Analysis of Materials for MEBT Absorber

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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]

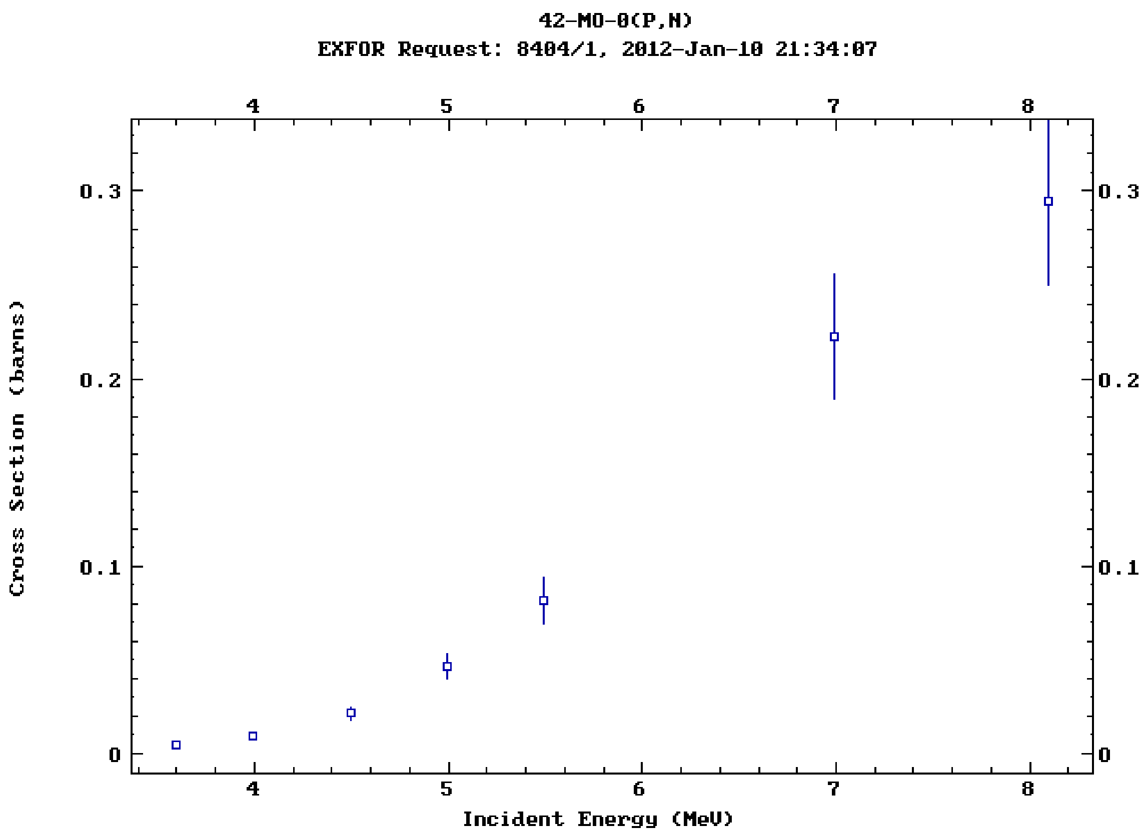
Data for **Mo**:

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
```

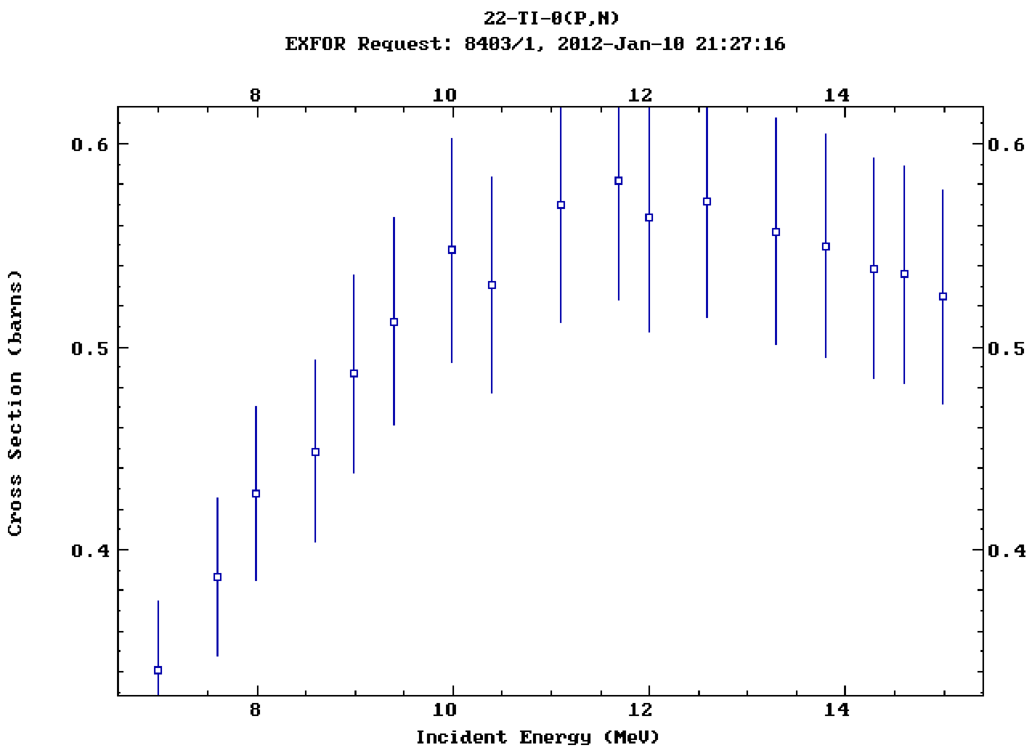
```
#data...
#             X             Y          +-dY  # Comments...
#           MeV         barns         barns  # Year,Author(s)       ## EXFOR-ID
            3.6         0.005       0.00075  # 1959,R.D.Albert      ## T0130015
              4          0.01        0.0015  # 1959,R.D.Albert      ## 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



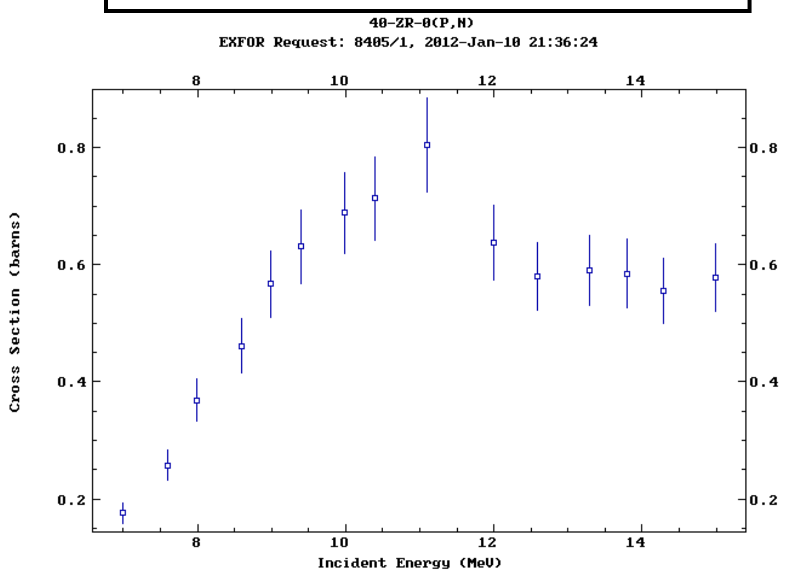

```
#ZVView-data-copy:  10-Jan-2012 21:27:16
#========================================
#
#name:   22-TI-0(P,N),,SIG
#X.axis: Incident Energy
#Y.axis: Cross Section
#wdata:  3
#ldata:  17
#data...
#       X          Y          +-dY  # Comments...
#      MeV       barns        barns  # Year,Author(s)      ## 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	$\rightarrow^{96}Nb \rightarrow^{96}Mo$



```
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#========================================
#
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#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:

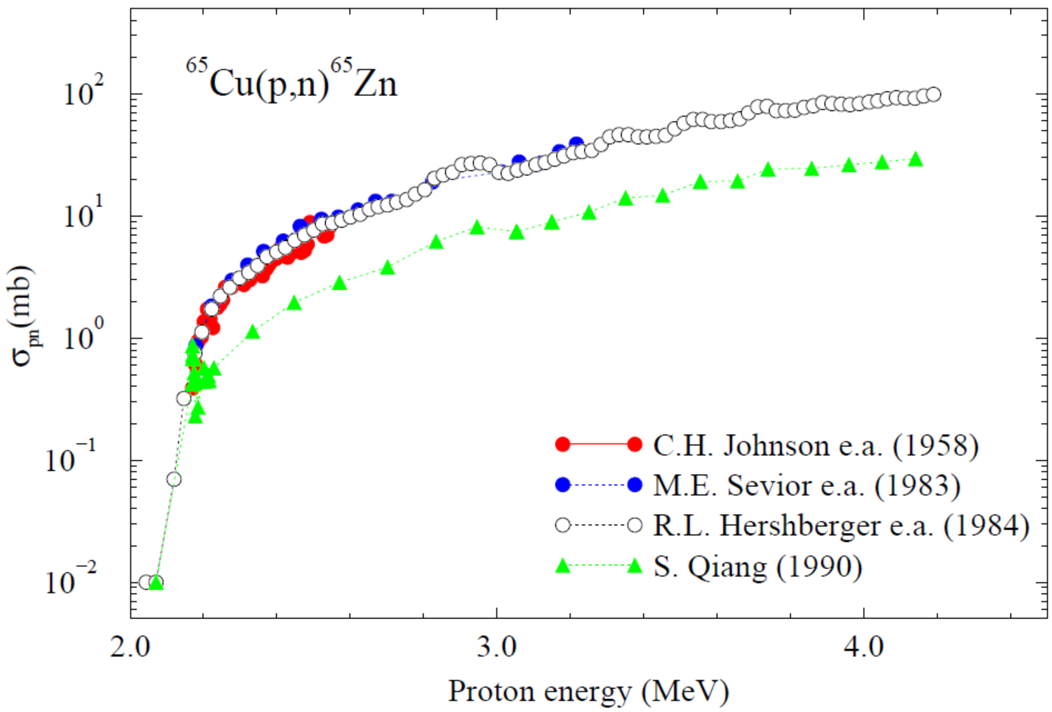
Isotope	Abundance,%	Final Isotope
^{63}Cu	69.17	^{63}Cu
^{65}Cu	30.83	^{65}Cu

```
#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

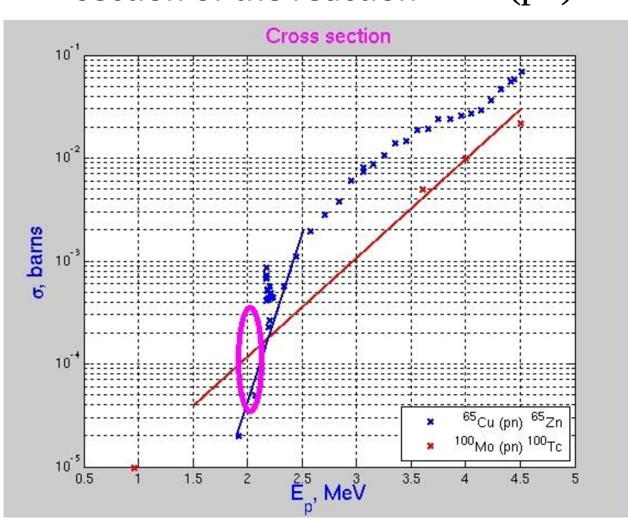
Experimental data for cross section [3]:

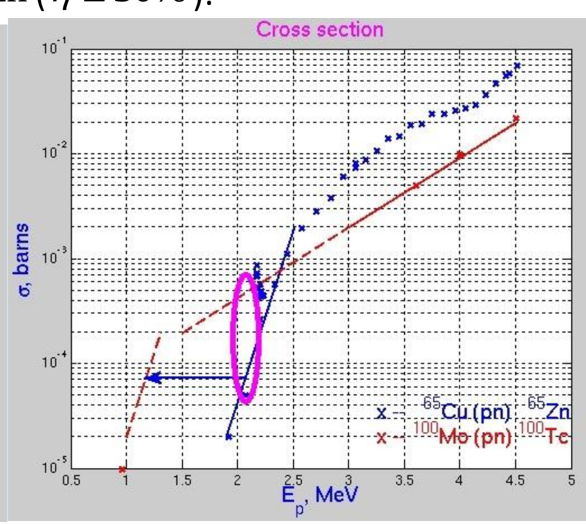


Cross Section Analysis

1. In the production of neutrons it can be neglected of the contribution for all reactions except $^{100}\mathrm{Mo\,(pn)}\,^{100}\mathrm{Tc}$ and $^{97}\mathrm{Mo\,(pn)}\,^{97}\mathrm{Tc}$. 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 $^{65}\mathrm{Cu\,(pn)}\,^{65}\mathrm{Zn}$ ($\eta \le 30\%$):



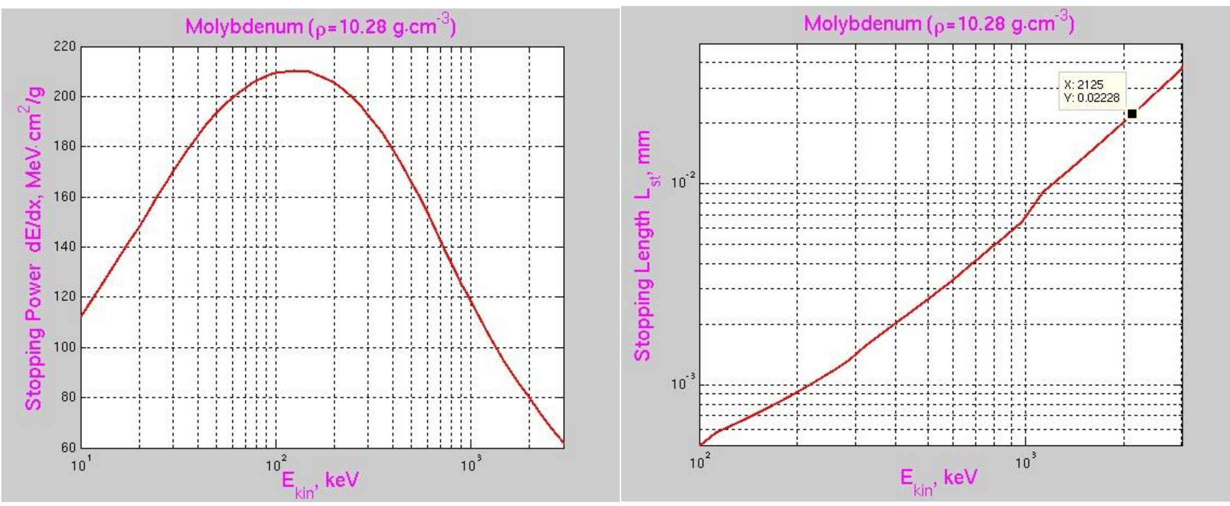


3. From these plots one can find (using different approaches) that for $E_p \approx 2.1\ \mathrm{MeV}$ the cross sections for Mo larger than for Cu from 2 to 8 times:

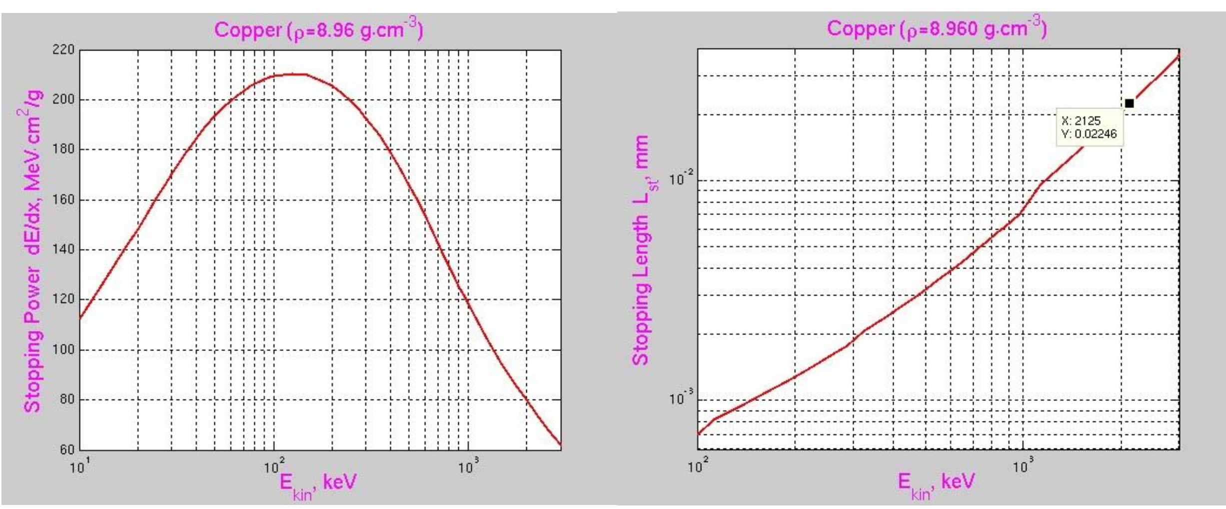
$$\sigma \approx \begin{cases} 0.12 - 0.50\ \mathrm{mb} & \text{for Mo;} \\ 0.06\ \mathrm{mb} & \text{for Cu.} \end{cases}$$

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:

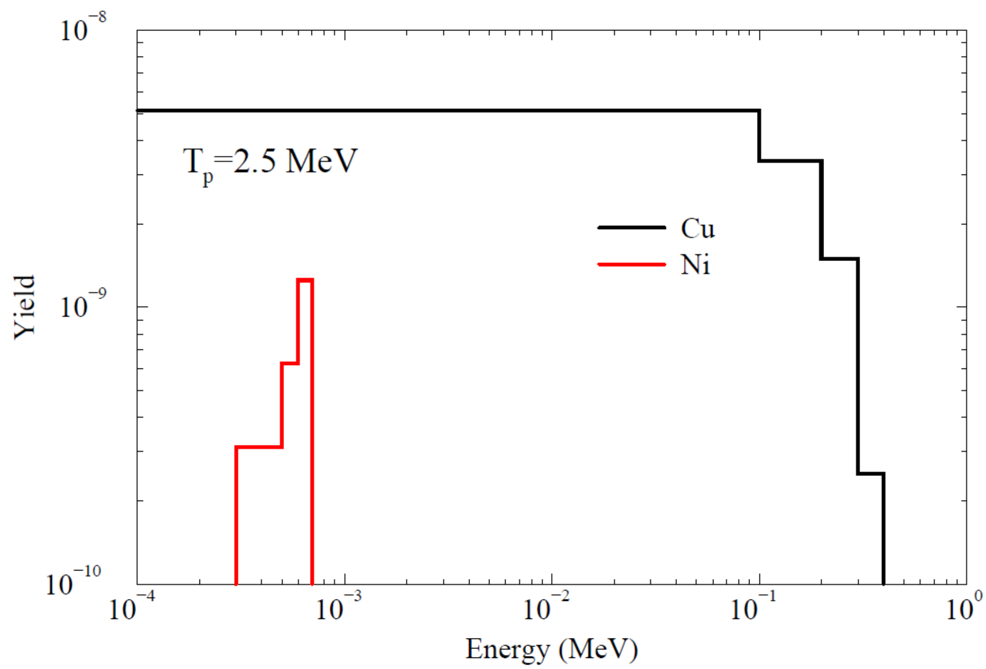
$$\boxed{Y_n \approx \begin{cases} (6.6 - 26.4) \cdot 10^{-9}\ \text{p/p} & \text{for Mo;} \\ 3.5 \cdot 10^{-9}\ \text{p/p} & \text{for Cu.} \end{cases}}$$

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 $22\ \mathrm{pSv}\cdot\mathrm{cm}^2 = 22\cdot10^{-12}\cdot10^5 = 2.2\cdot10^{-6}\ \mathrm{mrem}\cdot\mathrm{cm}^2$ [5]. The dose is defined as

$$D_{[mrem/hr]} = \frac{P_{eff_{[mrem\cdot cm^2]}}\cdot N_{neutron_{[hr]}}}{S} = 3.6\cdot10^3\,\frac{P_{eff_{[mrem\cdot cm^2]}}\cdot\bar{Y}\cdot N_{proton}}{4\pi R^2},$$

where R is a distance from neutron source and number protons per second is determined with beam current I. For $I = 10\ \mathrm{mA} \to N_{protons} \approx 6\cdot10^{16}\,\mathrm{sec}^{-1}$ and $R = 1\ \mathrm{m}$ the very conservative estimation of dose is as follows:

$$D \approx \frac{3.6\cdot10^3}{4\pi\cdot10^4}\underbrace{2.2\cdot10^{-6}}_{P_{eff}}\cdot\underbrace{1.6\cdot10^{-8}}_{\bar{Y}}\cdot\underbrace{6\cdot10^{16}}_{N_{proton}} \approx 60\ \mathrm{mrem/hr}.$$

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

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.