Analysis of Materials for MEBT Absorber

Compiled by Yu. Eidelman, X6321
V4, Updated 7-24-2012
PX Doc DB ID: Project X-doc-986-v3

Abstract: Neutron yields from copper and molybdenum MEBT absorber are compared.

Input data

The present favorite material is for the MEBT absorber is TZM alloy:

Ti 0.55% Max
Zr 0.12% Max
Mo Balance

The beam parameters: 2.1 MeV H-, 10 mA CW.

Threshold for the possible reactions [1]

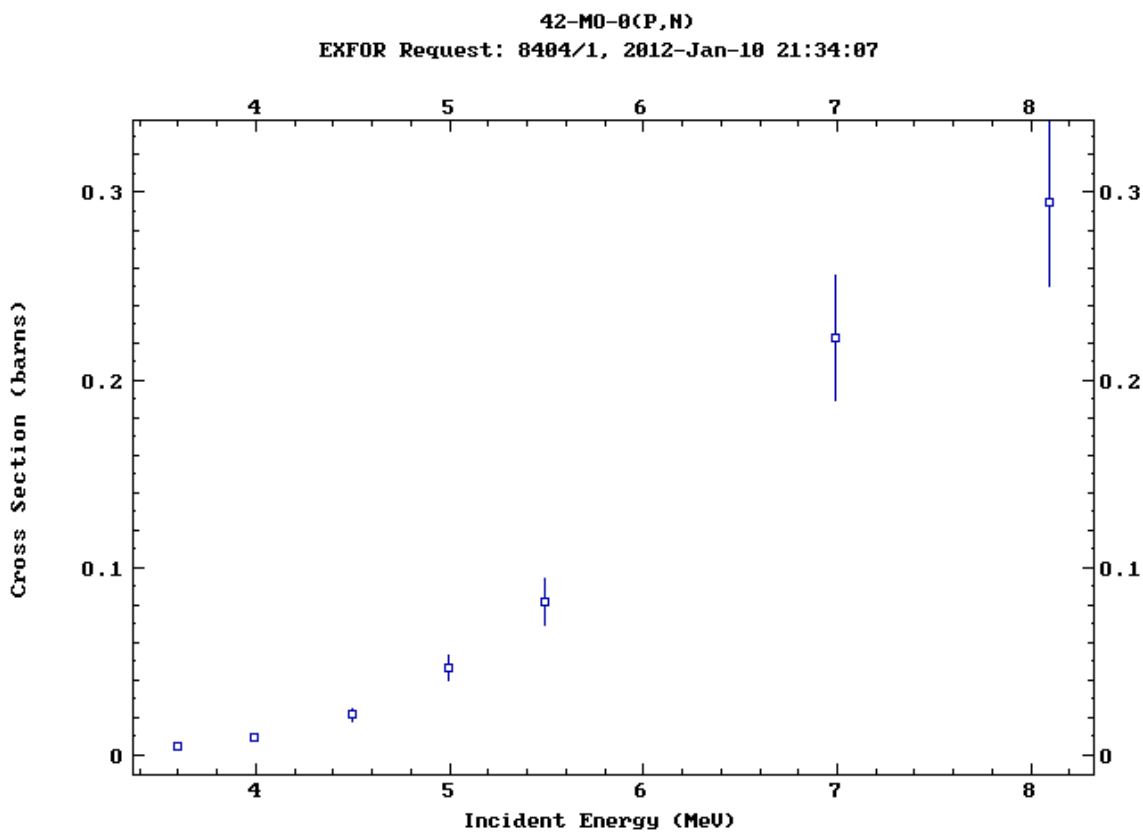
Data for **Mo**:

Isotope	Abundance,%	Reaction	Threshold, MeV
^{98}Mo	24.13	^{98}Mo (pn) ^{98}Tc	2.492
^{96}Mo	16.68	^{96}Mo (pn) ^{96}Tc	3.795
^{95}Mo	15.92	^{95}Mo (pn) ^{95}Tc	2.499
^{92}Mo	14.84	^{92}Mo (pn) ^{92}Tc	8.748
^{100}Mo	9.63	^{100}Mo (pn) ^{100}Tc	0.960
		^{100}Tc (pn) ^{100}Ru	0.0
		^{100}Ru (pn) ^{100}Rh	4.462
^{97}Mo	9.55	^{97}Mo (pn) ^{97}Tc	1.114
		^{97}Tc (pn) ^{97}Ru	1.910
		^{97}Ru (pn) ^{97}Rh	4.350
^{94}Mo	9.25	^{94}Mo (pn) ^{94}Tc	5.092

So, isotopic composition of residual:

Isotope	Abundance,%	Final Isotope
^{98}Mo	24.13	^{98}Mo
^{96}Mo	16.68	^{96}Mo
^{95}Mo	15.92	^{95}Mo
^{92}Mo	14.84	^{92}Mo
^{100}Mo	9.63	$\rightarrow$ ^{100}Tc $\rightarrow$ ^{100}Ru
^{97}Mo	9.55	$\rightarrow$ ^{97}Tc $\rightarrow$ ^{97}Ru
^{94}Mo	9.25	^{94}Mo

Cross sections [2]




```
#ZVView-data-copy:  10-Jan-2012 21:34:07
#=======================================
#
#name:   42-MO-0(P,N),,SIG
#X.axis: Incident Energy
#Y.axis: Cross Section
#wdata:  3
#ldata:  7
```

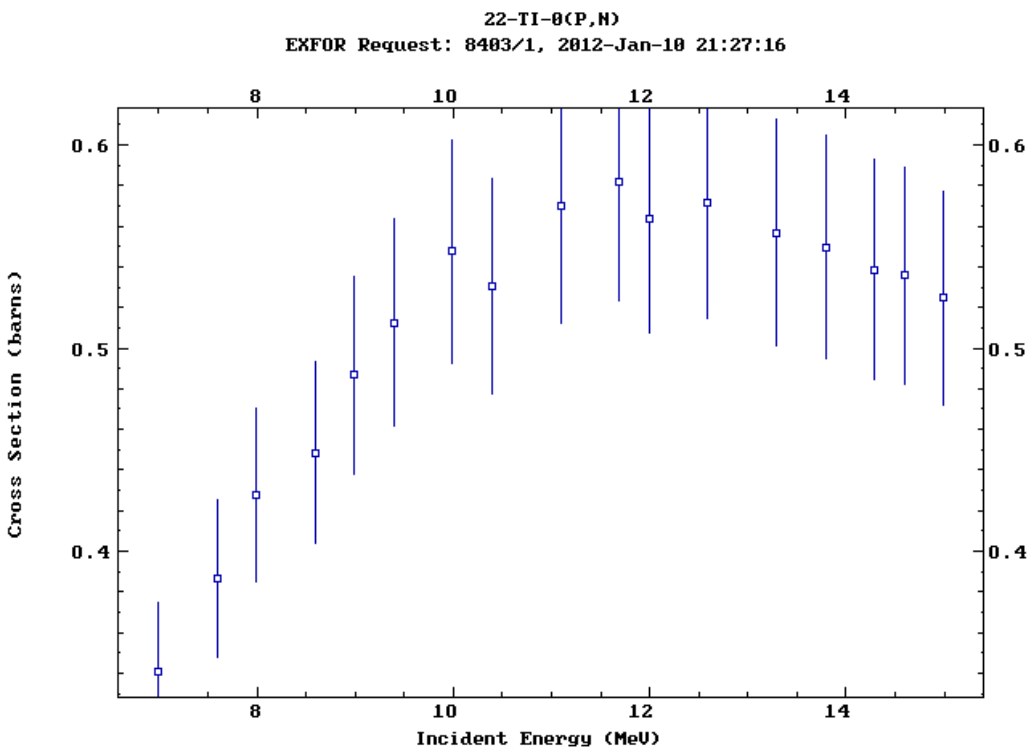
```
#data...
#            X            Y          +-dY  # Comments...
#          MeV        barns         barns  # Year,Author(s)      ## EXFOR-ID
           3.6        0.005       0.00075  # 1959,R.D.Albert     ## T0130015
             4         0.01        0.0015  # 1959,R.D.Albert     ## T0130015
           4.5        0.022        0.0033  # 1959,R.D.Albert     ## T0130015
             5        0.047       0.00705  # 1959,R.D.Albert     ## T0130015
           5.5        0.082        0.0123  # 1959,R.D.Albert     ## T0130015
             7        0.223       0.03345  # 1959,R.D.Albert     ## T0130015
           8.1        0.295       0.04425  # 1959,R.D.Albert     ## T0130015
//
#-----------------------------------------------------------------------------
```

Data for **Ti**:

Isotope	Abundance,%	Reaction	Threshold, MeV
^{48}Ti	73.80	^{48}Ti (pn) ^{48}V	4.895
^{46}Ti	8.00	^{46}Ti (pn) ^{46}V	8.005
^{47}Ti	7.30	^{47}Ti (pn) ^{47}V	3.792
^{49}Ti	5.50	^{49}Ti (pn) ^{49}V	1.413
		^{49}V (pn) ^{49}Cr	3.479
^{50}Ti	5.40	^{50}Ti (pn) ^{50}V	3.048

So, isotopic composition of residual:

Isotope	Abundance,%	Final Isotope
^{48}Ti	73.80	^{48}Ti
^{46}Ti	8.00	^{46}Ti
^{47}Ti	7.30	^{47}Ti
^{49}Ti	5.50	$\rightarrow$ V
^{50}Ti	5.40	^{50}Ti



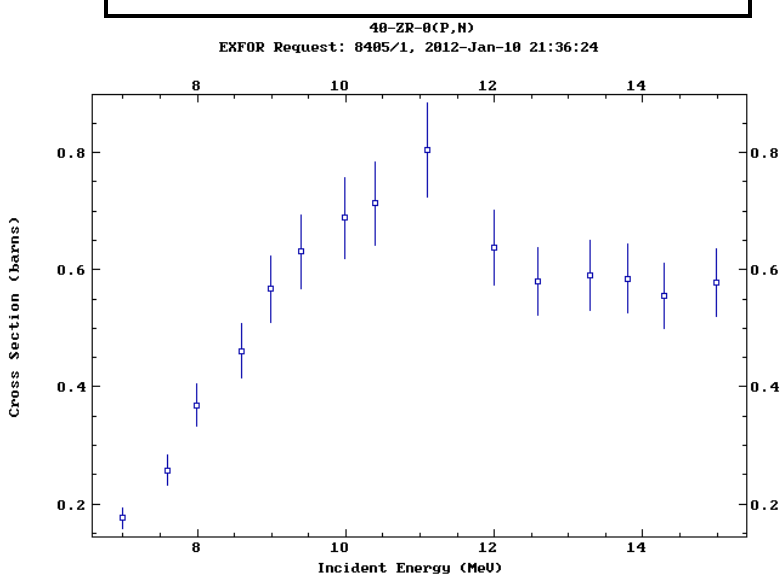

```
#ZVView-data-copy:  10-Jan-2012 21:27:16
#=====================================
#
#name:   22-TI-0(P,N),,SIG
#X.axis: Incident Energy
#Y.axis: Cross Section
#wdata:  3
#ldata:  17
#data...
#        X          Y          +-dY   # Comments...
#       MeV       barns        barns   # Year,Author(s)      ## EXFOR-ID
        7        0.341       0.0341   # 1967,G.Chodil+      ## C0693003
      7.6        0.387       0.0387   # 1967,G.Chodil+      ## C0693003
        8        0.428       0.0428   # 1967,G.Chodil+      ## C0693003
      8.6        0.449       0.0449   # 1967,G.Chodil+      ## C0693003
        9        0.487       0.0487   # 1967,G.Chodil+      ## C0693003
      9.4        0.513       0.0513   # 1967,G.Chodil+      ## C0693003
       10        0.548       0.0548   # 1967,G.Chodil+      ## C0693003
     10.4        0.531       0.0531   # 1967,G.Chodil+      ## C0693003
     11.1        0.57        0.057    # 1967,G.Chodil+      ## C0693003
     11.7        0.582       0.0582   # 1967,G.Chodil+      ## C0693003
       12        0.564       0.0564   # 1967,G.Chodil+      ## C0693003
     12.6        0.572       0.0572   # 1967,G.Chodil+      ## C0693003
     13.3        0.557       0.0557   # 1967,G.Chodil+      ## C0693003
     13.8         0.55        0.055   # 1967,G.Chodil+      ## C0693003
     14.3        0.539       0.0539   # 1967,G.Chodil+      ## C0693003
    14.6        0.536       0.0536   # 1967,G.Chodil+      ## C0693003
      15        0.525       0.0525   # 1967,G.Chodil+      ## C0693003
//
#-------------------------------------------------------------------------------
```

Data for **Zr**:

Isotope	Abundance,%	Reaction	Threshold, MeV
^{90}Zr	51.45	^{90}Zr (pn) ^{90}Nb	6.971
^{94}Zr	17.38	^{94}Zr (pn) ^{94}Nb	1.703
		^{94}Nb (pn) ^{94}Mo	0.0
		^{94}Mo (pn) ^{94}Tc	5.092
^{92}Zr	17.15	^{91}Zr (pn) ^{91}Nb	2.818
^{91}Zr	11.22	^{91}Zr (pn) ^{91}Nb	2.063
		^{91}Nb (pn) ^{91}Mo	5.264
^{96}Zr	2.80	^{96}Zr (pn) ^{96}Nb	0.628
		^{96}Nb (pn) ^{96}Mo	0.0
		^{96}Mo (pn) ^{96}Tc	3.795

So, isotopic composition of residual:

Isotope	Abundance,%	Final Isotope
^{90}Zr	51.45	^{90}Zr
^{94}Zr	17.38	$\rightarrow^{94}$ Nb $\rightarrow^{94}$ Mo
^{92}Zr	17.15	^{92}Zr
^{91}Zr	11.22	$\rightarrow^{91}$ Nb
^{96}Zr	2.80	$\rightarrow^{96}$ Nb $\rightarrow^{96}$ Mo



```
#ZVView-data-copy:  10-Jan-2012 21:36:24
#=======================================
#
#name:   40-ZR-0(P,N),,SIG
#X.axis: Incident Energy
#Y.axis: Cross Section
#wdata:  3
#ldata:  15
#data...
#            X            Y          +-dY  # Comments...
#          MeV        barns         barns  # Year,Author(s)      ## EXFOR-ID
             7        0.177        0.0177  # 1967,G.Chodil+      ## C0693006
           7.6        0.258        0.0258  # 1967,G.Chodil+      ## C0693006
             8         0.37         0.037  # 1967,G.Chodil+      ## C0693006
           8.6        0.462        0.0462  # 1967,G.Chodil+      ## C0693006
             9        0.568        0.0568  # 1967,G.Chodil+      ## C0693006
           9.4        0.632        0.0632  # 1967,G.Chodil+      ## C0693006
            10         0.69         0.069  # 1967,G.Chodil+      ## C0693006
          10.4        0.714        0.0714  # 1967,G.Chodil+      ## C0693006
          11.1        0.805        0.0805  # 1967,G.Chodil+      ## C0693006
            12        0.639        0.0639  # 1967,G.Chodil+      ## C0693006
          12.6        0.581        0.0581  # 1967,G.Chodil+      ## C0693006
          13.3        0.591        0.0591  # 1967,G.Chodil+      ## C0693006
          13.8        0.586        0.0586  # 1967,G.Chodil+      ## C0693006
          14.3        0.557        0.0557  # 1967,G.Chodil+      ## C0693006
            15        0.579        0.0579  # 1967,G.Chodil+      ## C0693006
//
#-----------------------------------------------------------------------------
```

Data for **Cu** (for future reference):

Isotope	Abundance,%	Reaction	Threshold, MeV
^{63}Cu	69.17	^{63}Cu (pn) ^{63}Zn	4.215
^{65}Cu	30.83	^{65}Cu (pn) ^{65}Zn	2.167

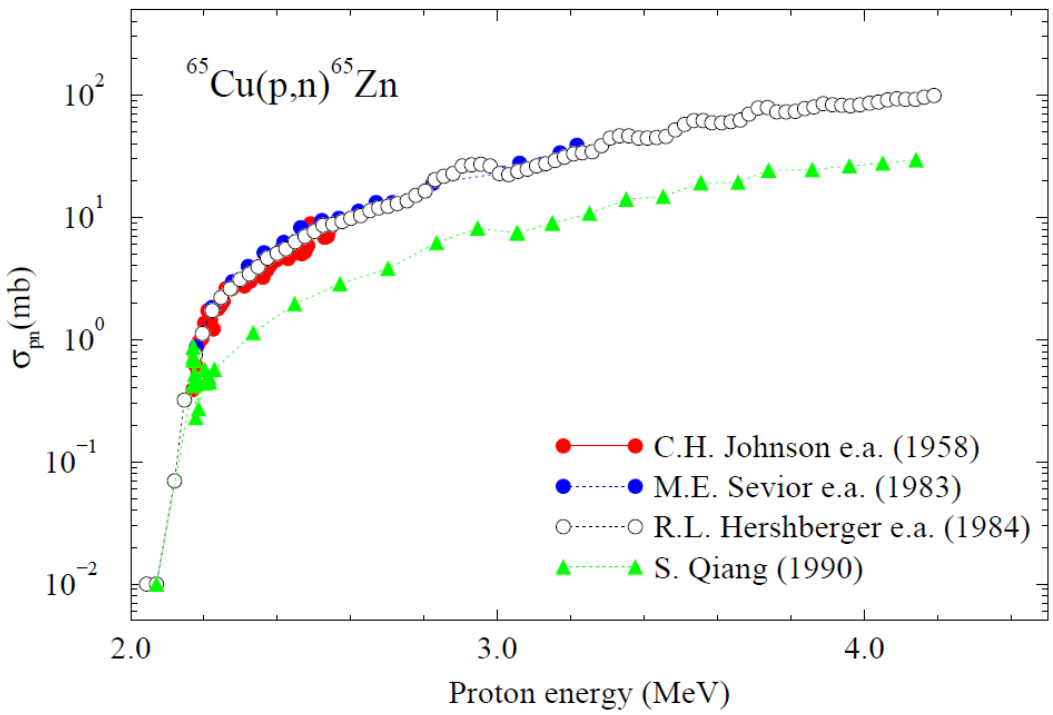
So, isotopic composition of residual:

Isotope	Abundance,%	Final Isotope
^{63}Cu	69.17	^{63}Cu
^{65}Cu	30.83	^{65}Cu

```
#ZVView-data-copy:  18-Jan-2012 23:36:28
#=======================================
#
#name:   29-CU-0(P,N),,SIG
#X.axis: Incident Energy
#Y.axis: Cross Section
#wdata:  3
```

```
#ldata:  84
#data...
#            X            Y         +-dY  # Comments...
#          MeV        barns        barns  # Year,Author(s)          ## EXFOR-ID
         1.917         2e-5       7.4e-7  # 1990,S.Qiang             ## C0739002
         1.927            0            0  # 1990,S.Qiang             ## C0739002
          2.07         5e-5      9.15e-7  # 1990,S.Qiang             ## C0739002
          2.07         1e-5      7.34e-7  # 1990,S.Qiang             ## C0739002
         2.169      0.00042    1.6212e-5  # 1990,S.Qiang             ## C0739002
          2.17      0.00068    1.6184e-5  # 1990,S.Qiang             ## C0739002
         2.171      0.00073    1.4965e-5  # 1990,S.Qiang             ## C0739002
         2.171      0.00087     1.479e-5  # 1990,S.Qiang             ## C0739002
         2.172       0.0007     1.246e-5  # 1990,S.Qiang             ## C0739002
         2.175      0.00052     8.684e-6  # 1990,S.Qiang             ## C0739002
         2.178      0.00043     6.622e-6  # 1990,S.Qiang             ## C0739002
         2.178      0.00023     5.221e-6  # 1990,S.Qiang             ## C0739002
         2.185      0.00044     5.236e-6  # 1990,S.Qiang             ## C0739002
         2.185      0.00027     4.239e-6  # 1990,S.Qiang             ## C0739002
         2.202      0.00057     4.275e-6  # 1990,S.Qiang             ## C0739002
         2.202      0.00044     3.784e-6  # 1990,S.Qiang             ## C0739002
         2.214      0.00046     3.312e-6  # 1990,S.Qiang             ## C0739002
         2.214      0.00049     3.381e-6  # 1990,S.Qiang             ## C0739002
         2.214      0.00045     3.285e-6  # 1990,S.Qiang             ## C0739002
         2.214      0.00046     3.266e-6  # 1990,S.Qiang             ## C0739002
         2.214      0.00045      3.24e-6  # 1990,S.Qiang             ## C0739002
         2.229      0.00057     3.192e-6  # 1990,S.Qiang             ## C0739002
         2.334      0.00113     3.955e-6  # 1990,S.Qiang             ## C0739002
         2.447      0.00196     5.292e-6  # 1990,S.Qiang             ## C0739002
          2.57      0.00287     8.897e-6  # 1990,S.Qiang             ## C0739002
         2.701       0.0038     1.026e-5  # 1990,S.Qiang             ## C0739002
         2.834      0.00616    1.2936e-5  # 1990,S.Qiang             ## C0739002
         2.946      0.00816    1.9584e-5  # 1990,S.Qiang             ## C0739002
         3.053       0.0074      1.85e-5  # 1990,S.Qiang             ## C0739002
         3.054      0.00742     1.855e-5  # 1990,S.Qiang             ## C0739002
         3.149      0.00893    2.5004e-5  # 1990,S.Qiang             ## C0739002
         3.149      0.00892    2.4976e-5  # 1990,S.Qiang             ## C0739002
         3.251      0.01071    2.7846e-5  # 1990,S.Qiang             ## C0739002
         3.351      0.01409    3.0998e-5  # 1990,S.Qiang             ## C0739002
         3.452      0.01475     3.245e-5  # 1990,S.Qiang             ## C0739002
         3.554      0.01907    3.6233e-5  # 1990,S.Qiang             ## C0739002
         3.554      0.01913    3.6347e-5  # 1990,S.Qiang             ## C0739002
         3.655      0.01939    5.2353e-5  # 1990,S.Qiang             ## C0739002
         3.739      0.02415     5.796e-5  # 1990,S.Qiang             ## C0739002
         3.858      0.02444    5.8656e-5  # 1990,S.Qiang             ## C0739002
         3.959      0.02637    6.0651e-5  # 1990,S.Qiang             ## C0739002
          4.05      0.02777    6.1094e-5  # 1990,S.Qiang             ## C0739002
         4.141      0.02952    6.4944e-5  # 1990,S.Qiang             ## C0739002
         4.231      0.03678    6.9882e-5  # 1990,S.Qiang             ## C0739002
         4.323      0.04715    8.0155e-5  # 1990,S.Qiang             ## C0739002
         4.323      0.04734    8.0478e-5  # 1990,S.Qiang             ## C0739002
         4.323      0.04719    8.0223e-5  # 1990,S.Qiang             ## C0739002
         4.412      0.05565   0.00012243  # 1990,S.Qiang             ## C0739002
          4.44      0.05876    0.0001234  # 1990,S.Qiang             ## C0739002
          4.44      0.05875   0.00012337  # 1990,S.Qiang             ## C0739002
          4.51      0.06964   0.00013928  # 1990,S.Qiang             ## C0739002
```

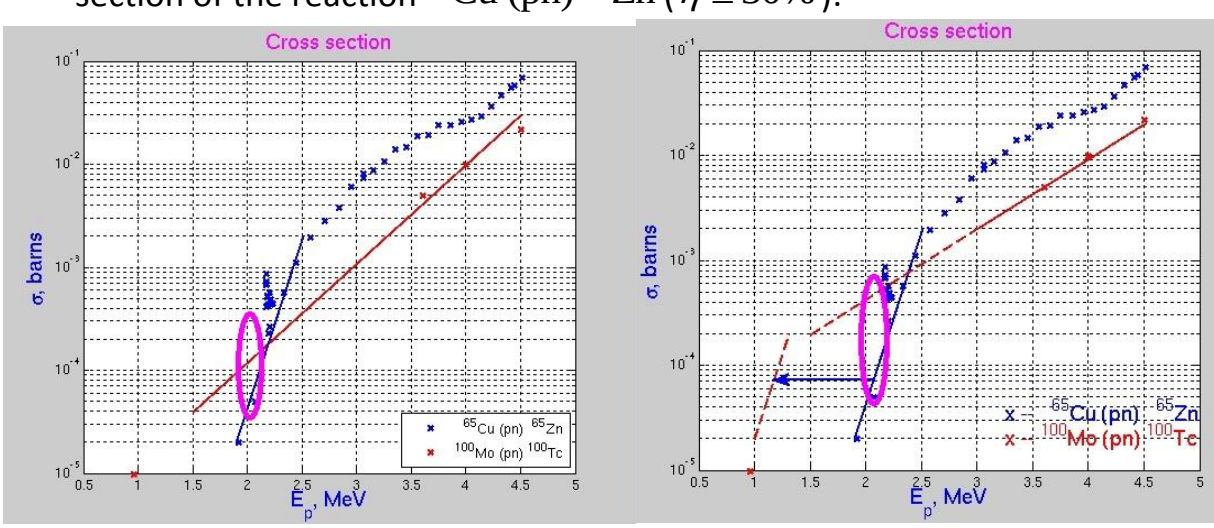
Experimental data for cross section [3]:



Cross Section Analysis

1. In the production of neutrons it can be neglected of the contribution for all reactions except $^{100}\mathrm{Mo}\ (\mathrm{pn})\ ^{100}\mathrm{Tc}$ and $^{97}\mathrm{Mo}\ (\mathrm{pn})\ ^{97}\mathrm{Tc}$. Overall abundance for these isotopes is $\eta \le 20\%$.

2. For these reactions it is possible to compare their cross sections with cross section of the reaction $^{65}\mathrm{Cu}\ (\mathrm{pn})\ ^{65}\mathrm{Zn}$ ($\eta \le 30\%$):

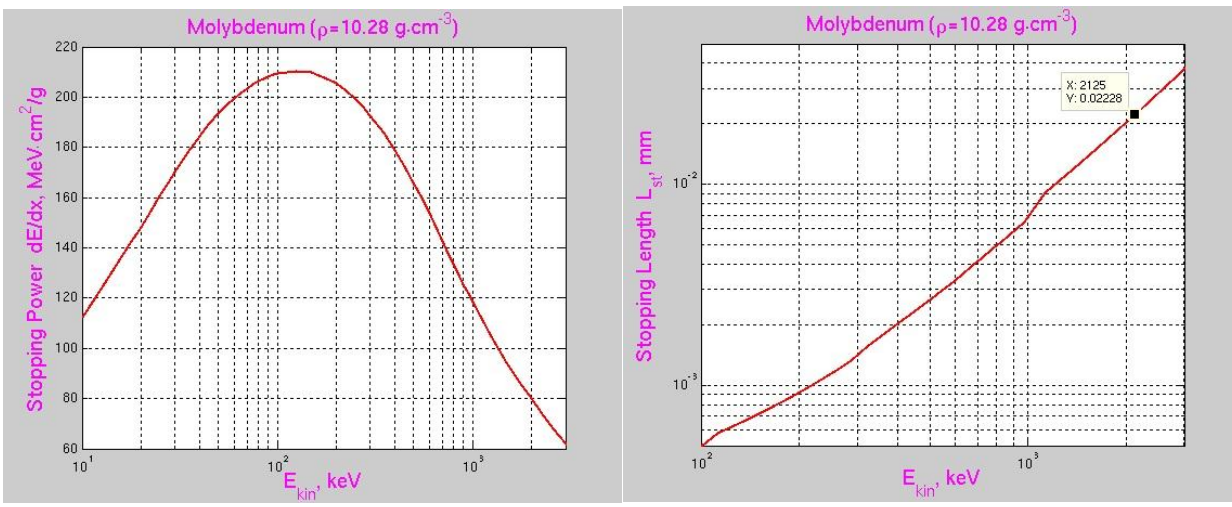


3. From these plots one can find (using different approaches) that for $E_p \approx 2.1\ \mathrm{MeV}$ the cross sections for Mo larger than for Cu from 2 to 8 times:

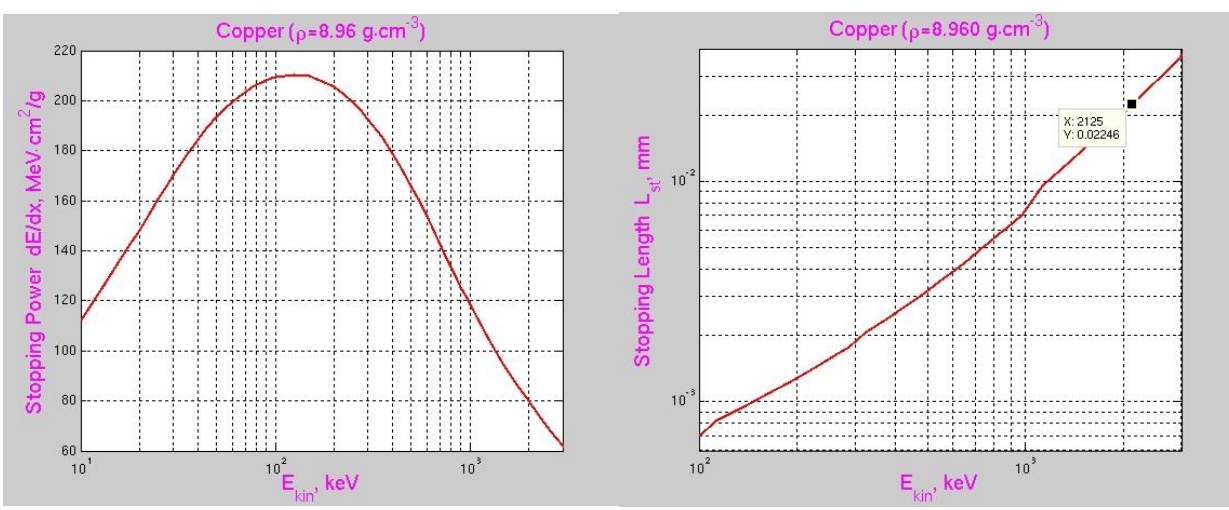
$$\boxed{\sigma \approx \begin{cases} 0.12 - 0.50\ \mathrm{mb} & \text{for Mo;} \\ 0.06\ \mathrm{mb} & \text{for Cu.} \end{cases}}$$

Stopping Length Data

Using data from [4] one can find the stopping powers for protons (with energy $E_p \approx 2.1\ \mathrm{MeV}$) and their stopping lengths in molybdenum and copper:



Molybdenum



Copper

From these data one have the following results:

$$\boxed{\lambda_{st} \approx 2.2 \cdot 10^{-3} \text{ cm} \quad \text{for Cu and Mo.}}$$

Neutron Yield

Let's calculate the neutron yield per proton:

$$N_n = 6.02 \cdot 10^{23} \frac{\rho}{A} \eta \sigma \lambda_{st},$$

For input data

	A	ρ, $\text{g} \cdot \text{cm}^{-3}$	σ, mb	η, %	λ_{st}, cm
Mo	95.94	10.28	$0.12 \div 0.50$	20	$2.2 \cdot 10^{-3}$
Cu	63.54	8.94	0.06	30	$2.2 \cdot 10^{-3}$

one has the following results:

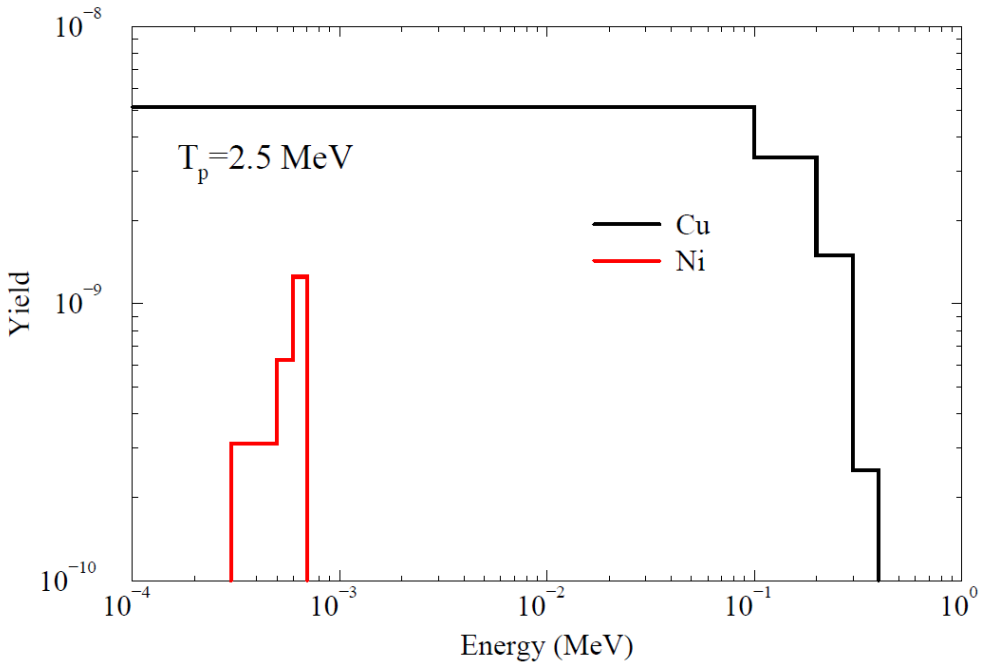
$$\boxed{Y_n \approx \begin{cases} (6.6 - 26.4) \cdot 10^{-9} \text{ p/p} & \text{for Mo;} \\ 3.5 \cdot 10^{-9} \text{ p/p} & \text{for Cu.} \end{cases}}$$

So, for molybdenum $\bar{Y} \approx 1.6 \cdot 10^{-8}$ p/p.

It is necessary to note, that this value is a very conservative: it was obtained under the assumption that the proton will fly the entire distance without changing its initial energy, so that the cross section of neutron production remains constant. In fact, the protons lose part of its energy is in the initial part of its trajectory. This means that the neutron cross section will decrease (and significantly!), and as soon as the proton energy is below the threshold of the corresponding reaction, the number of neutrons will fall sharply.

Dose Evaluation

To evaluate the dose it is necessary to know the energy spectrum of the radiated neutrons. It is shown for copper in the following figure [3] (these results were obtained with code MCNPX 2.6; by the way, the value of the neutron yield for copper agrees well with the above estimation):



It is seen that the maximal of neutron energy less than 400 keV, and the energy distribution of the neutrons is almost uniformly in the range from 0.1 keV till 100 keV, so that their average energy is about 50 keV.

Unfortunately, the similar spectrum data for molybdenum are not available. For these reasons let use for estimation data for copper: for these energies the dose per fluence conversion factor for neutrons $P_{eff}(E)$ is about $22\ \mathrm{pSv}\cdot\mathrm{cm}^2 = 22\cdot 10^{-12}\cdot 10^5 = 2.2\cdot 10^{-6}\ \mathrm{mrem}\cdot\mathrm{cm}^2$ [5]. The dose is defined as

$$\boxed{D_{[mrem/hr]} = \frac{P_{eff_{[mrem\cdot cm^2]}}\cdot N_{neutron_{[hr]}}}{S} = 3.6\cdot 10^3\,\frac{P_{eff_{[mrem\cdot cm^2]}}\cdot \bar{Y}\cdot N_{proton}}{4\pi R^2},}$$

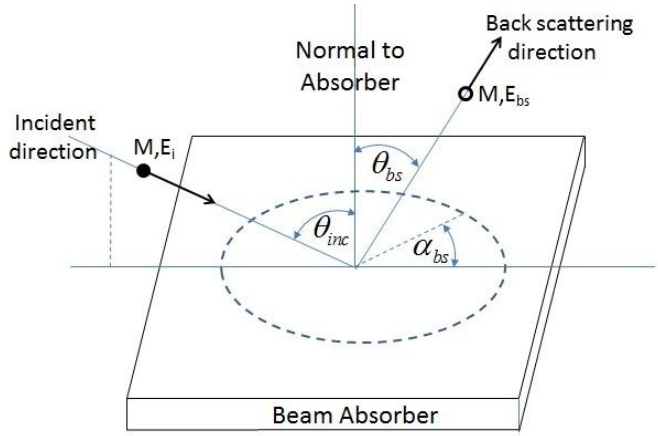
where R is a distance from neutron source and number protons per second is determined with beam current I. For $I = 10\ \mathrm{mA} \rightarrow N_{protons} \approx 6\cdot 10^{16}\,\mathrm{sec}^{-1}$ and $R = 1\ \mathrm{m}$ the very conservative estimation of dose is as follows:

$$\boxed{D \approx \frac{3.6\cdot 10^3}{4\pi\cdot 10^4}\underbrace{2.2\cdot 10^{-6}}_{P_{eff}}\cdot\underbrace{1.6\cdot 10^{-8}}_{\bar{Y}}\cdot\underbrace{6\cdot 10^{16}}_{N_{proton}} \approx 60\ \mathrm{mrem/hr}.}$$

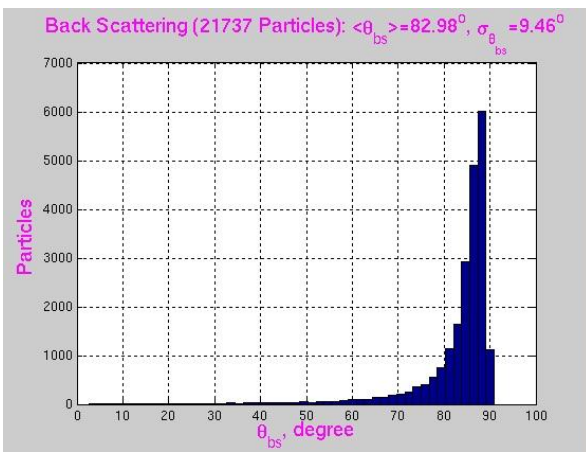
Again, this value should be regarded as a very conservative.

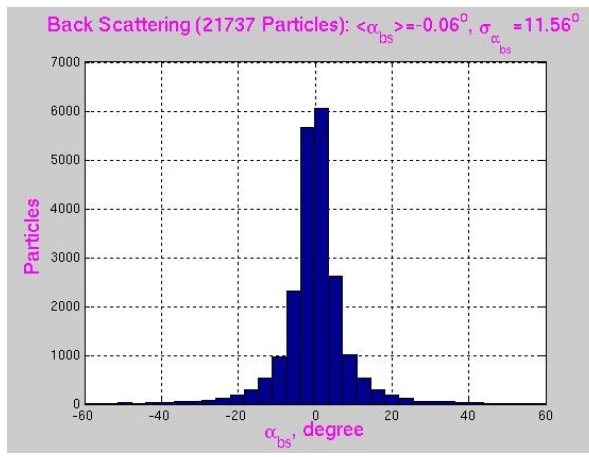
Results of Simulations with Code SRIM

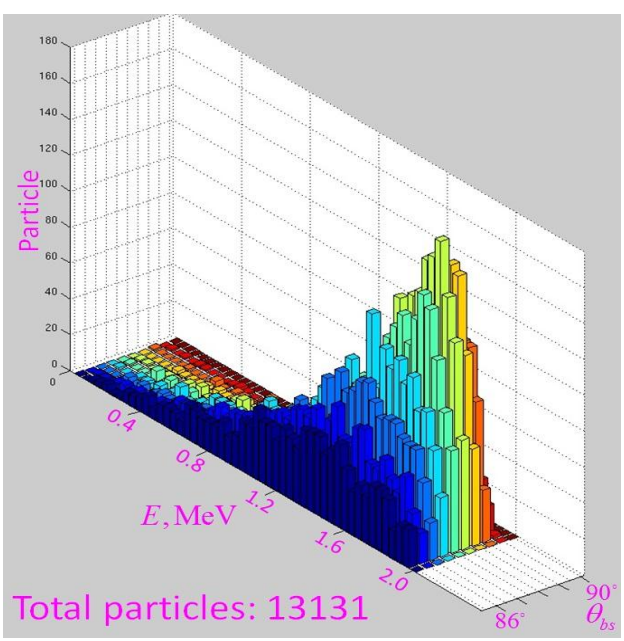
Code SRIM [6] was used to simulate backscattering effect. The geometry of simulation is shown in the left figure.



It was considered the fall of the proton beam with the energy 2.1 MeV on the molybdenum surface at a grazing angle of 0.29 mrad (≈2°). More than 40% of the 50,000 primary beam particles experienced backscatter. Angular distributions in the plane of incidence and perpendicular to it are shown below.

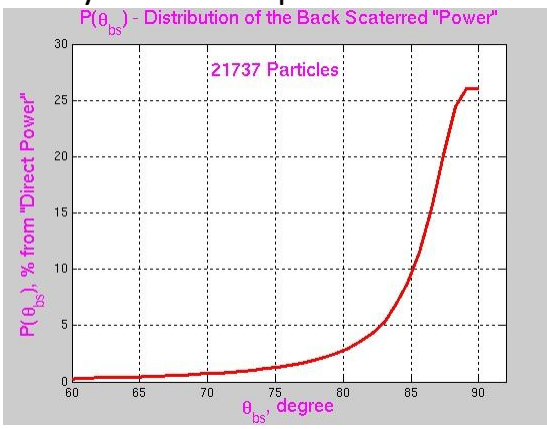






These particles have a broad distribution of energy (only particles in a small range of angles around the angle of reflection are shown). Based on this two-dimensional distribution is easy to calculate the fraction of energy carried away by these particles. The result for the angular distribution of this value is presented in the next figure. It shows that the particles have undergone back scattering, carry away

nearly 25% of the power of the incident beam.



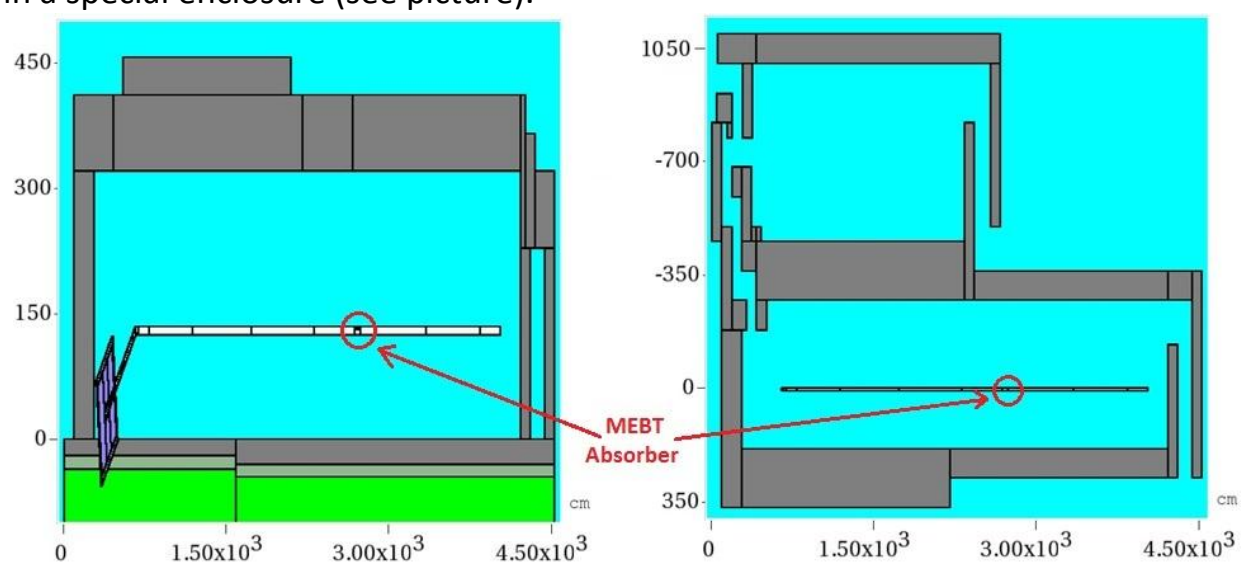
Simulation using the code TRIM also allows evaluate the difference in the maximal depth of penetration into the material of the absorber particles staying in it (L_{DR}) or have experienced back scattering (L_{BS}):

L_{BS}=0.19±0.21 μm for ≈22000 particles;
L_{BS}=1.75±1.24 μm for ≈28000 particles.

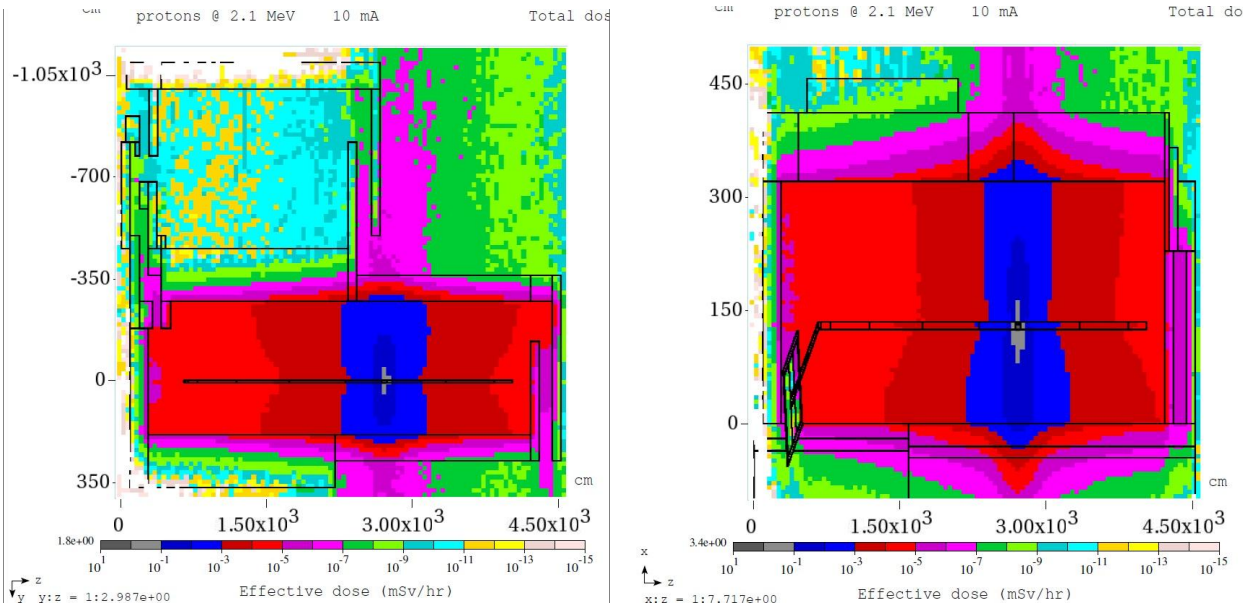
All these results indicate the need for more scrupulous simulation of the interaction of the incident beam with the absorber material and the elements surrounding it as well.

Results of Simulations with Codes MCNPX and MARS

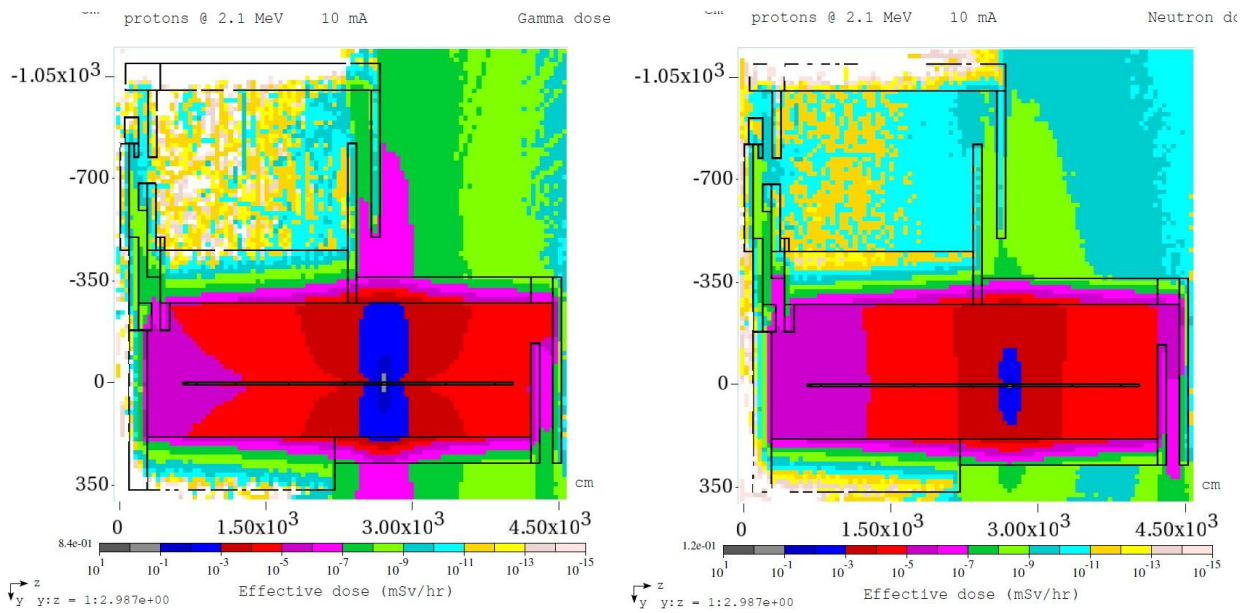
This simulation was conducted in two phases [3]. First, the code MCNPX 2.6 [7] was used to determine the yield of all secondary particles in the interaction of protons with energies of 2.1 MeV with the absorber material (TZM; its composition: 99.4% of Mo, 0.5% of Ti, 0.08% of Zr and 0.02% of C). At the same time it was taken into account that the absorber is part of the device PXIE, placed in a special enclosure (see picture).



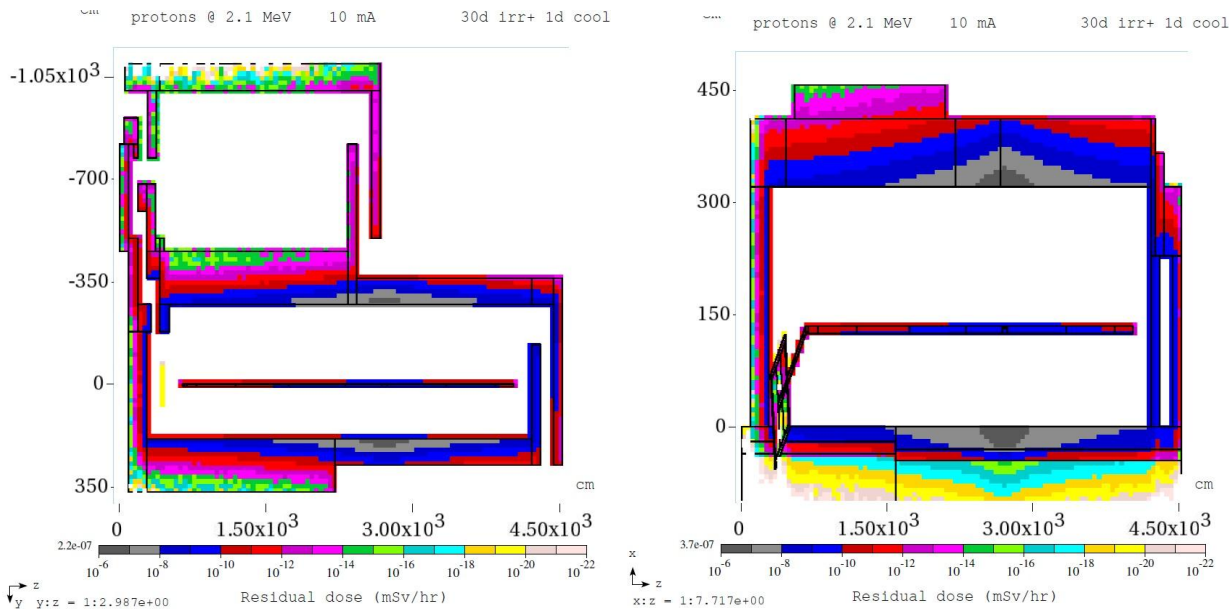
In the second stage of the first phase of the data used as input for code MARS [8] to simulate the distributions of the effective and residual doses (gammas, neutrons and total). The results of these simulations are shown in the following pictures.



Effective doses distributions (total).



Effective doses distributions: Gamma (left) and neutrons (right).



Residual doses distributions.

Main results if these simulations are as follows: the effective dose at a distance of ~1 m from absorber does not exceed the level ~10 mrem/hr (compare with the previous conservative evaluation). Another important result is that the effective dose for exits from the labyrinths does not exceed the level ~10^{-4} mrem/hr.

References

1. Q-value Calculator. http://nndc.bnl.gov
2. http://www.nndc.bnl.gov/exfor/exfor00.htm
3. N. Mokhov, I. Rakhno. “Neutron and Photon Production by Low Energy Protons”. Fermilab-FN-0909-APC, December 2010.
4. STAR code. http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html
5. J.D. Cossairt, K. Vaziri. “Neutron Dose per Fluence and Weighting Factors for Use at High Energy Accelerators”. Fermilab-Pub-08-244-ESH-REV, December 2008.
6. J.F. Zeigler, J.P. Biersack, M.D. Ziegler. “SRIM – the Stopping and Range of Ions in Mater”. http://www.srim.org.
7. Code MCNPX. https://mcnpx.lanl.gov.
8. N. Mokhov. “Code MARS”. http://www-ap.fnal.gov/MARS.