# Energy Depedence of the $^{nat}U(n,f)$, $^{nat}U(n,\gamma)$ and Co(n,x) Reaction Rates in the Volume of QUINTA Setup Irradiated by 1-4 AGeV Deuterons and $^{12}C$ Ions


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# Contents

# International collaboration “Energy+Transmutation RAW”
# Main purposes of the project «E and T – RAW»

Determination of optimum energy and type of particles (protons - deuterons).

The study of the processes of the neutron formation and the spatial distribution of neutron spectra.

Determination of dependence of the beam power amplification on energy of the incident protons and deuterons.

Determination of the spatial distribution of dynamic of production destruction (fission) $^{239}Pu$ depending on its concentration and determination its equilibrium concentration.

Determination of the reaction rate of processing the most relevant isotopes from the spent nuclear fuel.

Obtaining a set of experimental data for modifying existing models and transport codes.

# Main purposes

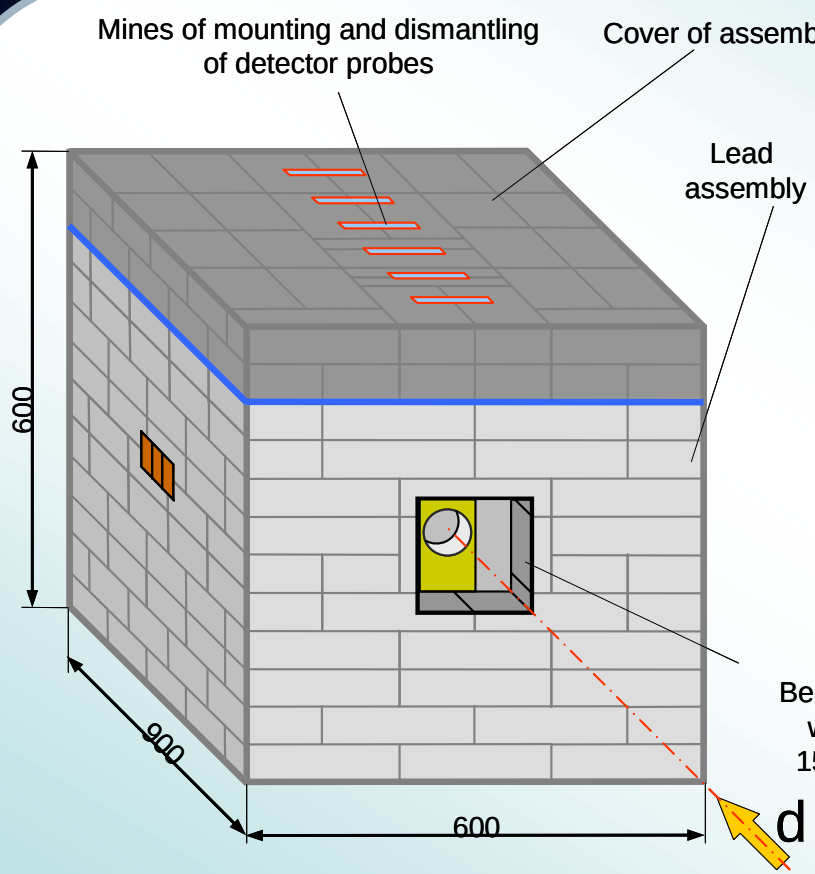
to perform the monitoring of deuteron and $^{12}C$ ion beam;

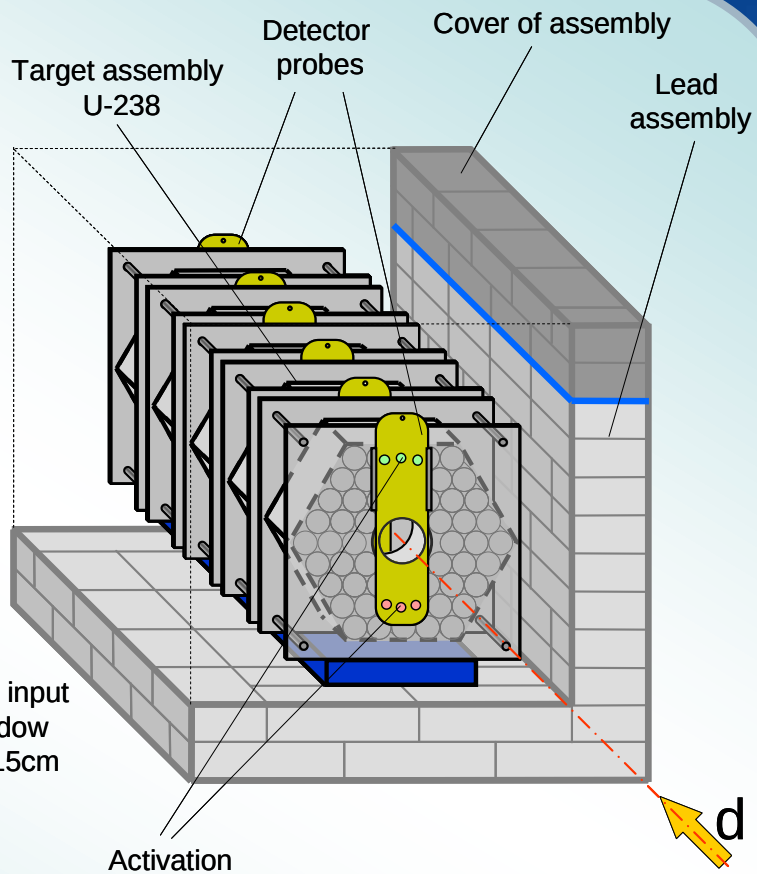
to obtain spatial distributions of density of radiative capture reactions (the number of accumulating $^{239}Pu$ nuclei) and density of $^{238}U$ fissions in the volume of uranium target of assembly "QUINTA";

to obtain spatial distribution of spectral indices;

to compare obtained experimental results in dependence on the energy of deuteron beam and type of particles (per unit of beam power).

# Experimental assembly “QUINTA”



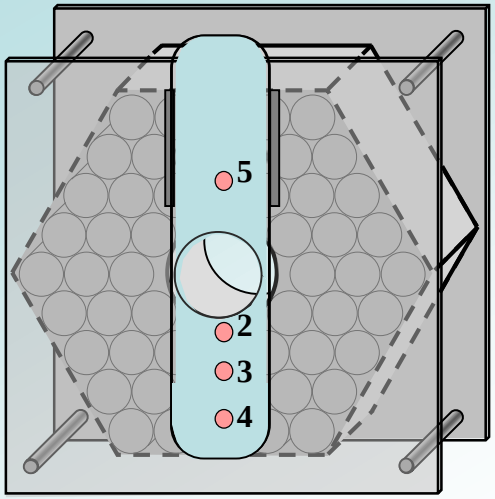

$m_{\Sigma} \approx 3100$ kg

$m_{Pb} \approx 2545$ kg

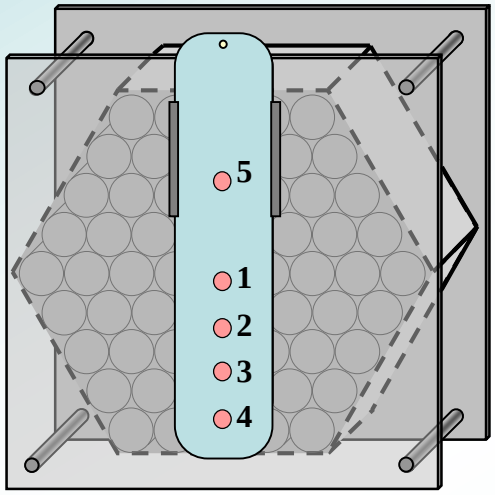
$m_{U} \approx 512$ kg

# Location of detectors on the plate

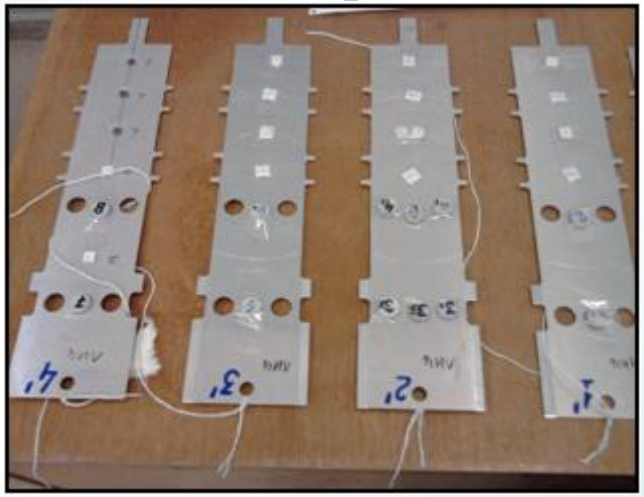
**Section № 1**

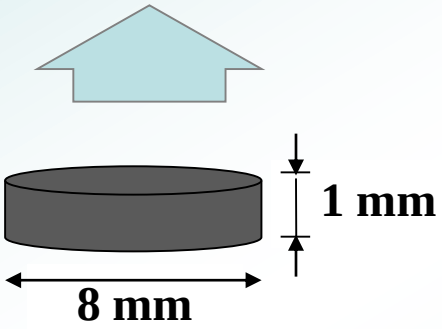



**Sections № 2,3,4,5**




**Detector plates**

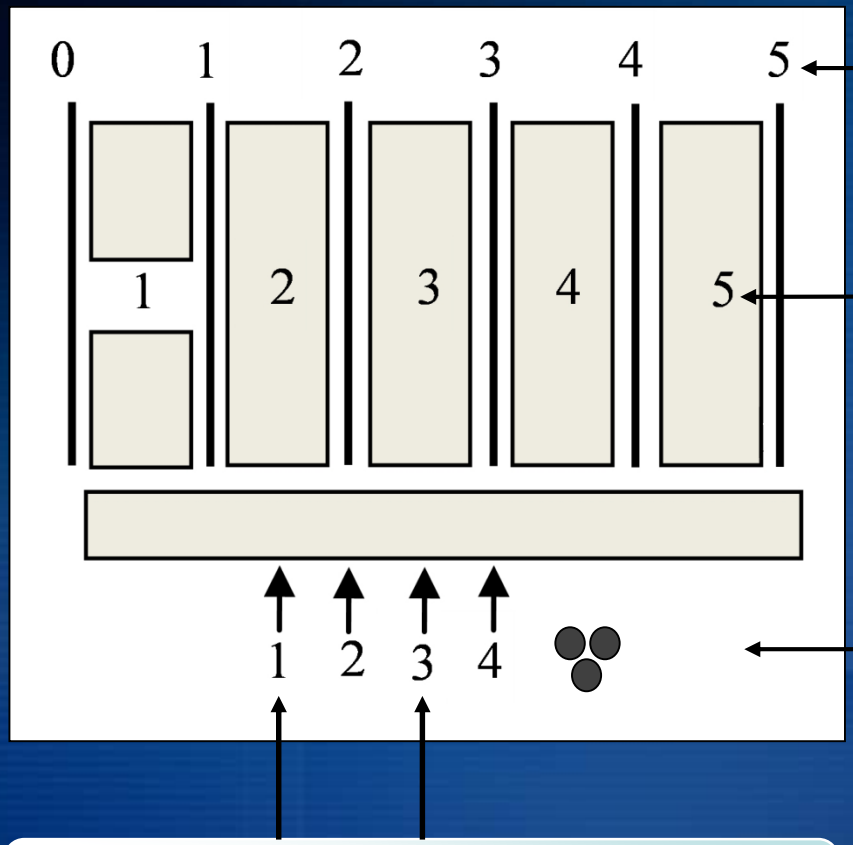





| | | | | | |
|---|---|---|---|---|---|
| 0 plate | - | - | -40 | -80 | -120 |
| 1 plate | - | 0 | -40 | -80 | -120 |
| 2 plate | +80 | 0 | -40 | -80 | -120 |
| 3 plate. | | 0 | -40 | -80 | -120 |
| 4 plate. | +80 | 0 | -40 | -80 | -120 |
| 5 plate. | - | 0 | -40 | -80 | -120 |

- **5** R = -80 mm
- **1** R = 0
- **2** R = 40 mm
- **3** R = 80 mm
- **4** R = 120 mm

# QUINTA with detector plates



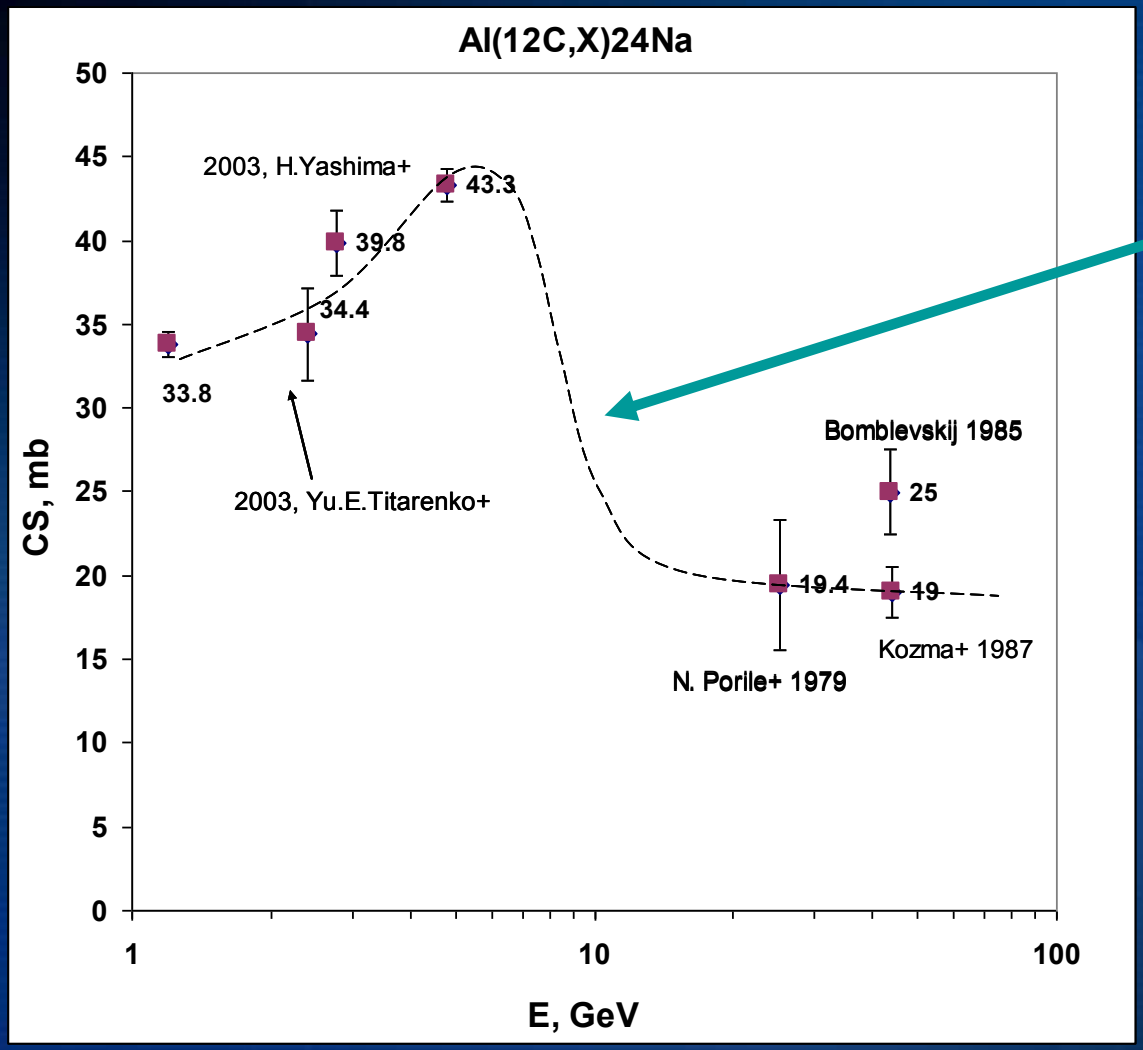

№ of plate

№ of section

№ of uranium foils (3 pieces glued together), placed on the QUINTA outside on Pb

thin-film breakdown counters

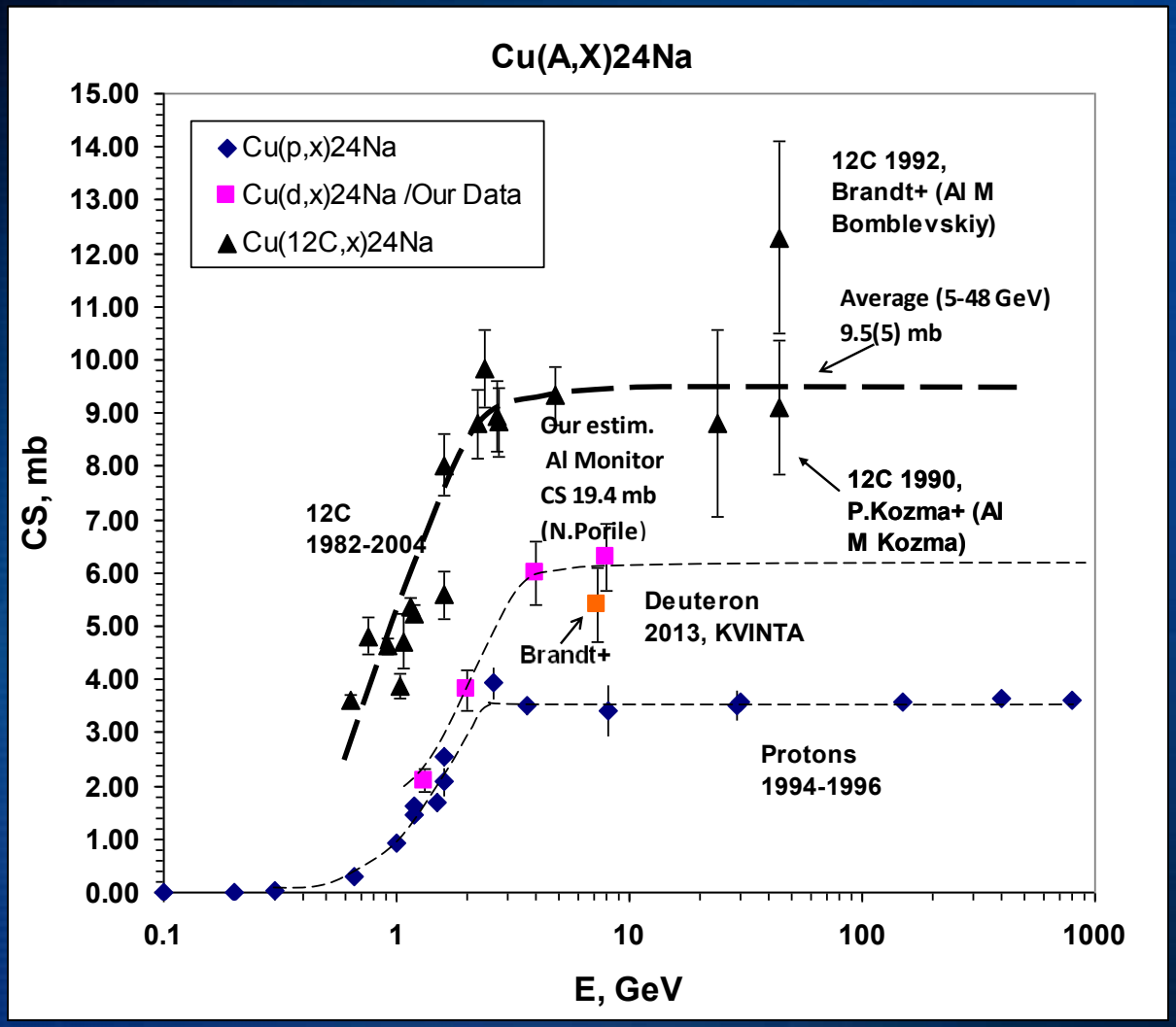
# Cross section of the reaction $Al(^{12}C,X)^{24}Na$




???

$Al(n,\alpha)^{24}Na$

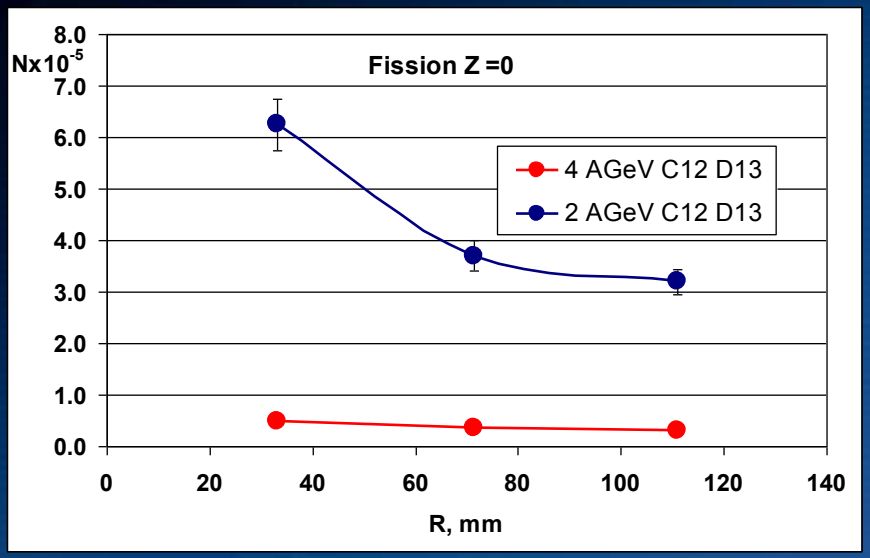
# Cross section of the reaction Cu(A,X)$^{24}$Na

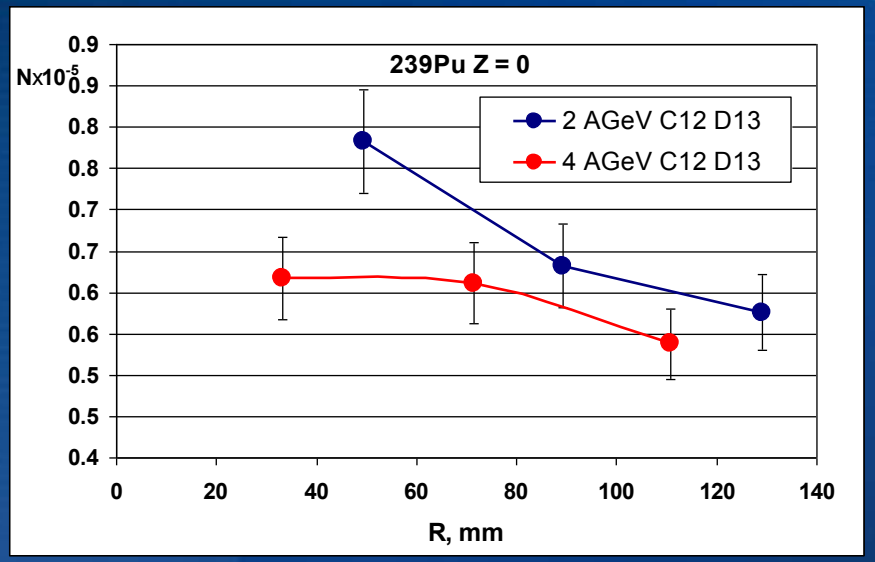


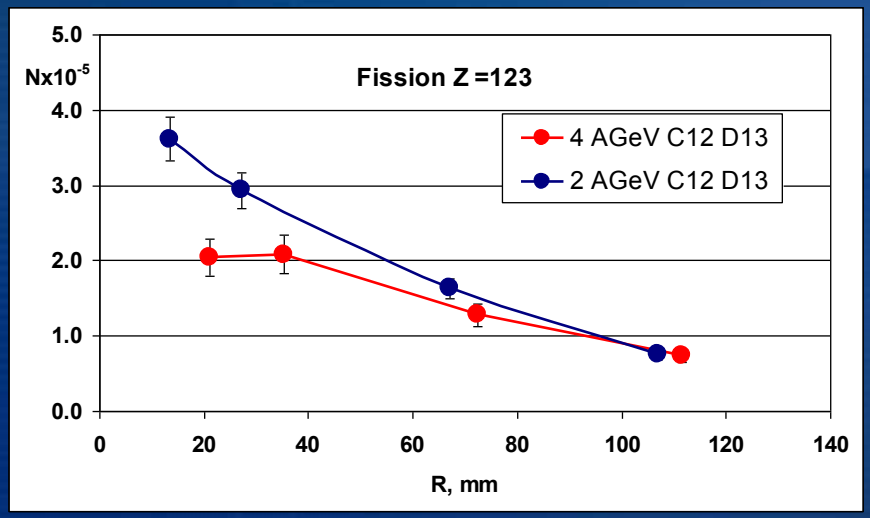
# Total intensities

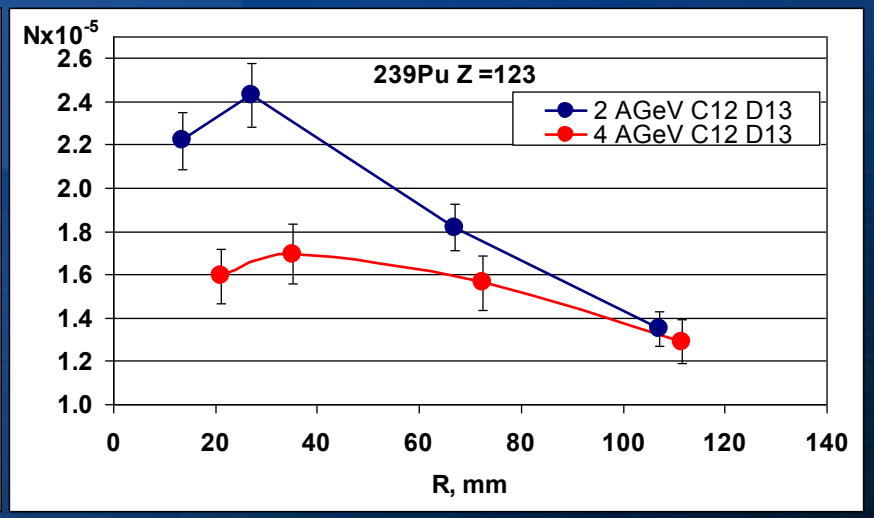
| | Energy, GeV/A | Intensity |
|---|---|---|
| **Deuterons** | 2 | **$2.16 \cdot 10^{13}$** |
| | 4 | **$6.11 \cdot 10^{12}$** |
| **$^{12}C$** | 2 | **$2.14 \cdot 10^{11}$** |
| | 4 | **$6.18 \cdot 10^{10}$** |

# Radial distributions of density of $^{nat}U(n,f)$ and $^{238}U(n,\gamma)$ reactions per 1 gram, 1 nucleus $^{12}C$ and 1 GeV at Z = 0 mm and Z = 123 mm

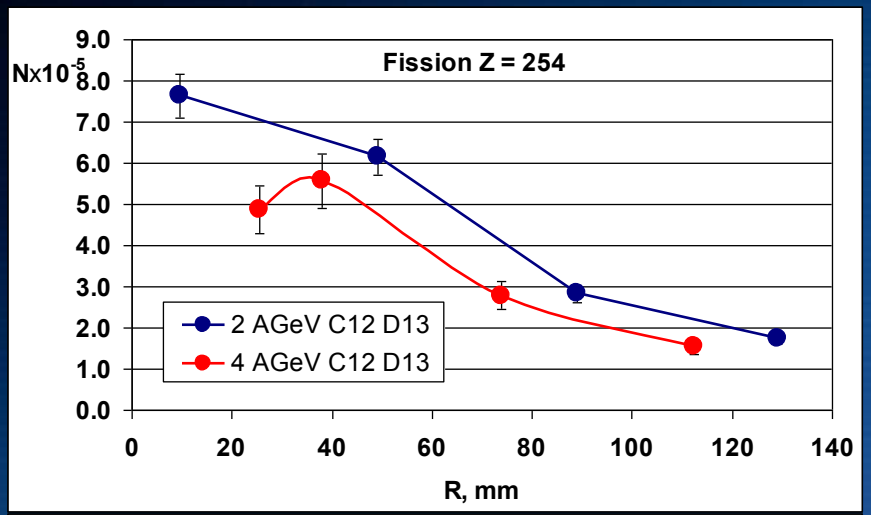


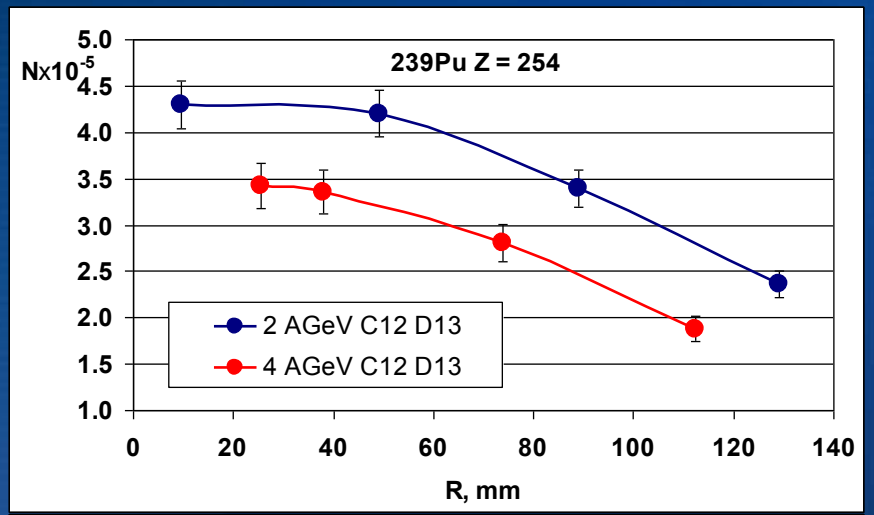



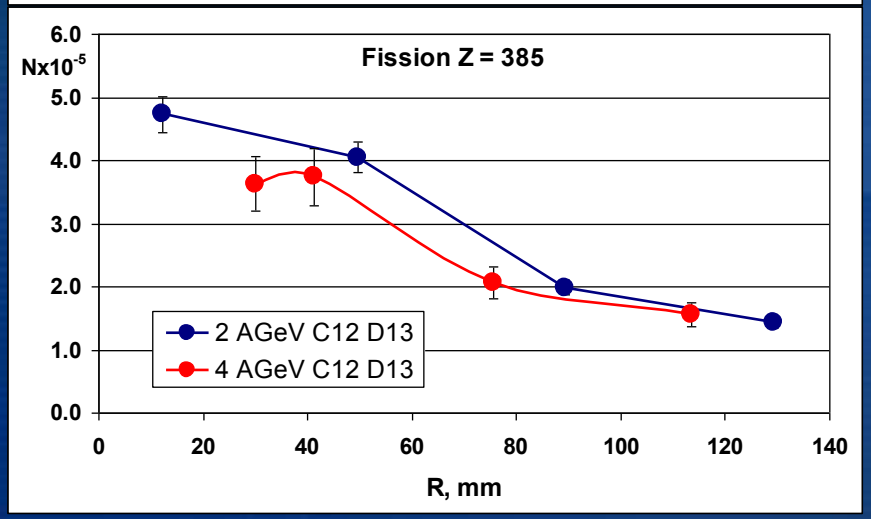



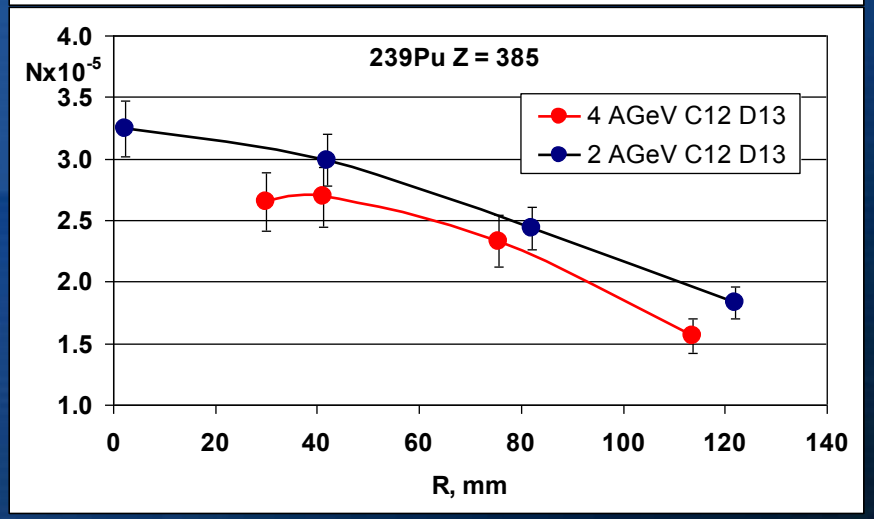



# Radial distributions of density of $^{nat}U(n,f)$ and $^{238}U(n,\gamma)$ reactions per 1 gram, 1 nucleus $^{12}C$ and 1 GeV at Z = 254 mm and Z = 385 mm

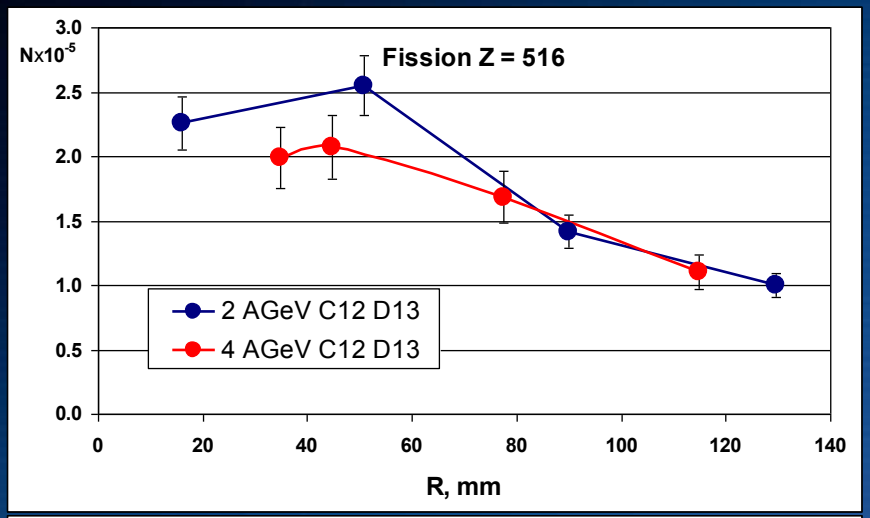


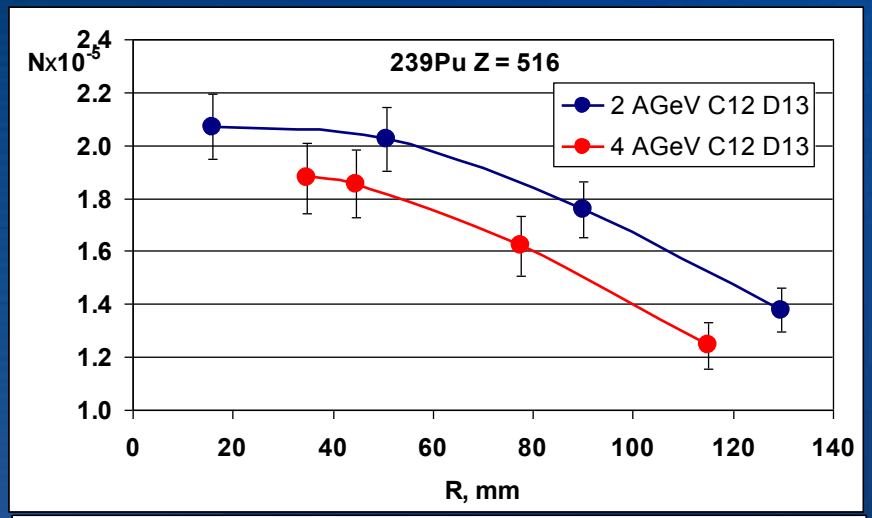



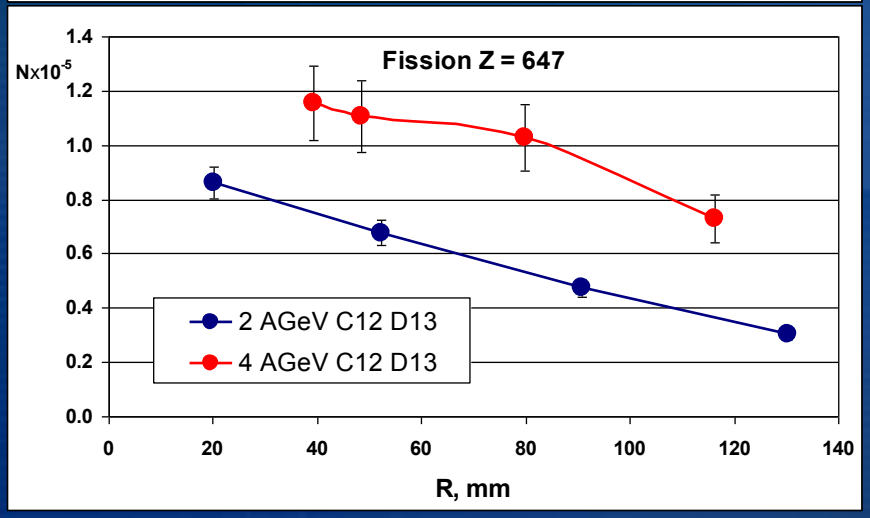



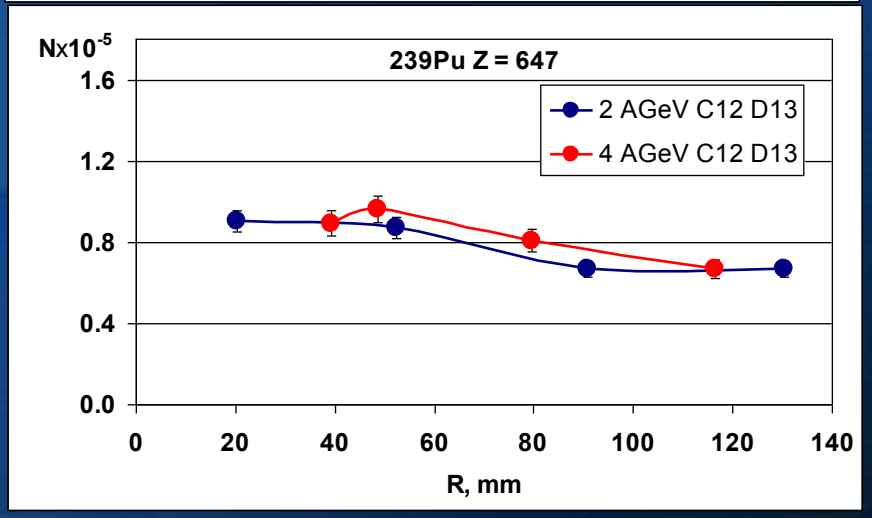



# Radial distributions of density of $^{nat}U(n,f)$ and $^{238}U(n,\gamma)$ reactions per 1 gram, 1 nucleus $^{12}C$ and 1 GeV at Z = 516 mm and Z = 647 mm

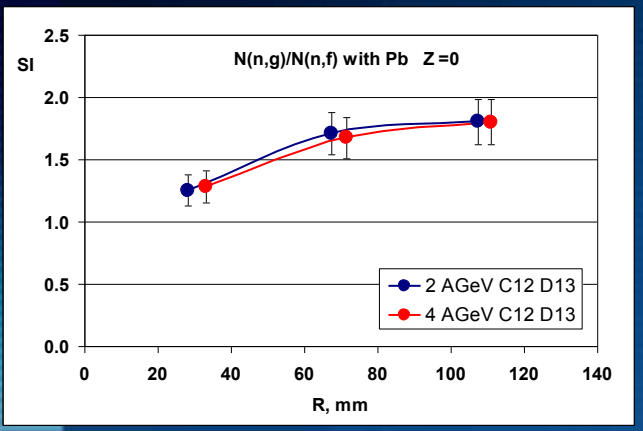


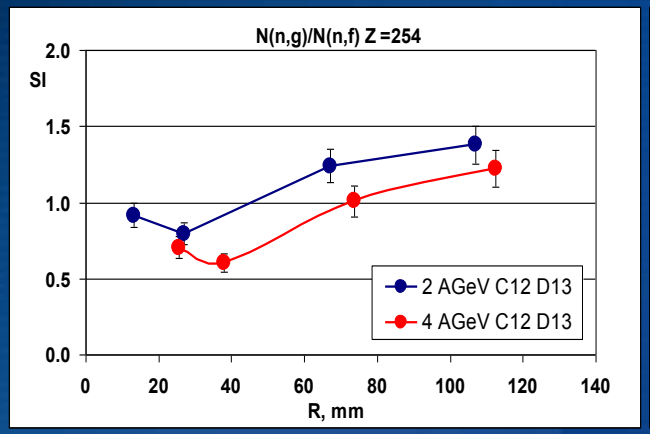



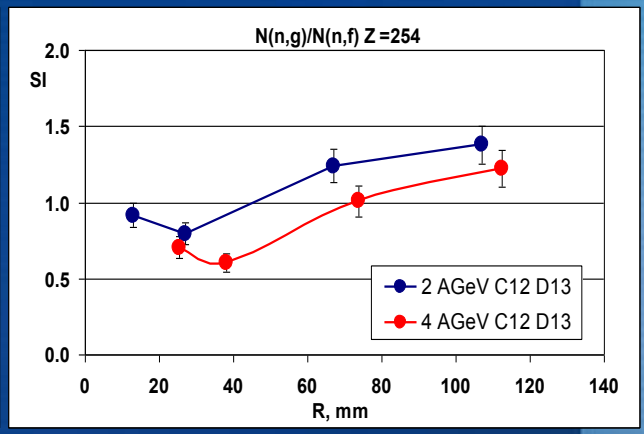



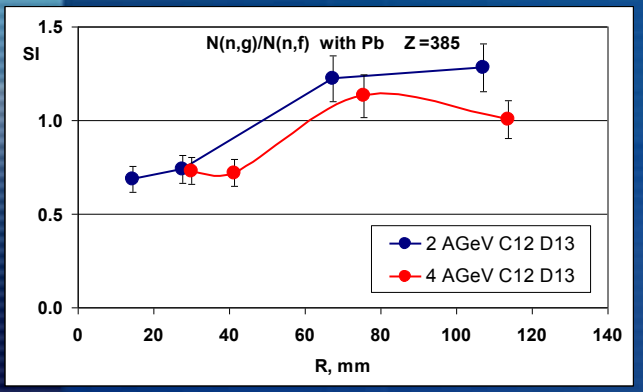



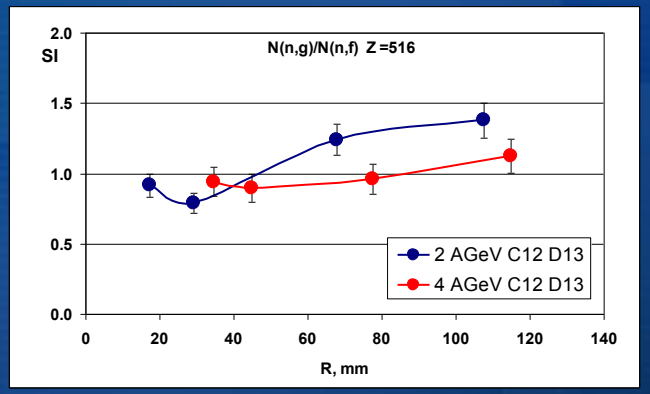
# Radial distributions of spectral indices ($^{238}U(n,\gamma)$ /$^{nat}U(n,f)$ ) at Z = 0, 123, 254, 385, 516, 647 mm

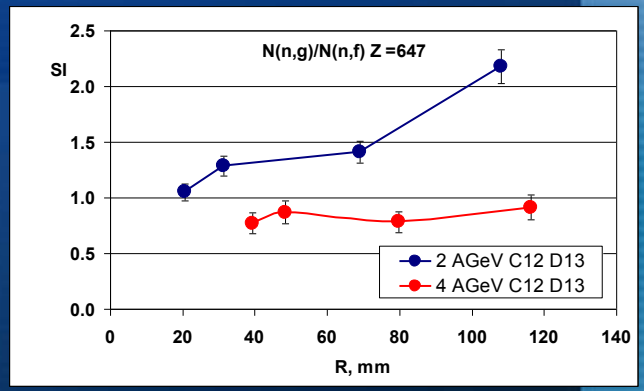


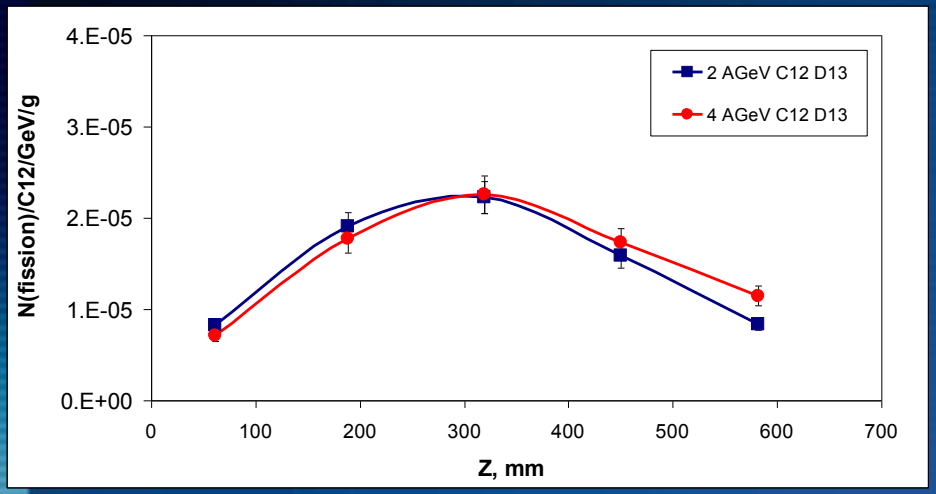



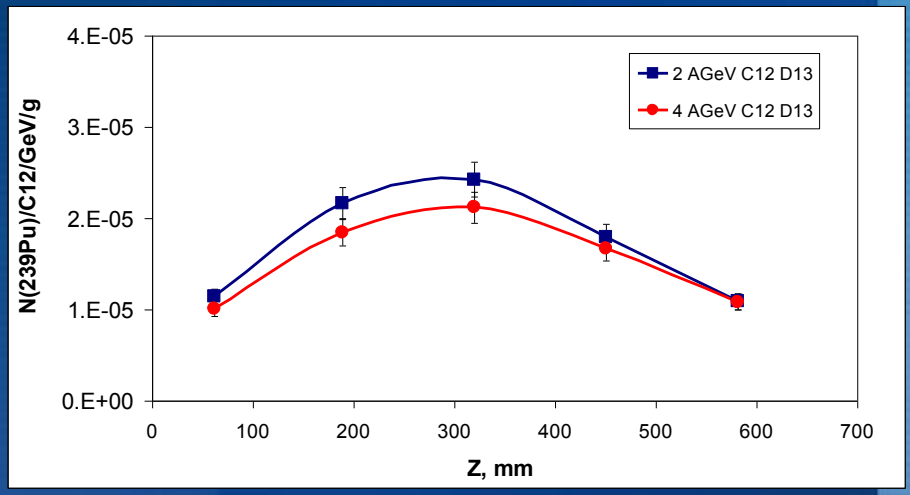



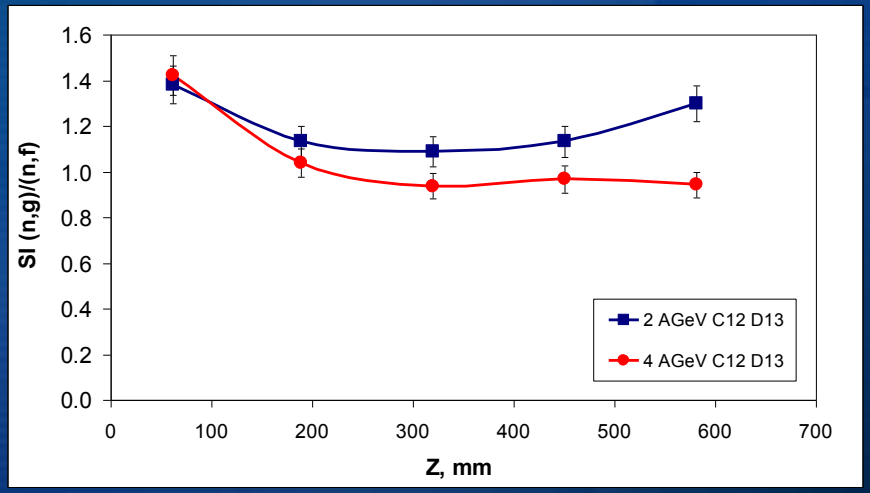



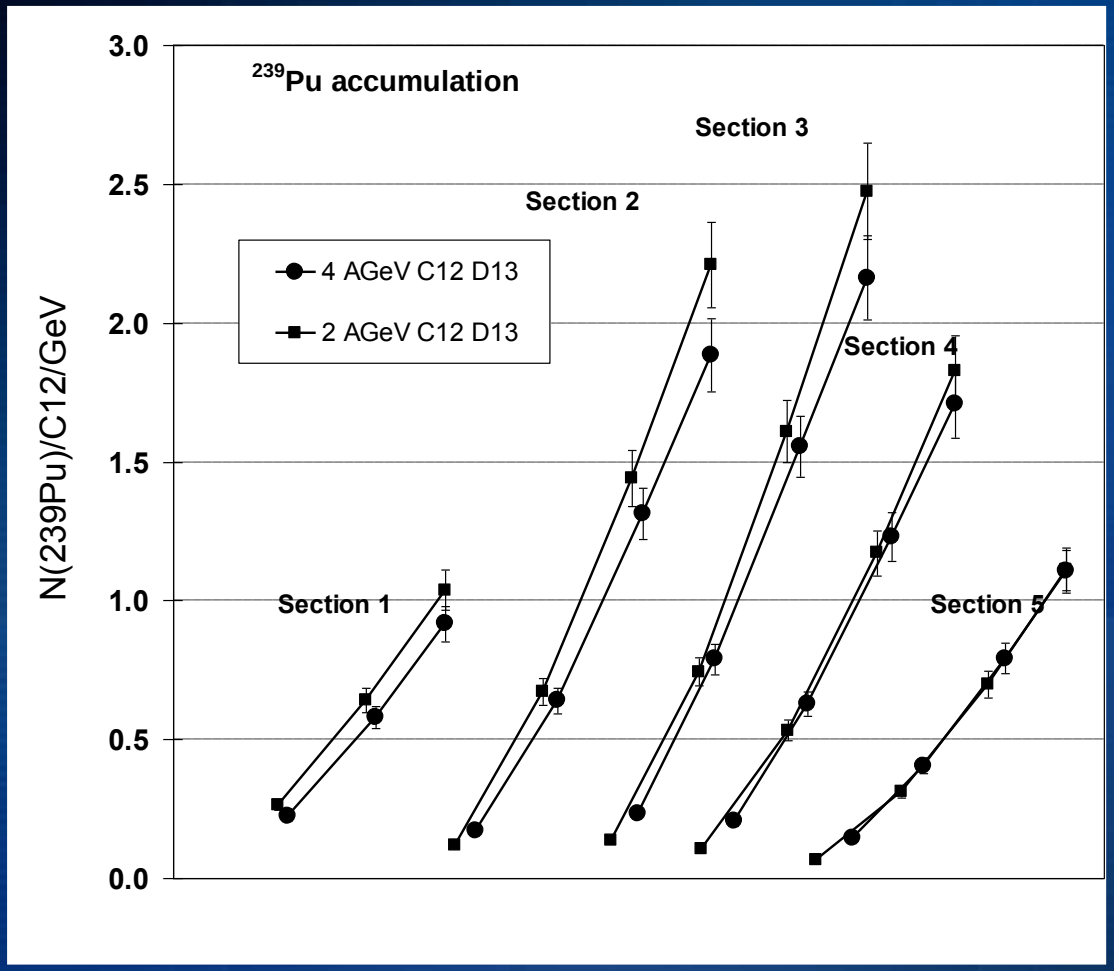
# Average spatial distributions of (n,γ), (n,f) reactions and spectral index

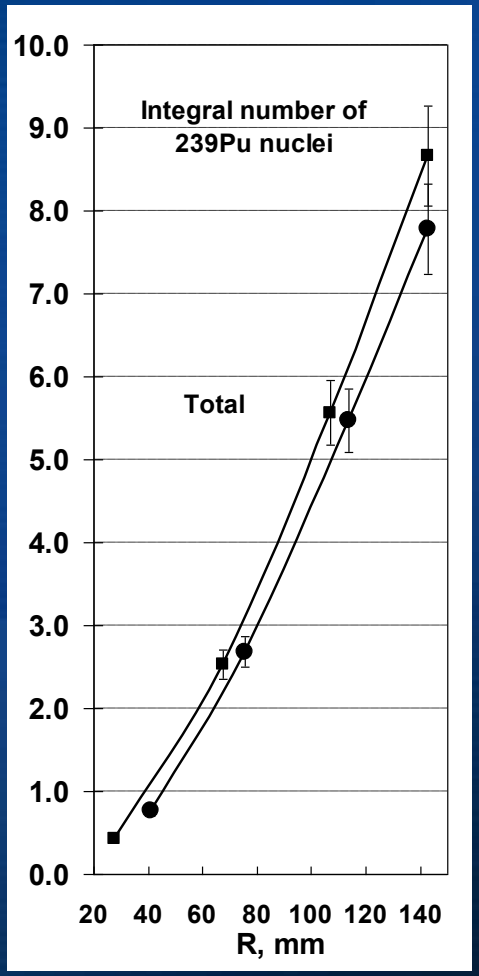


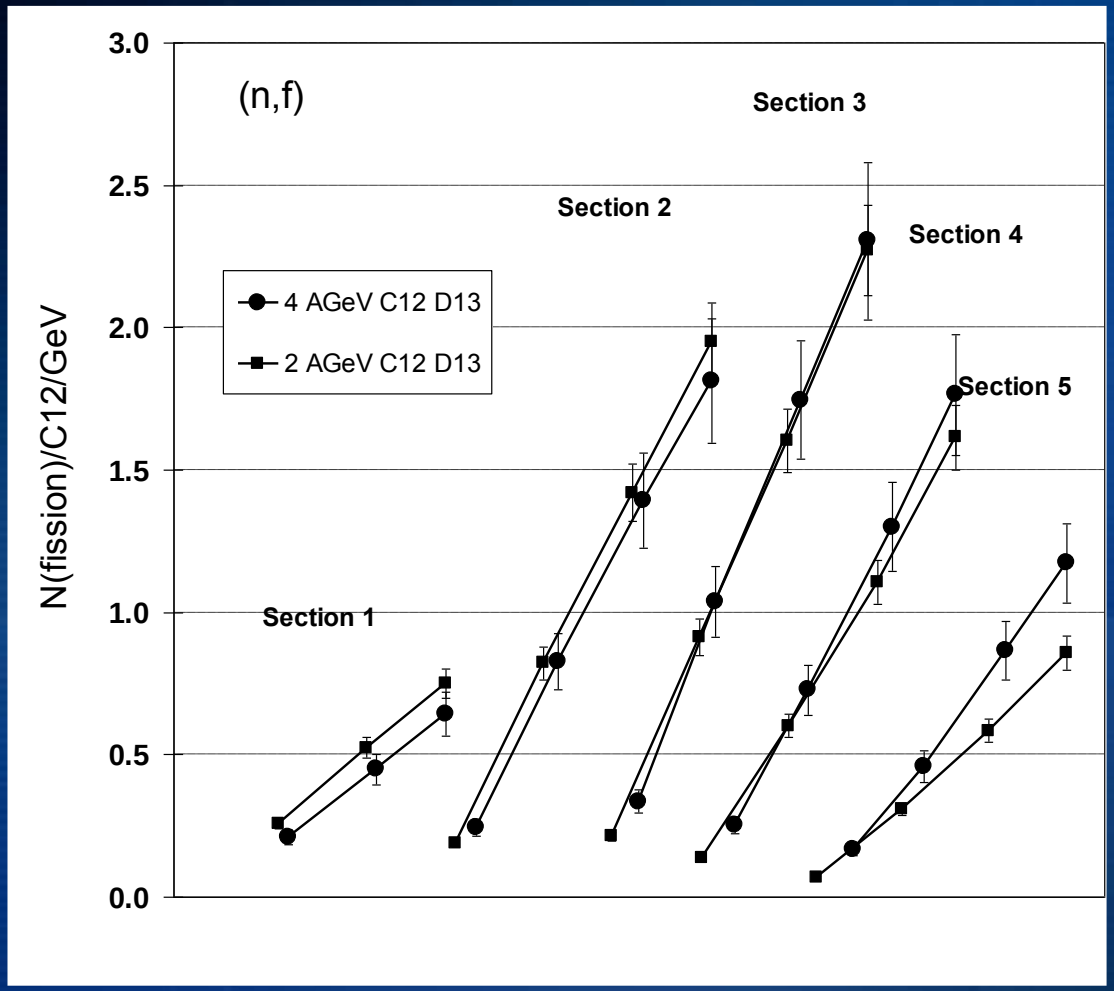



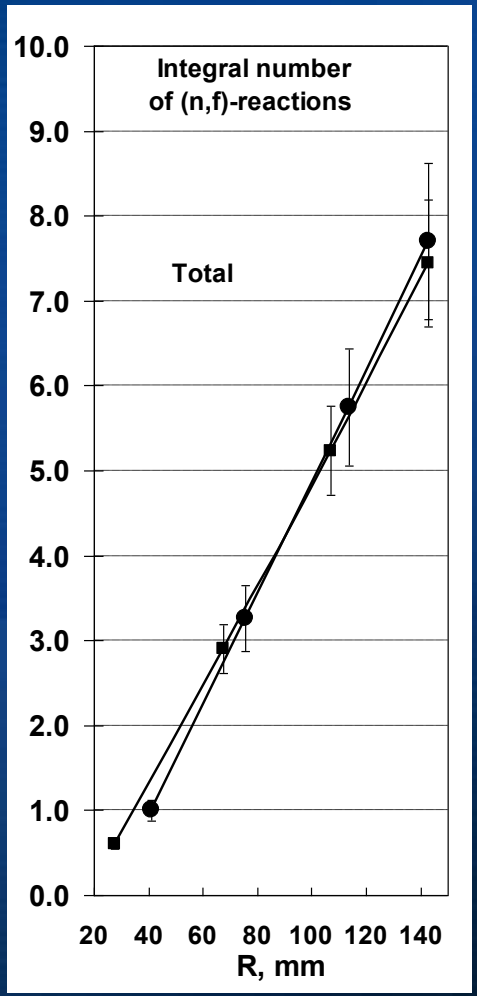
# Integral distribution of (n,γ) reaction (dependencies on uranium target radius)



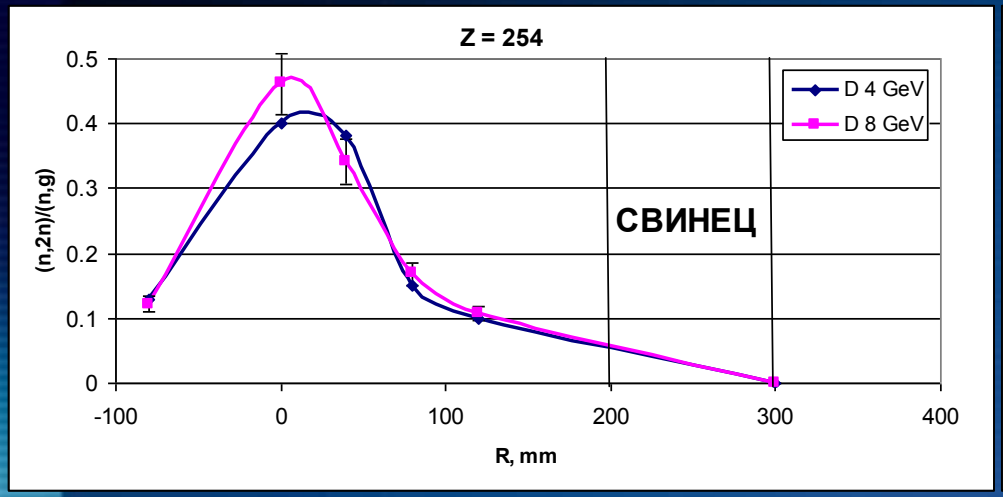



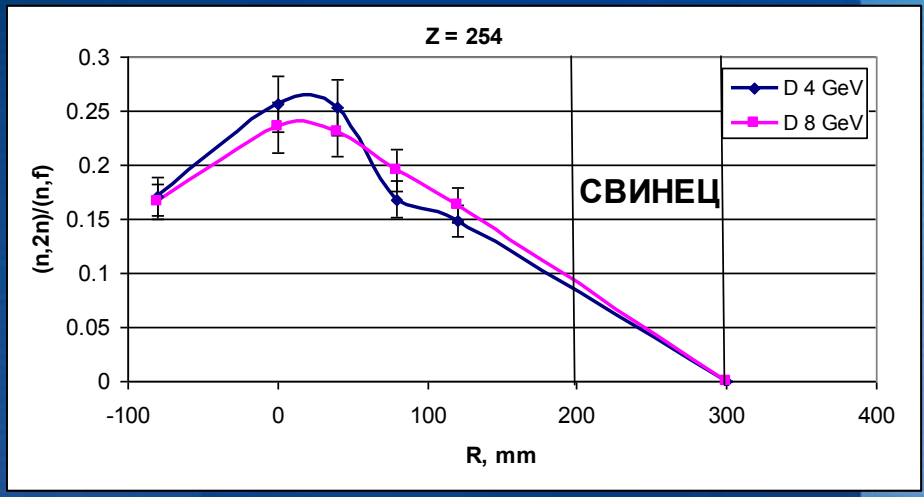
# Integral distribution of (n,f) reaction (dependencies on uranium target radius)

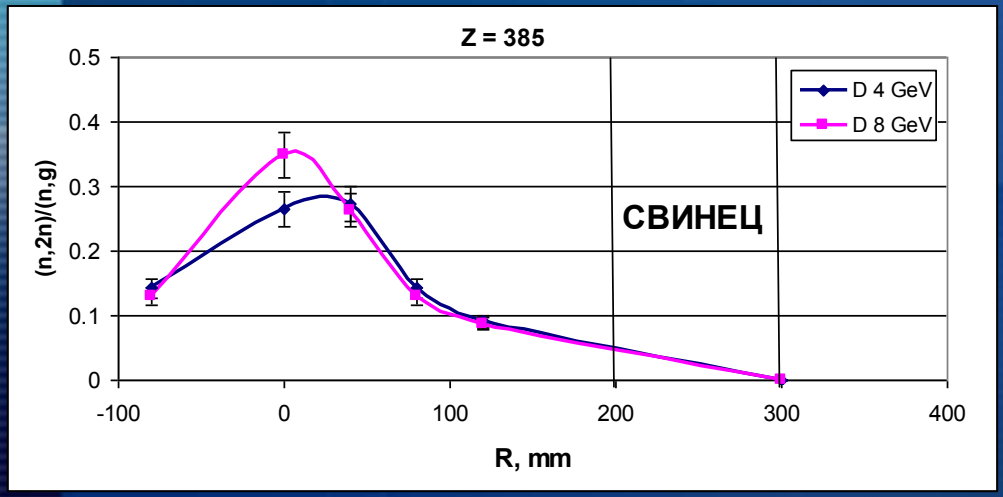


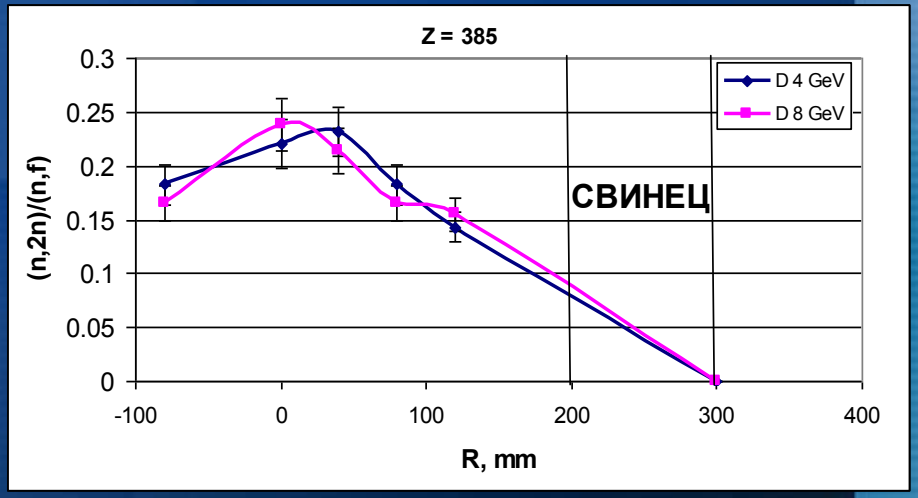



# Radial distributions of spectral indices ($^{238}$U(n,2n)/ $^{238}$U(n,γ) and $^{238}$U(n,2n)/$^{nat}$U(n,f) ) at Z = 254 mm and Z = 385 mm



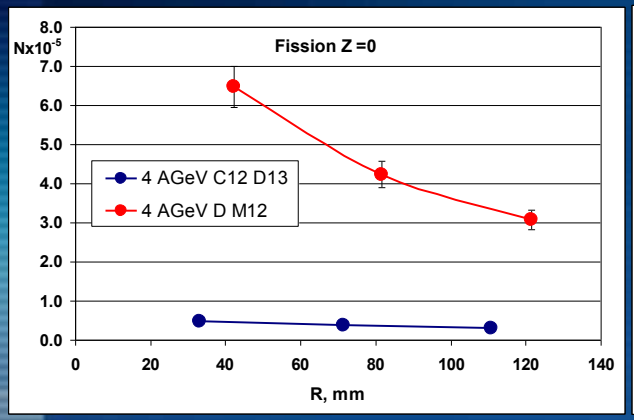



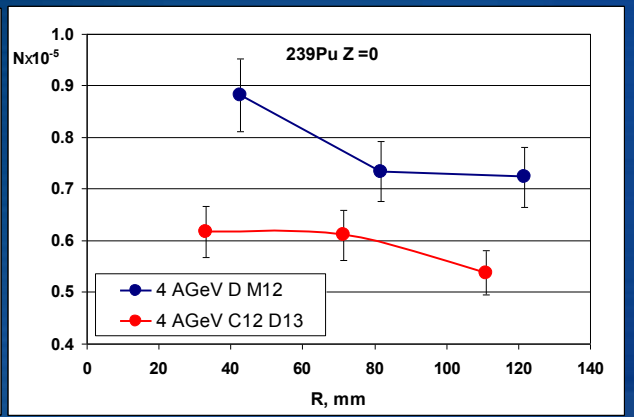



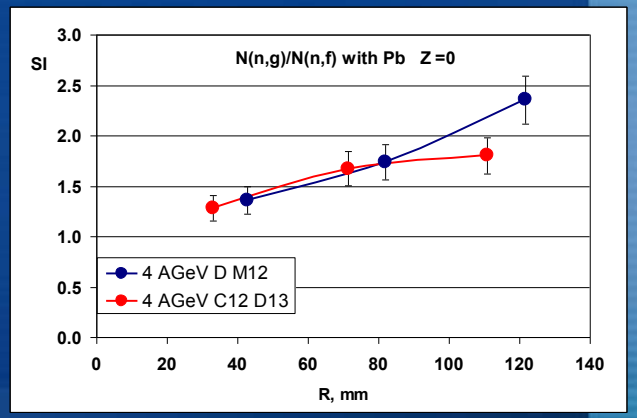



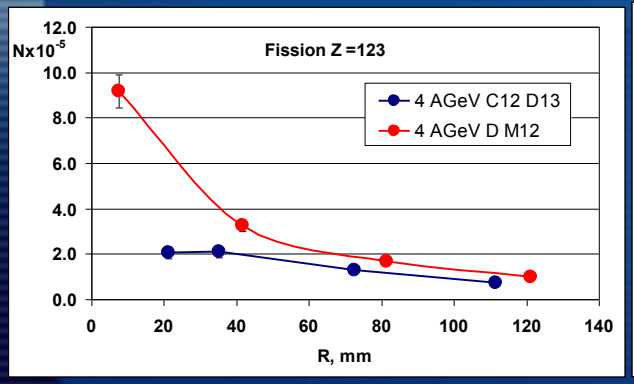
# Comparison of results between irradiations by deuterons and $^{12}C$ ions

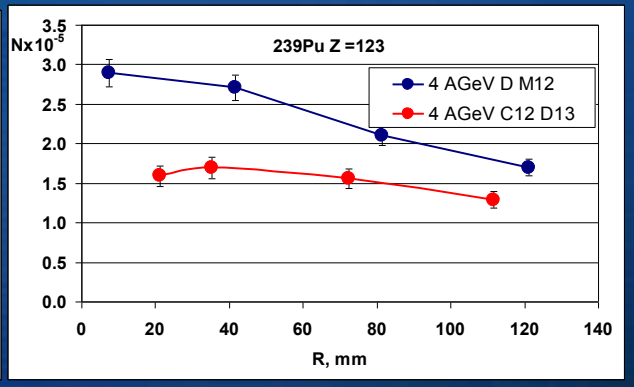
Radial distributions of density of $^{nat}U(n,f)$, density of $^{238}U(n,\gamma)$ reactions and spectral indices per 1 gram, 1 accelerated particle and 1 GeV at Z = 0, 123 mm

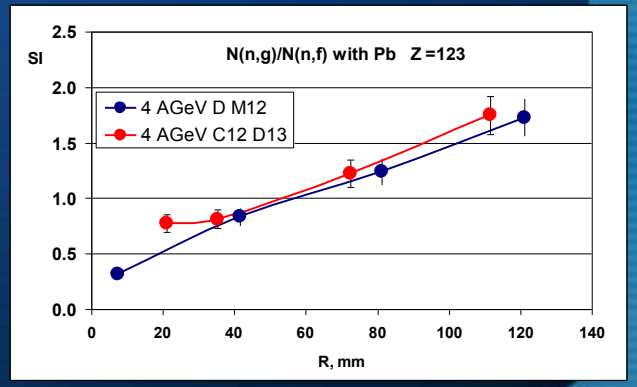


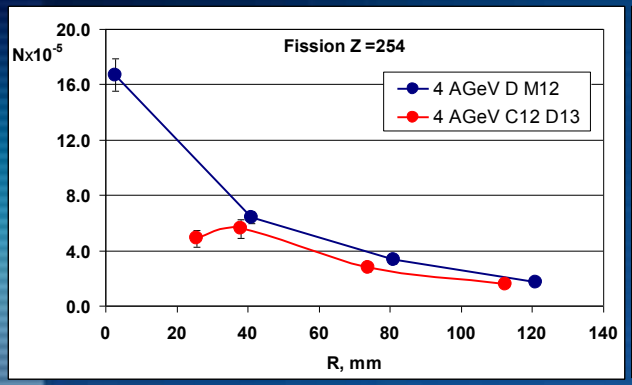



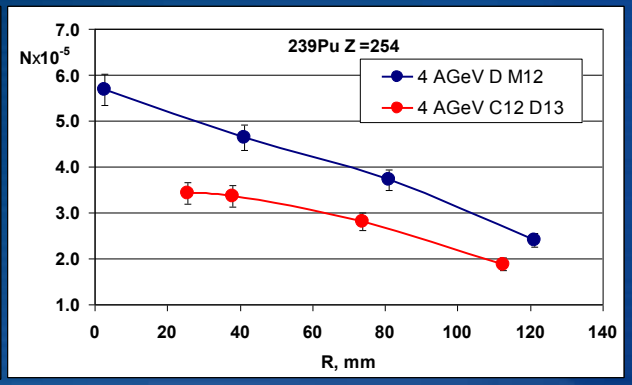



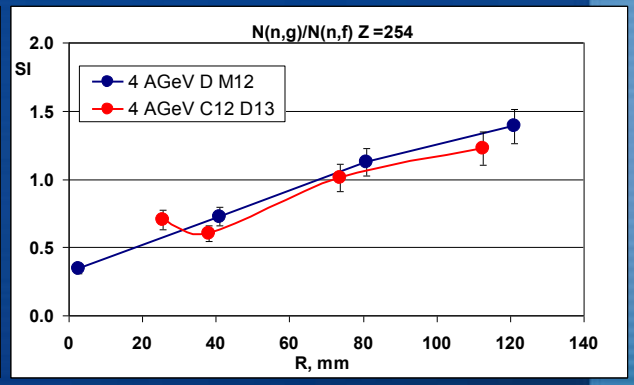



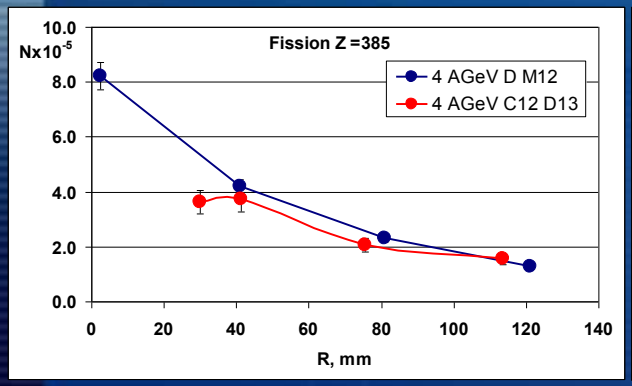
# Comparison of results between irradiations by deuterons and $^{12}C$ ions

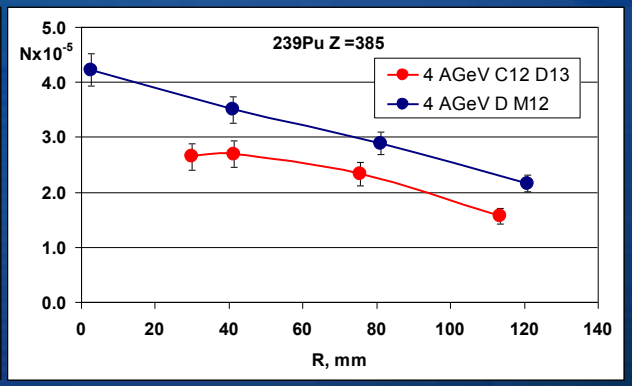
Radial distributions of density of $^{nat}U(n,f)$, density of $^{238}U(n,\gamma)$ reactions and spectral indices per 1 gram, 1 accelerated particle and 1 GeV at Z = 254, 385 mm

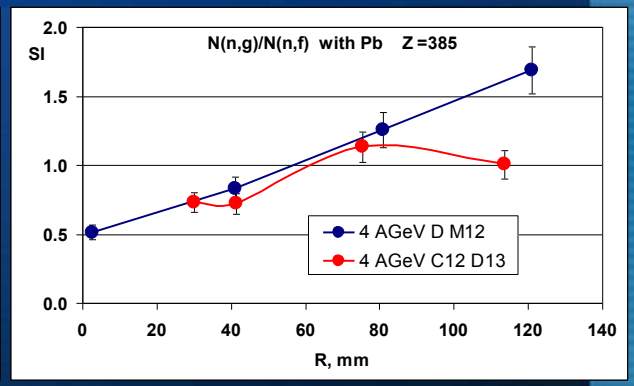


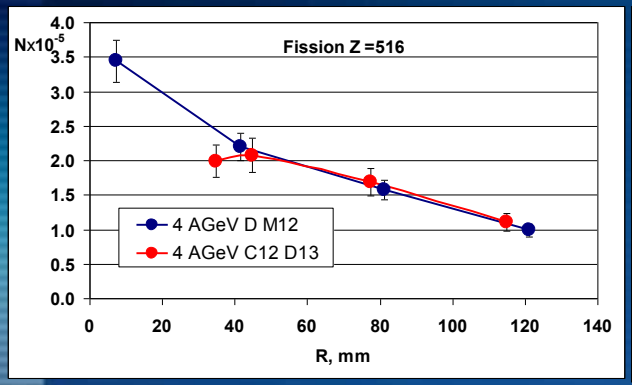



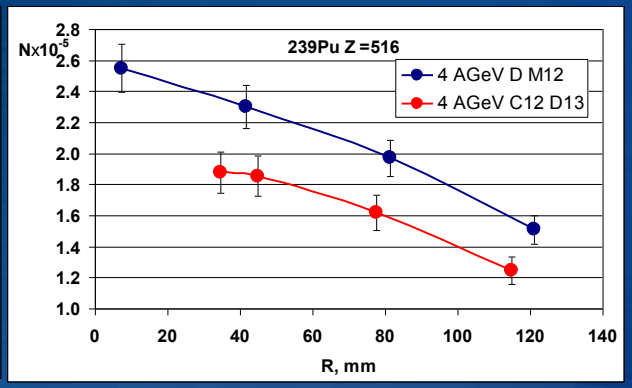



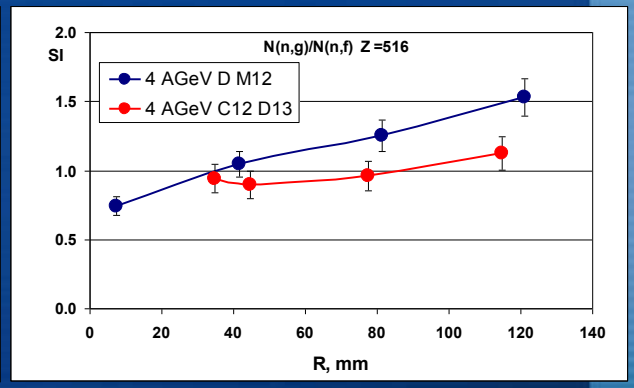



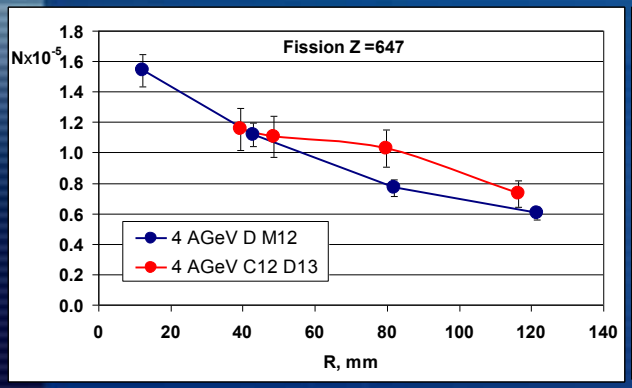
# Comparison of results between irradiations by deuterons and $^{12}C$ ions

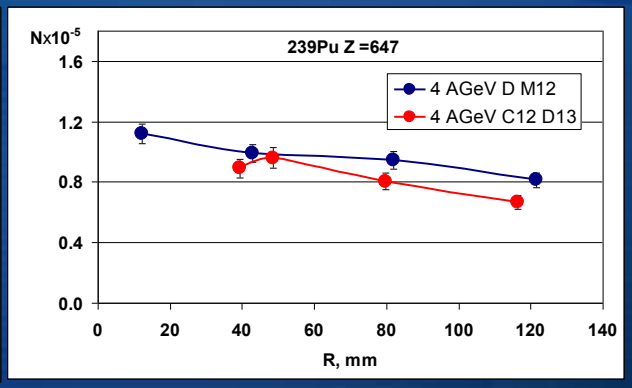
Radial distributions of density of $^{nat}U(n,f)$, density of $^{238}U(n,\gamma)$ reactions and spectral indices per 1 gram, 1 accelerated particle and 1 GeV at Z = 516, 647 mm

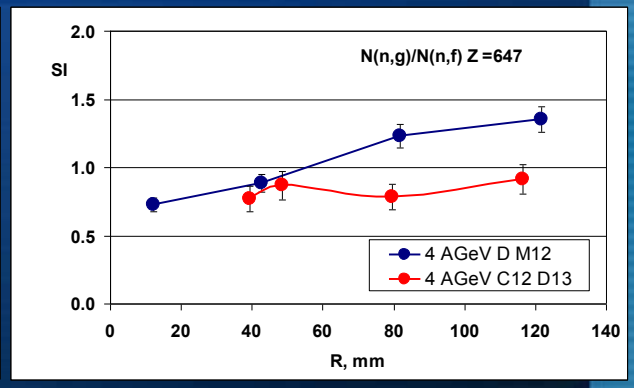


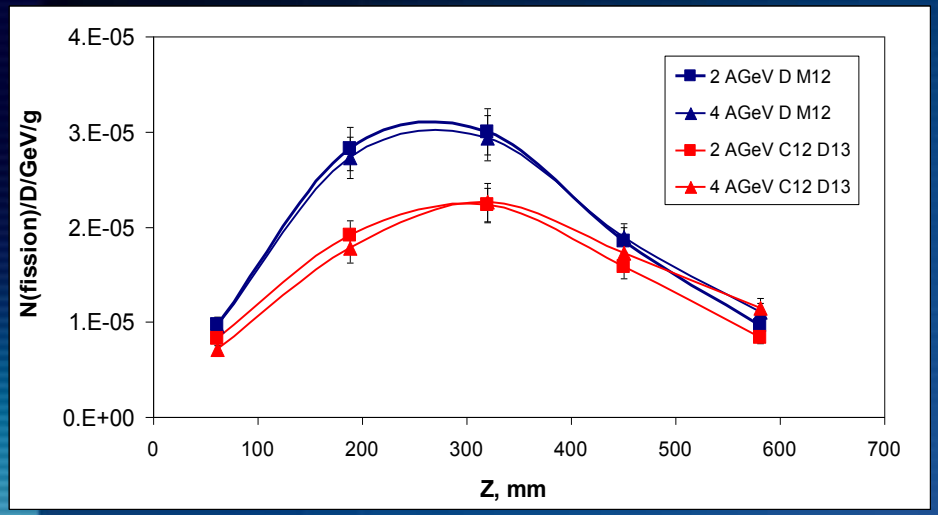



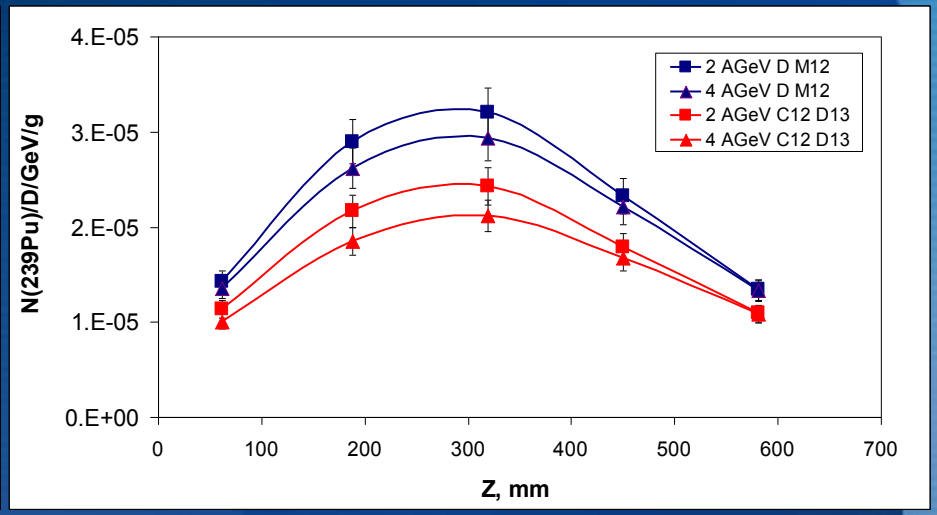



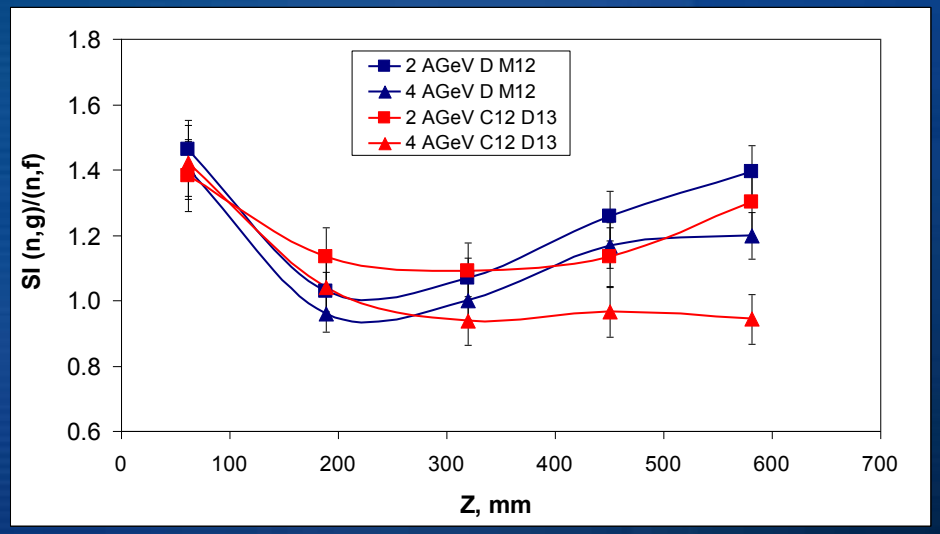



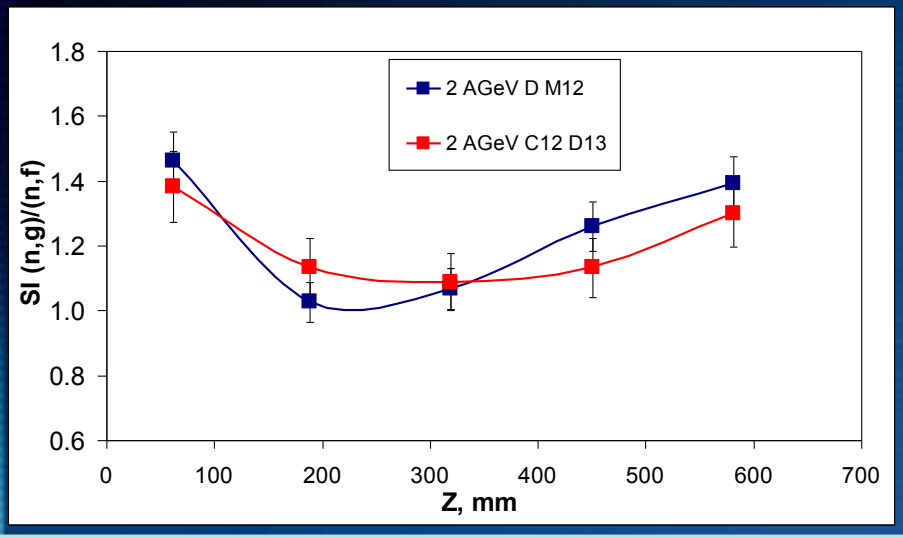
# Comparison of results between irradiations by deuterons and $^{12}C$ ions

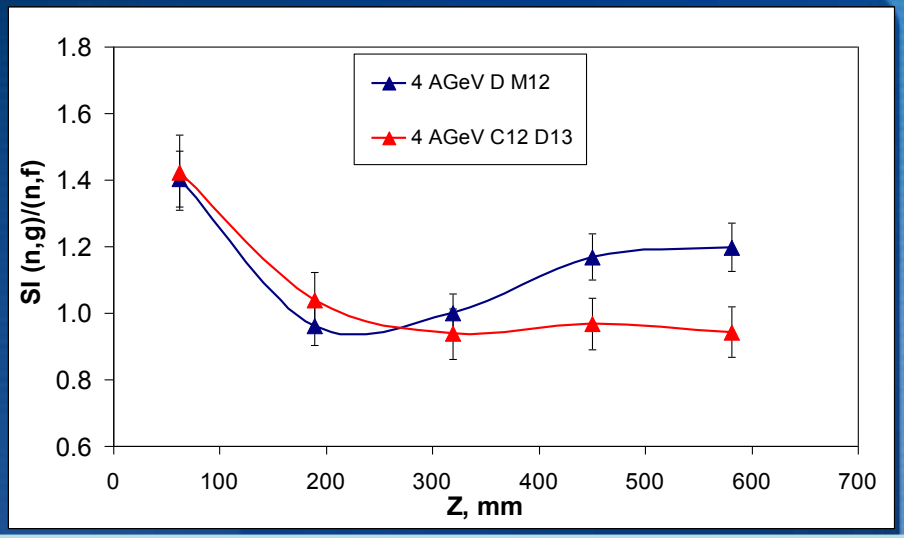


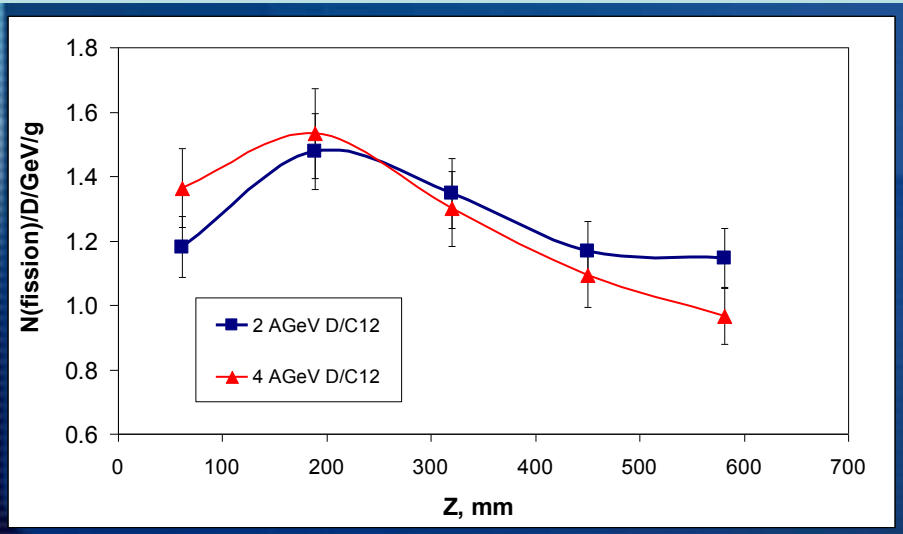



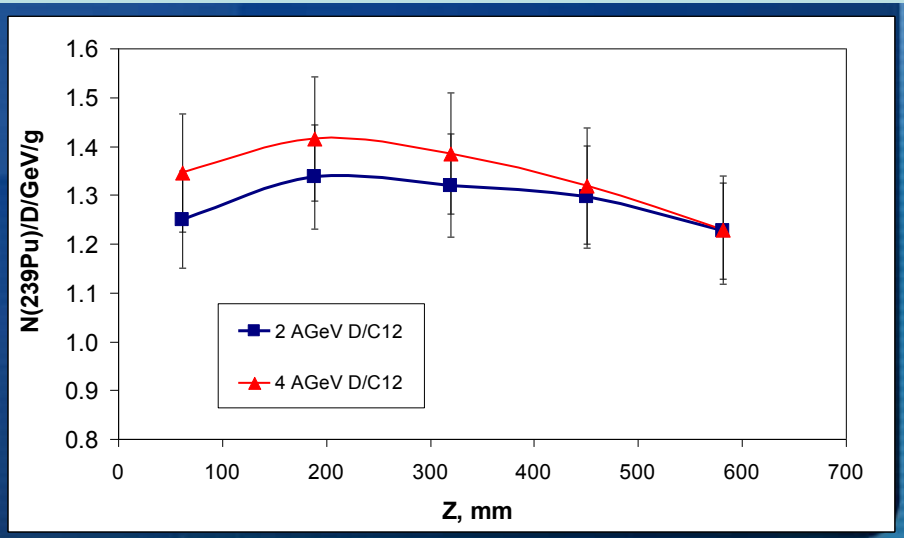



# Comparison of results between irradiations by deuterons and $^{12}C$ ions



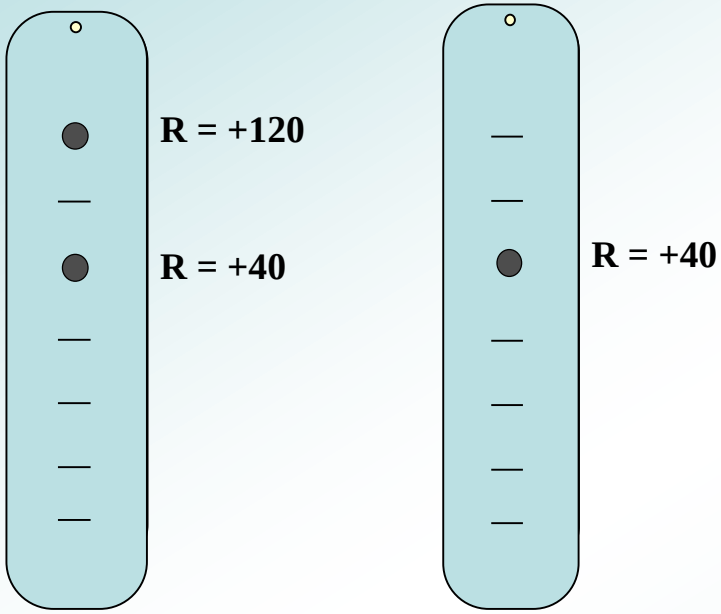



# Integral numbers of $^{239}$Pu accumulation and $^{nat}$U fissions in the volume of uranium target

| | Energy, GeV/A | (n,γ) | (n,f) |
|---|---|---|---|
| **Deuterons** | 2 | 11.3 ± 0.6 | 9.6 ± 0.7 |
| | 4 | 10.5 ± 0.6 | 9.5 ± 0.7 |
| **$^{12}$C** | 2 | 8.7 ± 0.7 | 7.5 ± 0.8 |
| | 4 | 7.8 ± 0.7 | 7.7 ± 0.8 |

# Location of Co detectors on the plates

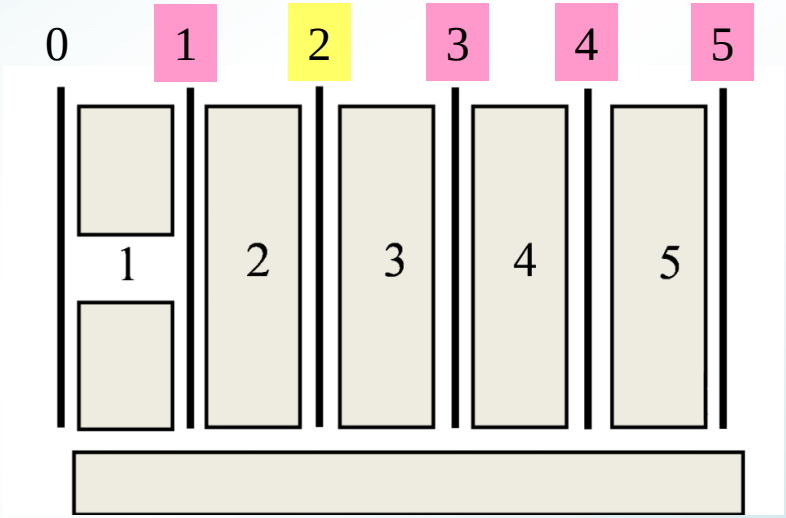



**Detector plate**

**№ 2**

**Detector plates**

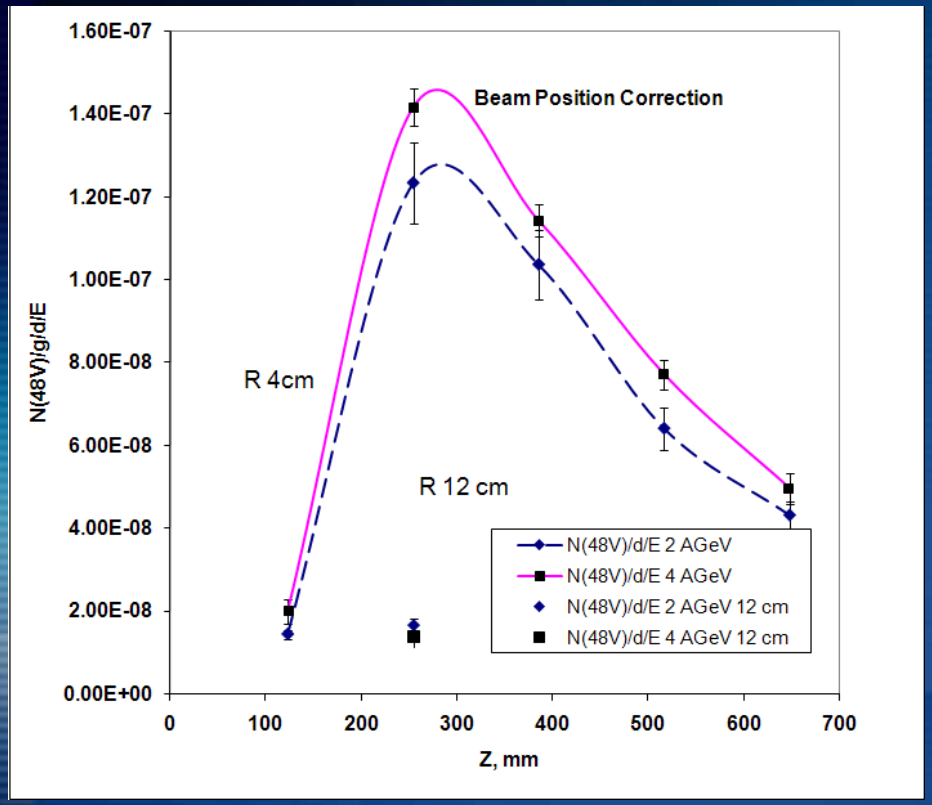
**№ 1,3,4,5**

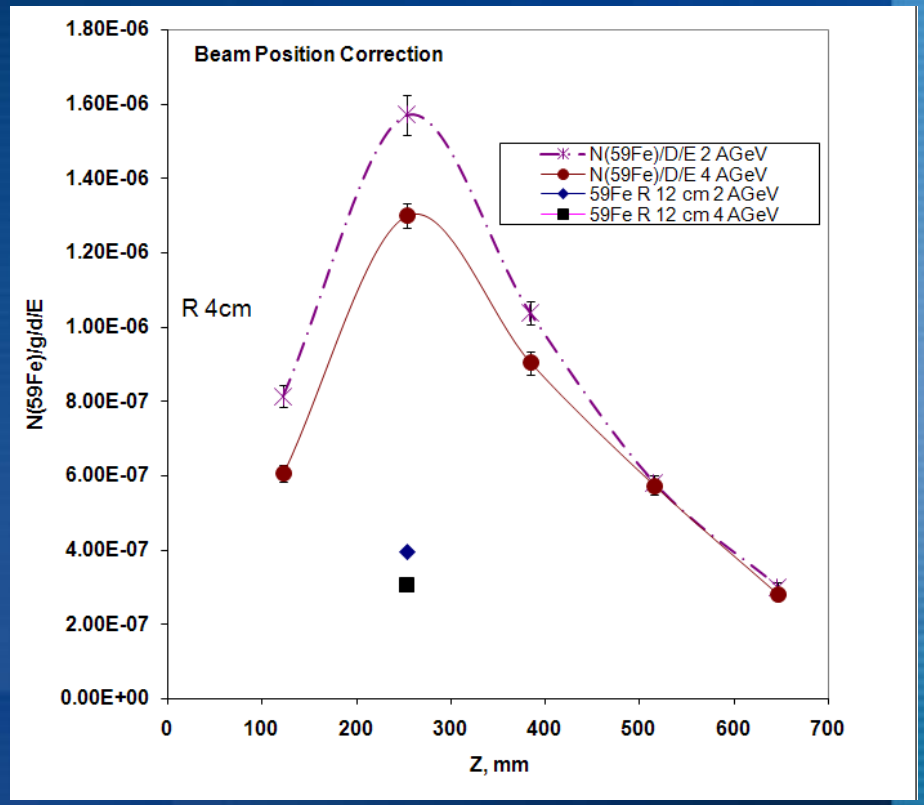


# Reaction characteristics at the neutron interaction with Co

| | T1/2 | | Eth, MeV | E CSmax/10 | Emax, MeV | E CSmax/10 | max CS, mb TENDL |
|---|---|---|---|---|---|---|---|
| 59Co(n,x)60Co | 5.2714 | y | 0 | 1.00E-11 | | | 1.00E+06 |
| 59Co(n,x)59Fe | 44.503 | d | 0.79 | 4.4 | 13 | 58 | 50 |
| 59Co(n,x)56Mn | 2.5785 | h | 0 | 6.8 | 16(60) | 200 | 17.5(13) |
| 59Co(n,x)58Co | 70.86 | d | 10.63 | 11 | 18 | 90 | 767 |
| 59Co(n,x)57Co | 271.79 | d | 19.35 | 21.2 | 36 | 200 | 224 |
| 59Co(n,x)56Co | 77.27 | d | 30.92 | 36 | 52 | 200 | 33.5 |
| 59Co(n,x)54Mn | 312.3 | d | 17.46 | 30 | 90 | 200 | 48 |
| 59Co(n,x)55Co | 17.53 | h | 41.2 | 48 | 75 | 200 | 3.5 |
| 59Co(n,x)52Mn | 5.591 | d | 38.8 | 59 | 120 | 200 | 26.4 |
| 59Co(n,x)51Cr | 27.7 | d | 36.84 | 70 | 130 | 200 | 36.5 |
| 59Co(n,x)48V | 15.97 | d | 47.6 | 100 | 160 | 200 | 26.6 |
| 59Co(n,x)48Sc | 43.67 | h | 17.22 | 100 | 180 | 200 | 0.2 |
| 59Co(n,x)48Cr | 21.56 | h | 70.25 | 110 | 180 | 200 | 1.75 |
| 59Co(n,x)47Sc | 3.3492 | d | 25.6 | 110 | 180 | 200 | 1.6 |
| 59Co(n,x)46Sc | 83.79 | d | 36.4 | 120 | >~(200) | >200 | 3.89 |
| 59Co(n,x)44Sc | 58.61 | h | 56.86 | 130 | >(200) | >200 | 16.9 |
| 59Co(n,x)43Sc | 3.891 | h | 66.7 | 140 | >(200) | >200 | 12.7 |
| 59Co(n,x)43K | 22.3 | h | 35.9 | 150 | >(200) | >200 | 0.26 |
| 59Co(n,x)42K | 12.36 | h | 45.7 | 150 | >(200) | >200 | 0.85 |

# Axial distribution of $^{59}Co(n,x)^{48}V$ and $^{59}Co(n,p)^{59}Fe$ reaction rates

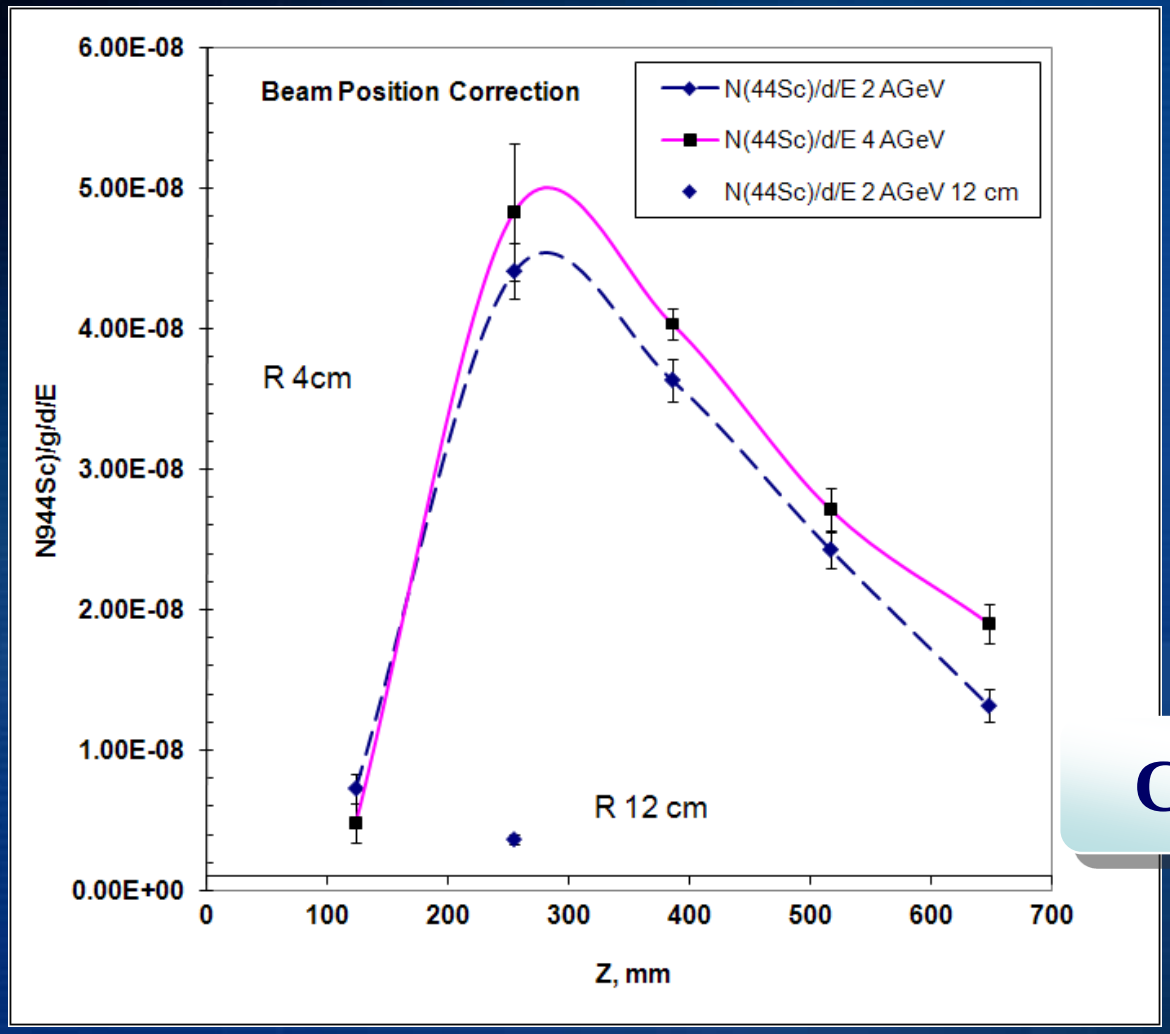



$CS_{eff}$ > 100 MeV

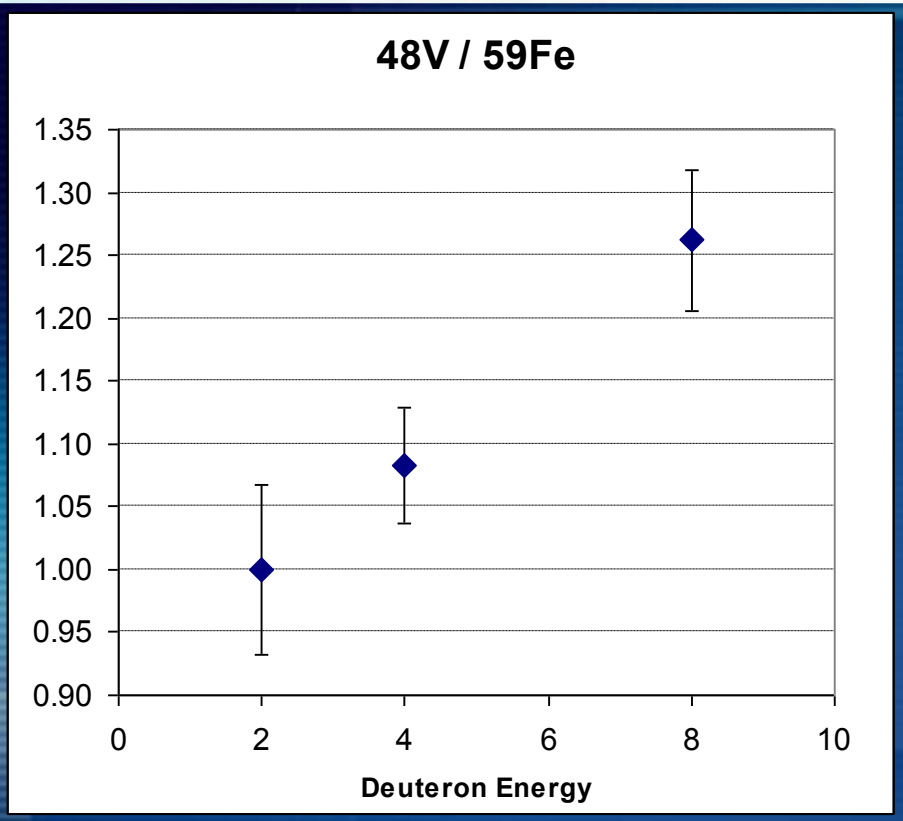
$CS_{eff}$ > 5 MeV

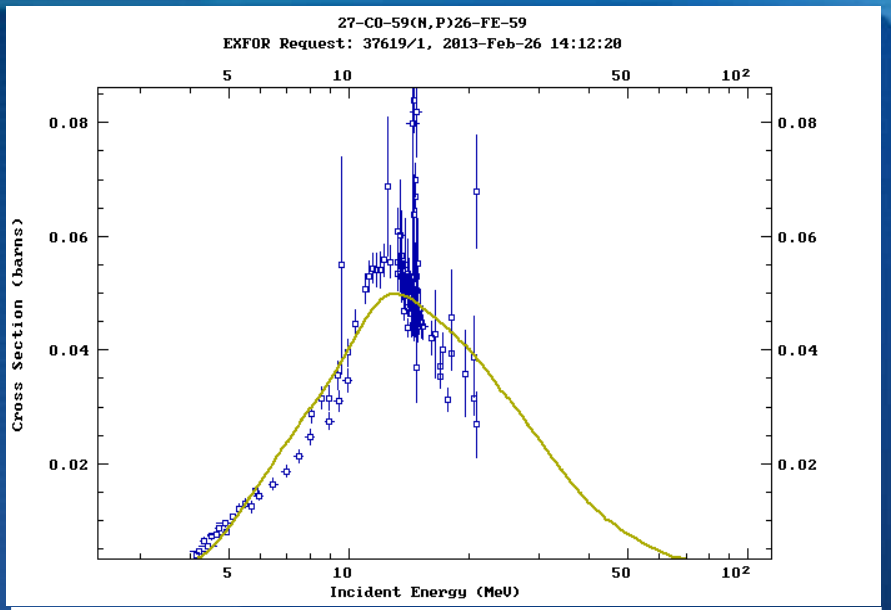
# Axial distribution of $^{59}Co(n,x)^{44}Sc$ reaction rates

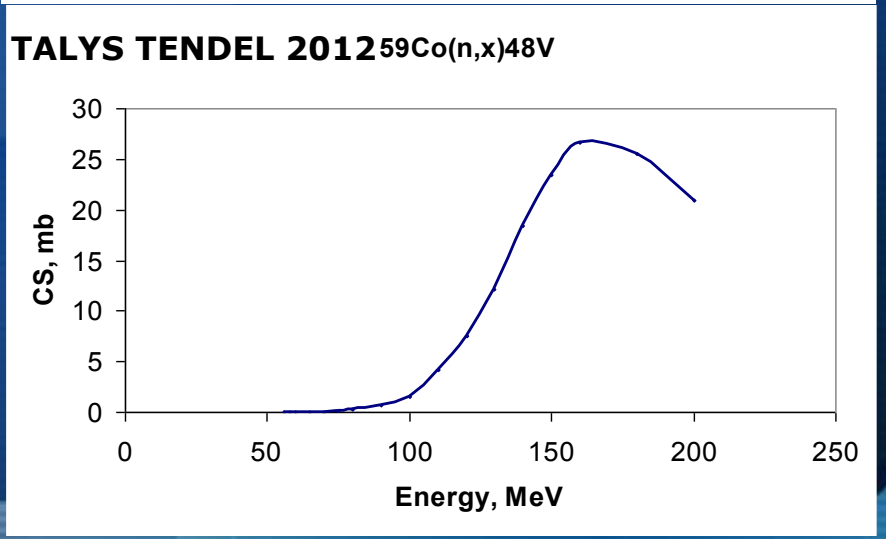



$CS_{eff}$ > 130 MeV

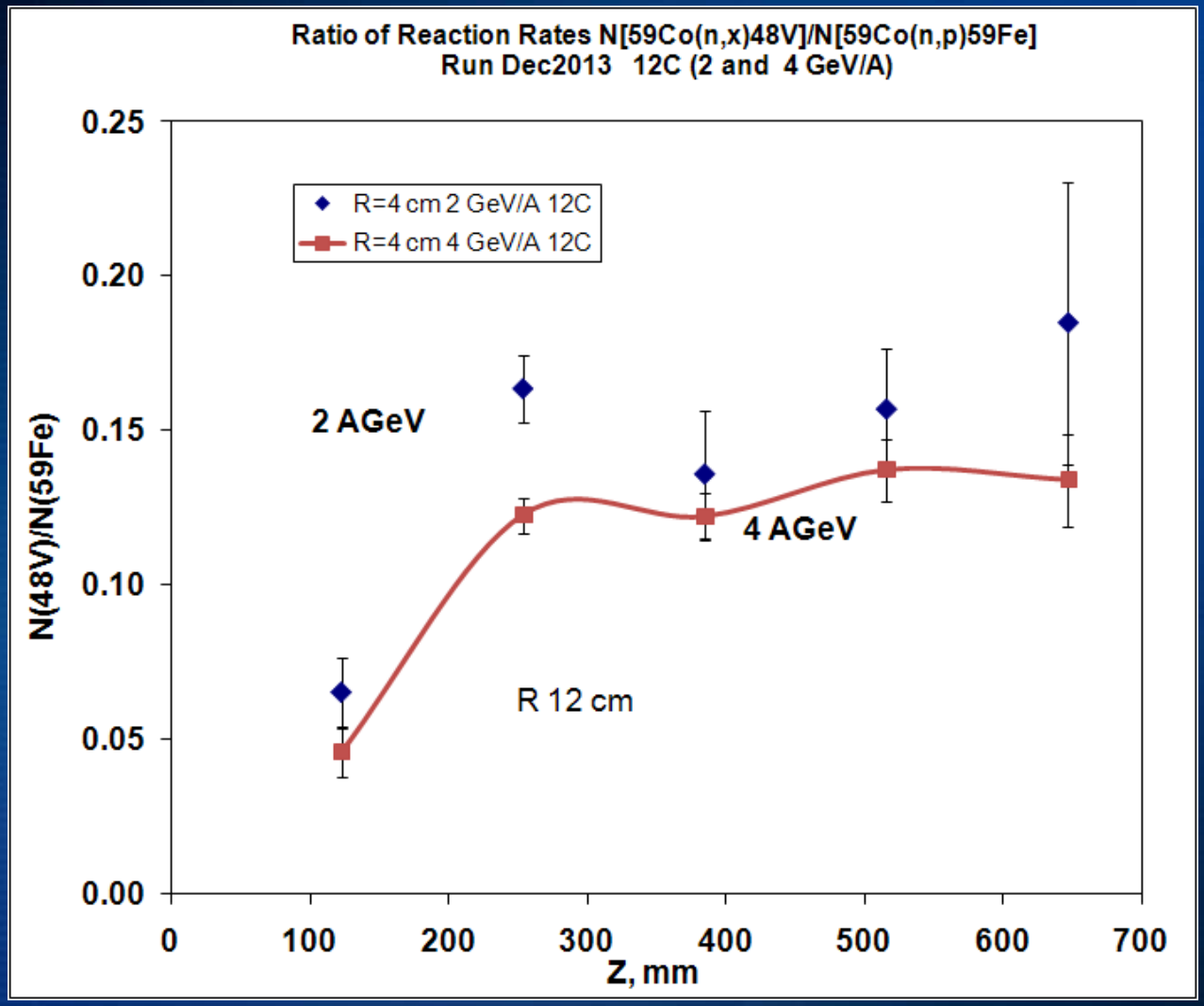
# N[$^{59}$Co(n, 2α+4n)$^{48}$V]/N[$^{59}$Co(n,p)$^{59}$Fe]




**$CS_{eff}$ > 100 MeV**


Ratio of Reaction Rates N[59Co(n,x)48V]/N[59Co(n,p)59Fe]
Run Dec2013 12C (2 and 4 GeV/A)
R=4 cm 2 GeV/A 12C
R=4 cm 4 GeV/A 12C
2 AGeV
4 AGeV
R 12 cm
N(48V)/N(59Fe)
Z, mm
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
300
400
500
600
700

# CONCLUSIONS

In case of $^{12}C$ ions the number of Pu accumulation and fissions are approximately the same within our statistical errors for energies 2 and 4 GeV.

The spectral index changes from the Carbon beam axis to the periphery of the uranium target from about 0.5 to 2 for “QUINTA” and behave identically for all cross sections of assembly.

Comparison of two runs with deuteron and $^{12}C$ ions showed that in the case of the deuteron the number of neutron capture reactions is more about 25% and the number of fissions more about 20%.

Increasing of number of neutrons in the energy range > 100 MeV and decreasing of number of neutrons with energy < 30 MeV is observed with increasing of energy of deuteron primary beam (per unit of deuteron beam power). At irradiation by $^{12}C$, this effect is not observed (preliminary results).

Due to the low intensity of the $^{12}C$ ion beam it would be advisable to repeat this experiment with higher intensity to verify all received data.

# Thank you for your attention !!!