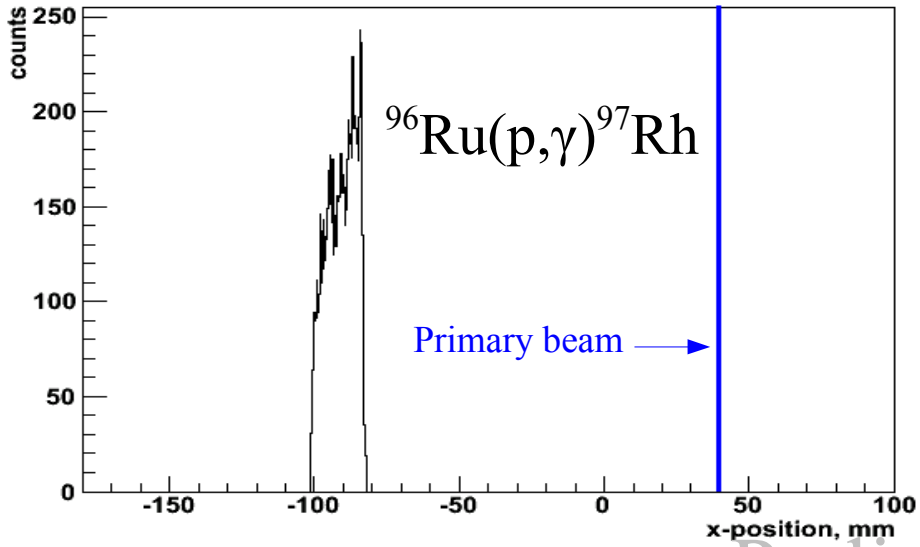
- gammow window from 3 to 5 MeV – area of astrophysical interest, where the nuclear reactions occur in stars;
- at energies 9, 10 and 11 MeV not only (p,γ) component is important, also components from (p,n) , (p,α) , (p,p) reactions appear.

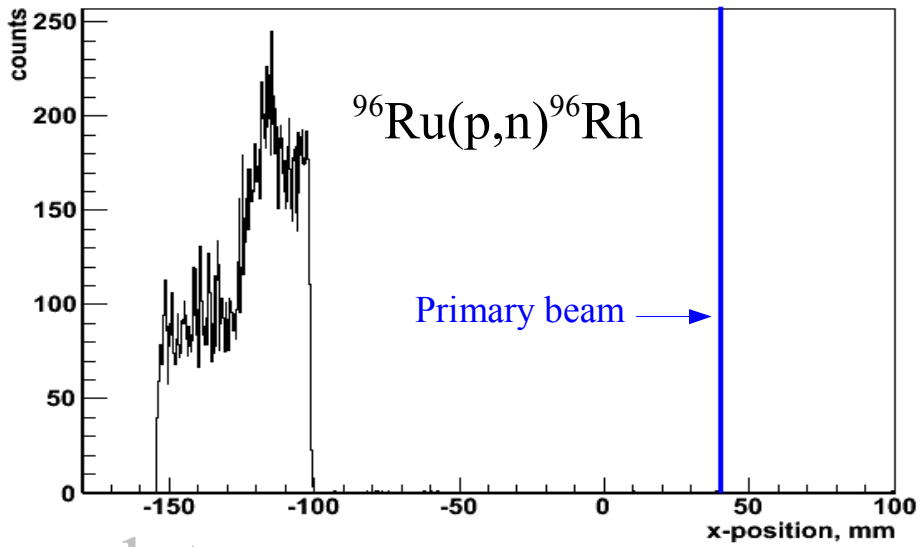
Monte-Carlo simulations using Geant4 code



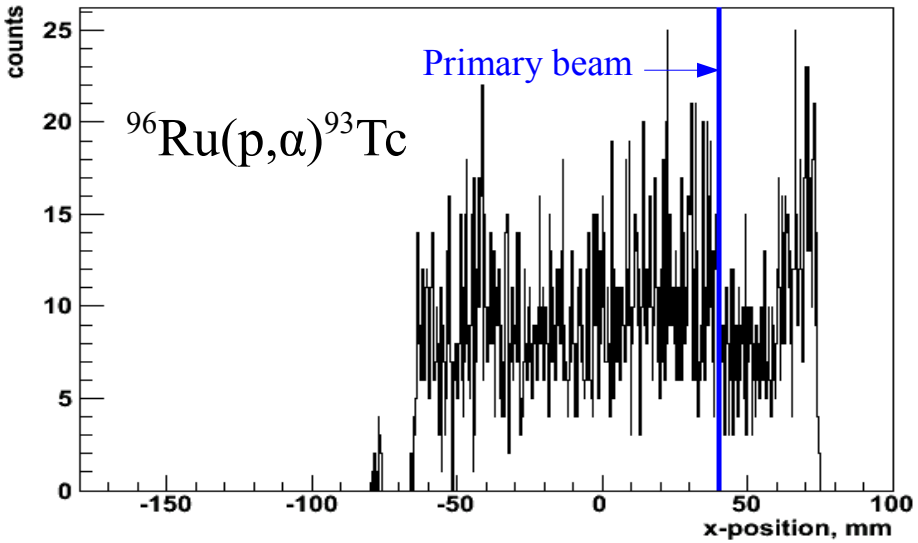
- describe the part of ESR from H_2-target to silicon detectors;
- simulate track of secondary particles through the experimental setup;
- sensitive to the beam position;
- calculate particles momentum.

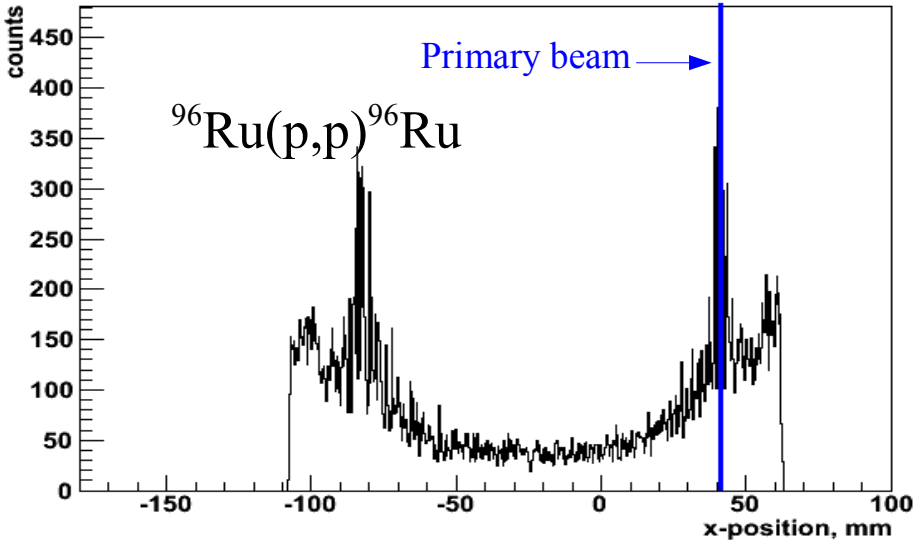
Nuclear reaction channels of proton-induced reactions on ruthenium-96 isotopes





Preliminary data





Cross-section definition

Measurement of ^{96}Ru(p,γ) cross section relative to the ^{96}Ru e- pick up cross section:

$$Z = \sigma * N * \Phi * t$$

Z – quantity of nuclei, produced in reaction (peak area),
σ - cross section,
N - quantity of target nuclei/area,
Φ - quantity of incoming particles (flux),
t - time of measurement.

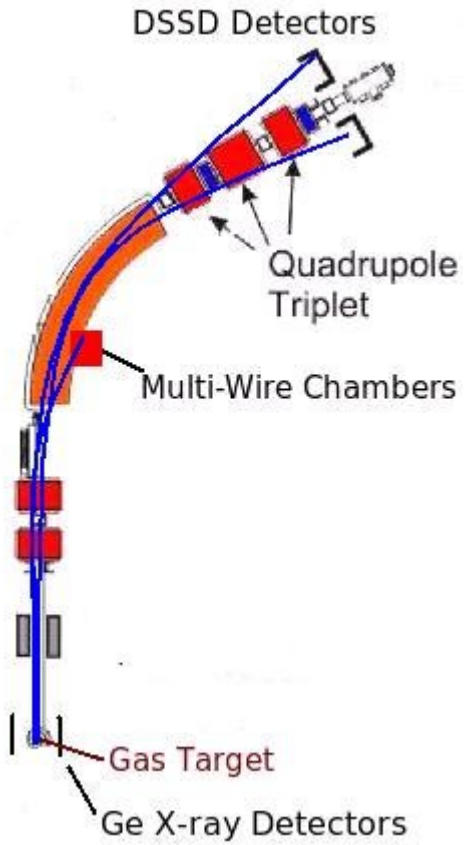
Cross section of electron capture:

$$\sigma_{ec} = Z_{ec} / (N*\Phi)*t,$$

$$N*\Phi = Z_{ec} /(\sigma_{ec} *t)$$

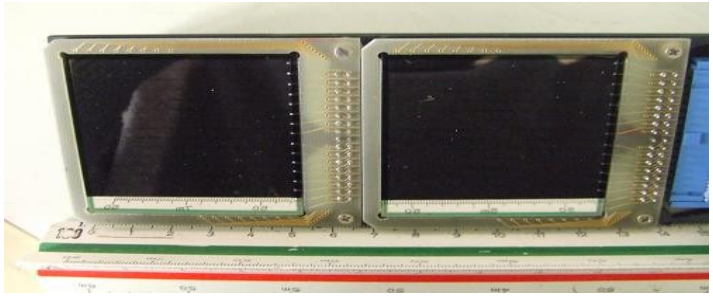
Reaction cross section:

$$\sigma_{p\gamma} = (Z_{p\gamma} *\sigma_{ec})/Z_{ec}$$

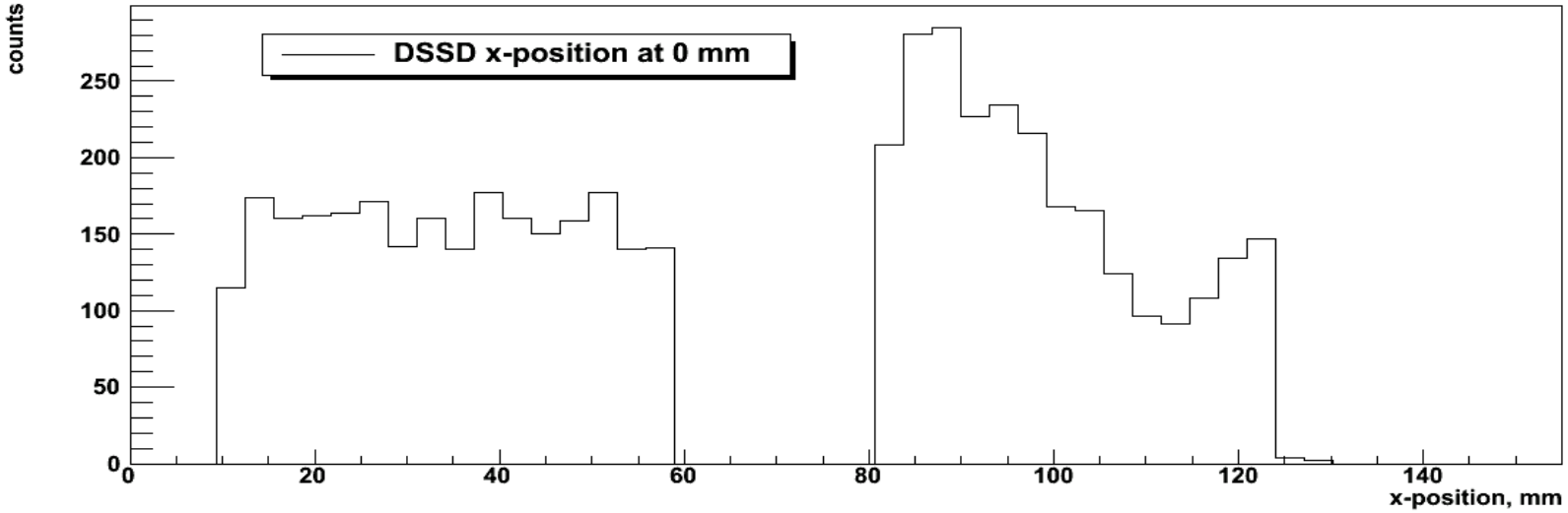


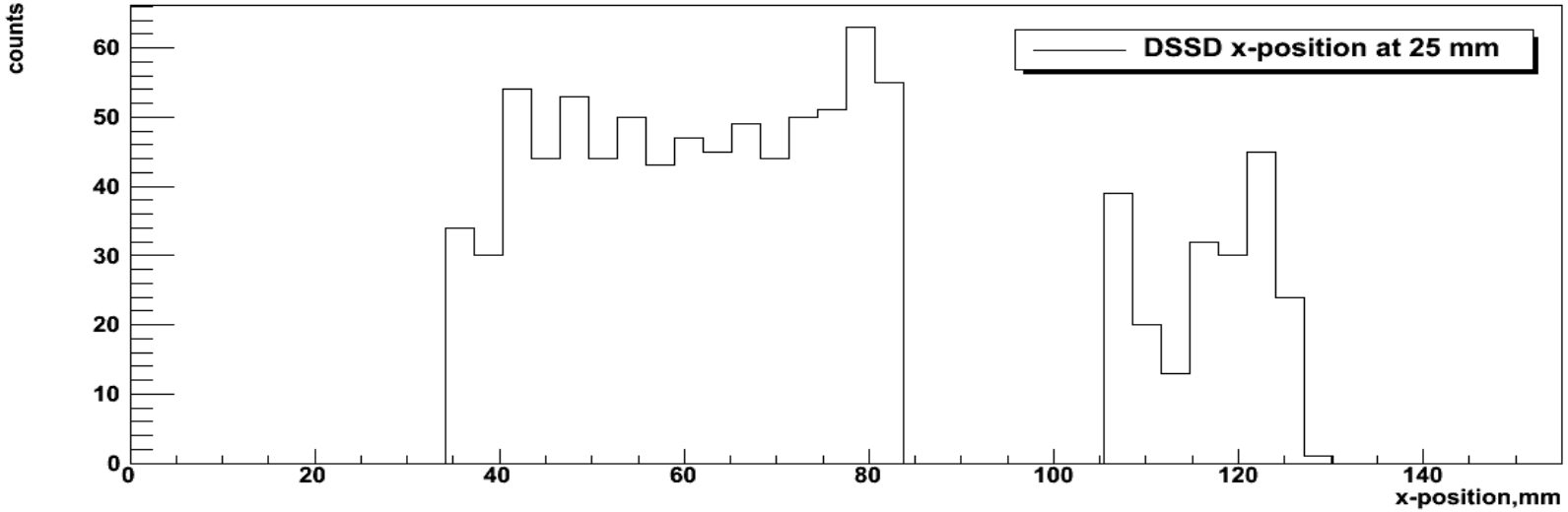
Double Sided Silicon Strip Detectors

- 2 silicon detectors for measuring position of reaction products;
- the distance between detectors was 21 mm;
- each detector had 16 strips in X- and Y-direction;
- strip pitch = 3.0 mm, strip length = 49.5 mm;
- the detection efficiency for (p,γ) events was about 100%;
- possibilities to get the full view of particles position spectrum by moving detector from 0 to 25 mm from the beam-line.

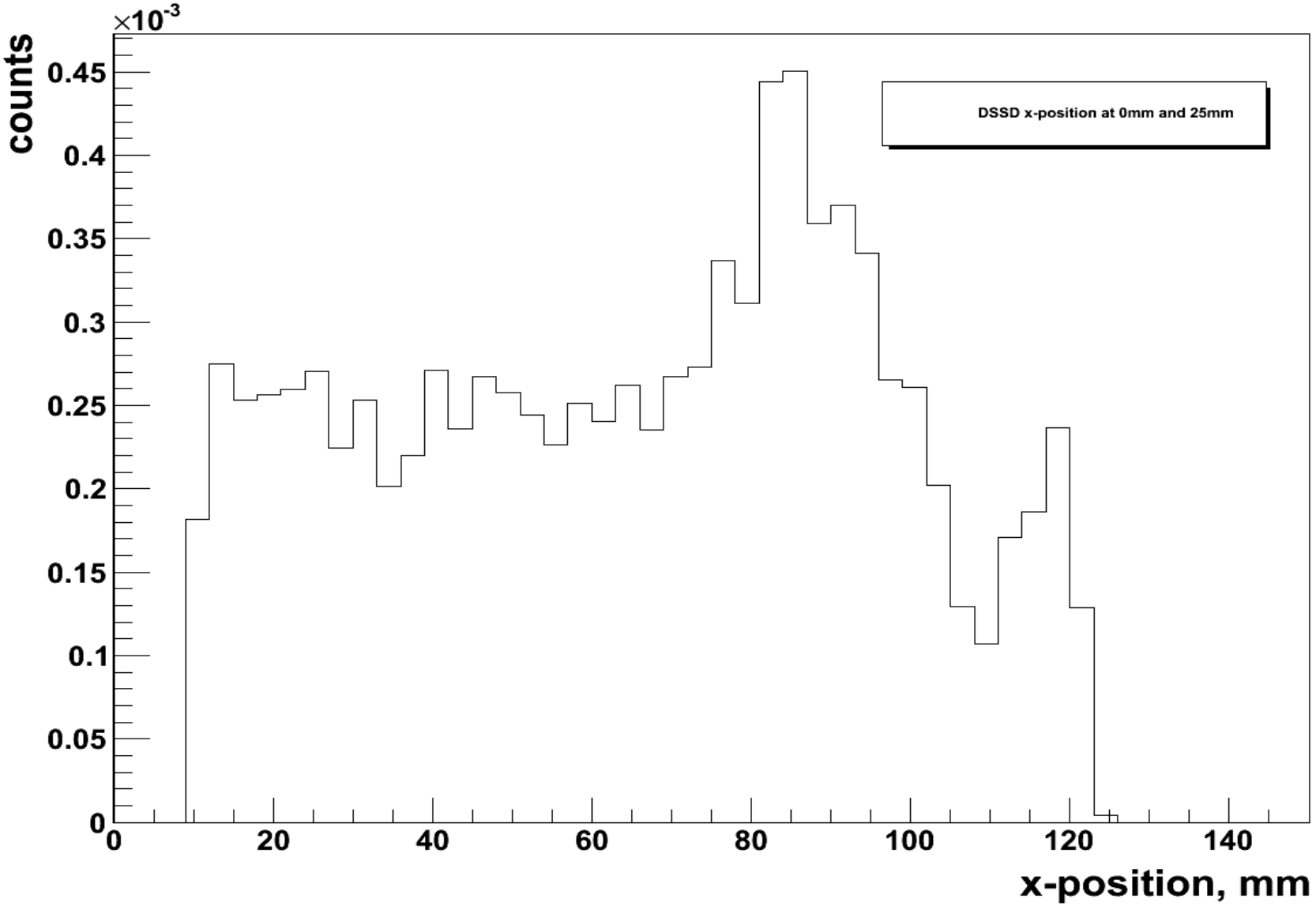


Position of secondary particles on silicon detectors at 0 and 25 mm

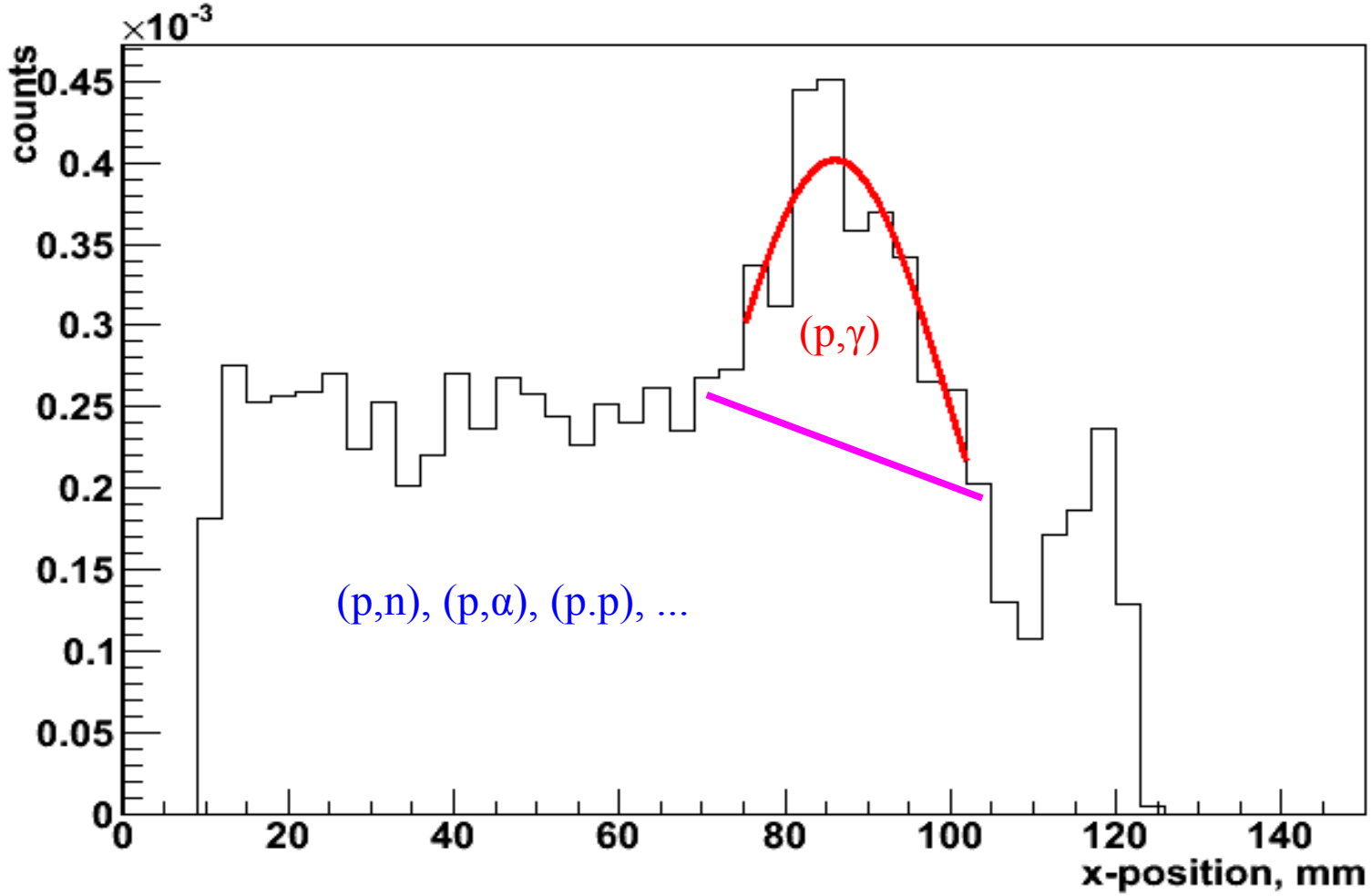




Combined DSSD position at 0 and 25 mm



Comparison results of simulation and analysis



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Cross section of electron capture:

$$\sigma_{ec} = Z_{ec} / (N*\Phi)*t,$$

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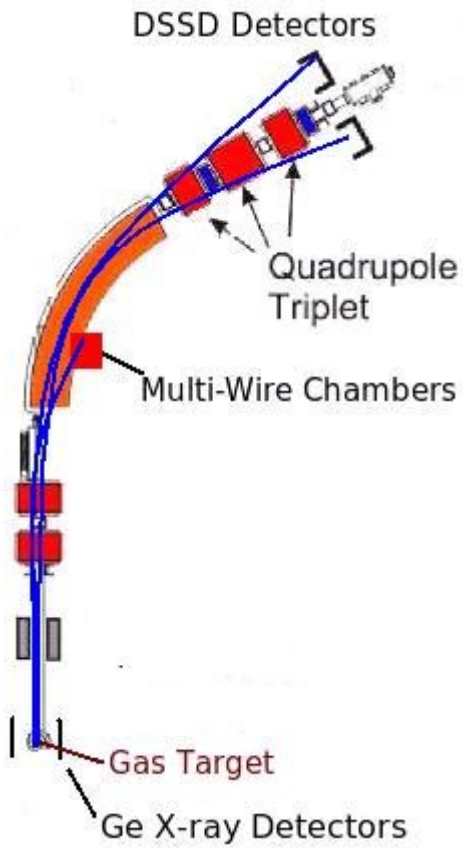
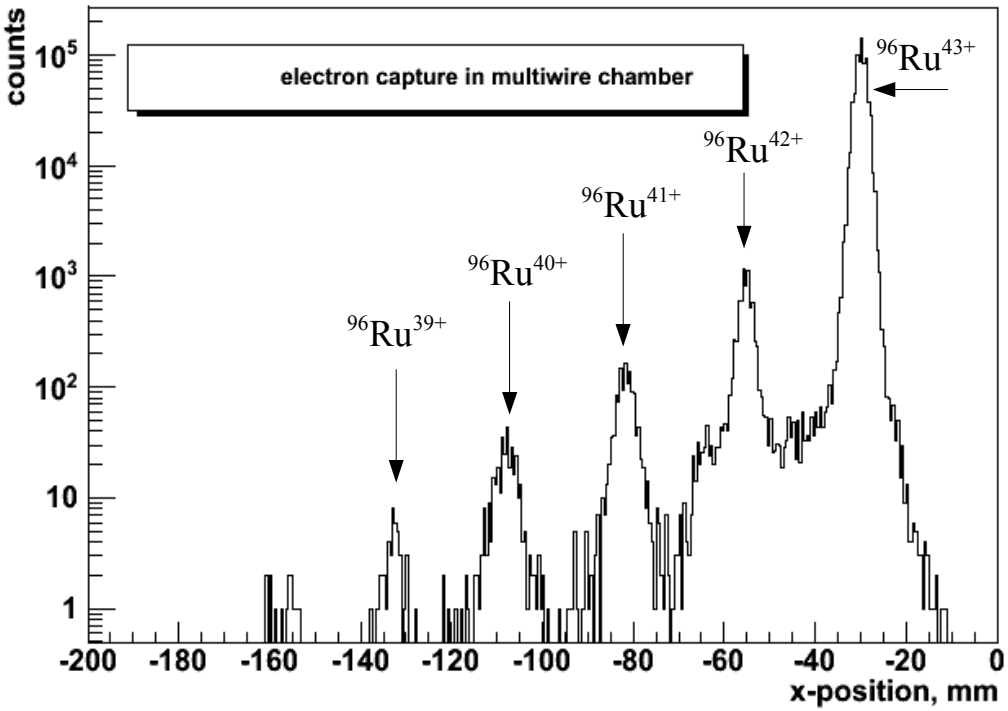
Reaction cross section:

$$\sigma_{p\gamma} = (Z_{p\gamma} *\sigma_{ec})/Z_{ec}$$



Multiwire chambers



- used for electron pick-up reactions;
- measured secondary particles position;
- able to handle the high flux of down charged ions from cooled heavy- ion beams;
- have efficiency close to 100%;
- particle position does not depend on the angle of incidence of the particle;
- have a good time resolution.

Preliminary result of cross-section

Preliminary result of cross section for $^{96}Ru(p,\gamma)^{97}Rh$ reaction:

$$\sigma_{p\gamma} = 1.5 \div 3.5 \text{ mb}$$

Summary

- Simulations with Geant4 code showed particles track through the experimental setup and made a good prediction of the shape for all nuclear components.
- Comparison of simulated $^{96}Ru(p,\gamma)^{97}Rh$ position spectrum and experimental results are in good agreement.
- Preliminary results of cross-section have been shown.
- Analysis of this experiment are in a progress.
- Future plans are to place detector at the end of the first dipole after the gas target for registration all nuclear reactions components.
- Detector installation in vacuum inside of the ESR.

Acknowledgements

E062 collaboration:

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