PHYSOR 2002, Seoul, Korea, October 7-10, 2002

NEUTRON SPALLATION SOURCE

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ABSTRACT

On benchmarking of the Dubna Cascade Code for the neutron multiplicity, a study of Intense Neutron Spallation Source (INSS) has been carried out in case of Lead, Lead + Bismuth, Thorium, Uranium and Tungsten spallation targets using the Code. Also, effect of Beryllium layer has been studied on angular and energy distributions and mean neutron multiplicity. The Code data obtained from this study helps in making selection of material of the spallation target as well as the design of INSS . It is suggested that application of layer (s) of Be- along with main Pb- and Pb+Bi target blocks help in focusing forward going neutrons at larger angles significantly in case of Pb-target. Broad energy distribution of spallation neutrons particularly on high energy side ($E_n > 50$ MeV) raises problem of their moderation in design of ADSS . It is also revealed that average heat contribution of escaped neutrons in case of Th- spallation source is about 50% higher than Uranium.

1. INTRODUCTION

For designing Accelerator Driven Sub-critical System one of the important requirement is designing of an Intense Neutron Spallation Source (INSS) [1-2] which can provide maximum neutron flux to the fuel assembly. For this purpose, mathematical modeling using a suitable computer code is highly perspective, time saving and economical particularly at the early stage of designing. Before using a mathematical code it is desirable to know about its benchmarking with respect to available experimental data for the purpose of confidence in design. In our earlier work Benchmarking of the Dubna Cascade Code-2001 [3] for the neutron yield has been done [4] using available experimental data of thick Pb- and W- targets and it may be said that the performance of the Code is found highly satisfactory for the average neutron multiplicity, N_n in case of proton collision with the large block of Pb- at beam energy $E < 1.2$ GeV. In case of collision with the block of W- the Code overestimates multiplicity of escaped neutrons within 15 % at $E < 1.2$ GeV and at all $E > 1.2$ GeV Code agrees within 25% . In fig.1 experimental results [5] of neutron multiplicity, Nn have been plotted with respect to length, L of the cylindrical target (diameter = 15 cm) for 1.22 GeV p+ Pb collision and compared with the results obtained from the Dubna Code. It may be seen from the figure that for the large target lengths, $L > 35$ cm rise of neutron multiplicity becomes slower.

For our further calculations we consider optimum size of the cylindrical target to be d x L = 20x60 cm^2 assuming that bigger cylindrical size may not be economical. For the detailed description of the Code reader is advised for publications [6,7] but it is worth mentioning that the

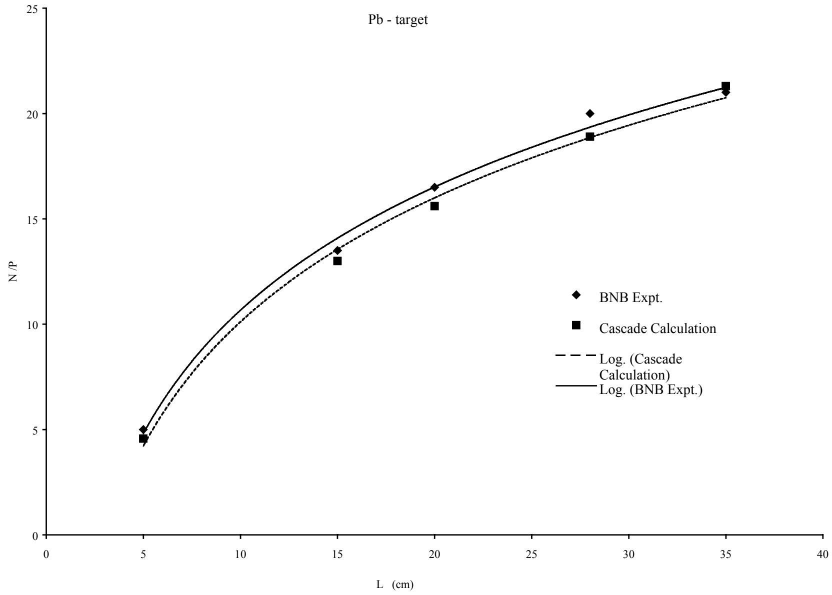


Figure 1. Variation of N / P with respect to length of the spallation target from BNB experiment and Dubna-Cascade-Code.

Code is highly comprehensive, there is no need of interfacing other Codes at any place of computation from the point of production of spallation neutrons, its transportation through the target material of any kind down up to thermal energy, 2.5×10^{-8}. Secondly, it has inbuilt features of mathematical designing and modeling of ADSS. In this paper we have presented estimates related to,

i) neutron multiplicity of escaped and captured neutrons from the Pb, Pb+Bi, W, Thorium and natural Uranium targets with their cylindrical geometry given as above. Simultaneously, effect on neutron number and angular distribution is also studied on including 10 cm length of Be-reflector just at the down stream end of spallation targets,

ii) heat contributions of different nuclear and atomic processes in collision of 1GeV proton beam with these targets using the Dubna Code and

iii) isotopic distribution of produced particles and nuclei .

In some cases these data are compared with the available experimental results also.

2 RESULTS OF THE DUBNA-CASCADE CODE

2.1 AVERAGE NEUTRON MULTIPLICITY PER BEAM PROTON (N / P)

In table 1 results of average neutron multiplicity per beam proton (N / P) obtained from the Code in case of 1 GeV proton beam colliding with the cylindrical blocks of Pb, Pb+ Bi (volume ratio being 45:55), Tungsten (W), Thorium ($_{90}Th^{232}$) and natural Uranium(U^{238} +U^{235}) spallation targets each of size d x L = 20 x 60 cm^2 and on adding a layer of Berillium($_4Be^9$) of size 2RxL = 20x10 cm^2 at the down stream end of the blocks . The beam is introduced axially at 5 cm dip in the target so that neutrons produced in backward direction are not lost . The purpose of introducing layer of Be- is to reflect those neutrons which may otherwise escape the block from the down stream end. On their reflection at larger angles they are directed towards the fuel assembly which in case of real design may exists out side of the cylindrical spallation targets. Be- reflector may first of all scatter out escaping neutrons at larger angles so that many of them enter the fuel assembly instead of escaping out and secondly it marginally increases their number through (n, 2n) reactions. The schematic design of such assembly is given in fig. 2.

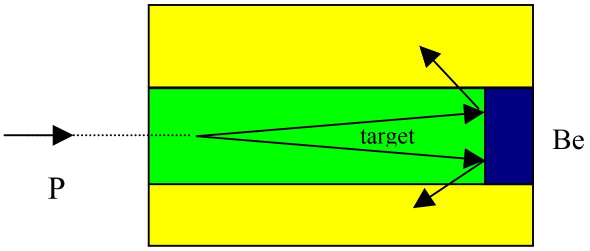


Figure 2. Spallation target of dimension d x L = 20 x 60 with Be- reflector for scattering of the escaping neutrons into the hypothetical fuel region shown around the target.

Table 1. Comparison of results of average neutron multiplicity per beam proton (N / P) calculated using Cascade Code for the bare target assemblies of Pb,Pb+Bi,Th, U(natural) and W- and on adding 10 cm length of Be- reflector .

Target	Pb	Pb+Be	Pb+Bi	Pb+Bi+Be	Th	Th+Be	U	U+Be	W	W+Be
Escaped	20.00	23.70	18.40	18.60	37.50	37.50	54.60	55.90	24.50	24.70
Captured	00.04	00.05	00.02	00.04	3.73	3.77	09.73	09.75	05.42	05.50
Total neutrons	20.04	23.75	18.42	18.64	41.23	41.27	64.33	64.65	29.92	30.20

In table 1 results of N / P from the Dubna –Code for the fixed proton beam energy, 1 GeV and different cylindrical targets with and without the Be- reflector have been given for the sake of comparison . On comparing results of non fission Pb, Pb+Bi and W- targets it may be said that W- is a better neutron source and when compared with Pb-, it is known that W- is very costly and hard in milling for shaping etc. Secondly, from the point of modeling by a mathematical code parameters of Pb are better available. Thirdly, number of escaped from W- spallation target is only 20% higher than Pb-target and on using Be-as reflector with Pb- even this difference of 20% is marginalized. Captured neutrons is no longer useful for fission. In all, Pb- is a good choice technically than W- even if it is used in molten condition as melting point of W-is very high compared to Pb-. In comparison to Pb+Bi eutectic again Pb- is better because Pb+Bi suffers from the higher radio-activity due to Polonium but slightly worse than the eutectic with melting point being 123 C for the eutectic and 327.5 C for the Pb-.

Estimates of neutron yield in case of Th- and U-targets are provided for their considerations in two reactor systems where inner reactor is assumed to provide very high yield of neutrons and the outer one is a reactor for burning of the Thorium like actinide. Alternatively it can also be used for the purpose of high rate of transmutation plus energy amplification. As can be seen from the data in table 1 both Thorium and Uranium provide much higher neutrons than the other targets. It may be pointed out that Nn is predicted to be 63.4 by the Dubna Code in case of natural Uranium target size d x L =20 x 60 cm^2 which is in close agreement with the Nn=55 given by HETC-KFA2 code [8] in case of U^{238} target of size d x L =10 x 100 cm^2 . In the two calculations difference of 9.3 neutrons may come firstly from the larger volume secondly because of U^{235} is mixed up with U^{238} in natural Uranium and that is a better source of neutrons. In figures 3-7 energy and angular distribution plots of escaped neutrons in case of the five sets of targets (Pb, Pb+Bi, Th, U and W-) are given for comparison and their application in ADSS design and modelling. The following observations are in order-

i) First important point about neutron energy distributions is that on adding Be-layer neutron energy is moderated significantly in case of all five targets.

ii) Secondly, from the figures 3b)-7 b) it is very clear that in case of Pb+Be combination a significant number of neutrons are scattered at larger angles to enter in the fuel cylinder while the number of scattered neutrons is insignificant in case of other targets.

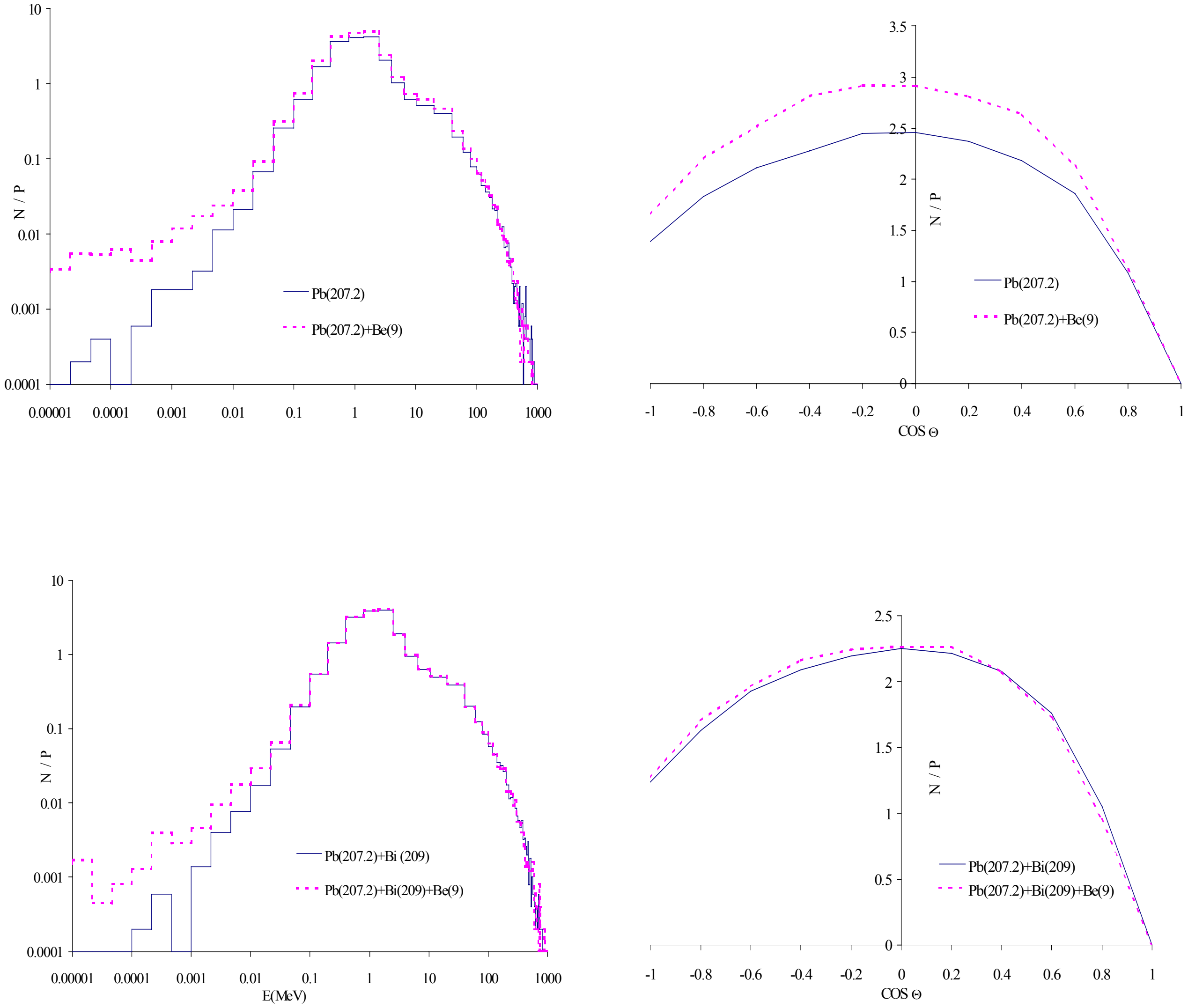
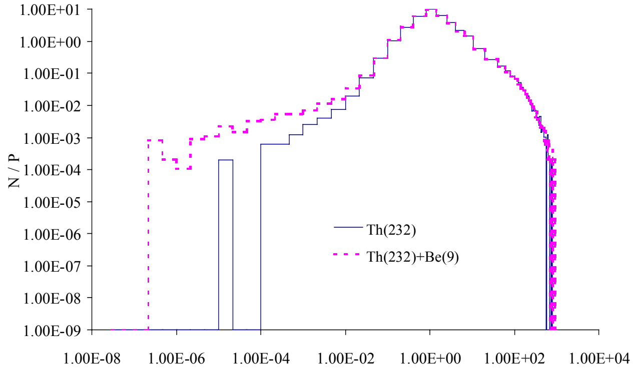

10
1
0.1
0.01
0.001
0.0001
N / P
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
Pb(207.2)
Pb(207.2)+Be(9)
3.5
3
2.5
2
1.5
1
0.5
0
N / P
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
COS Θ
Pb(207.2)
Pb(207.2)+Be(9)
10
1
0.1
0.01
0.001
0.0001
N / P
0.00001
0.0001
0.001
0.01
0.1
1
10
100
1000
E(MeV)
Pb(207.2)+Bi (209)
Pb(207.2)+Bi(209)+Be(9)
2.5
2
1.5
1
0.5
0
N / P
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
COS Θ
Pb(207.2)+Bi(209)
Pb(207.2)+Bi(209)+Be(9)

Fig. 2a
fig. 4 a)


N / P
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
1.00E-08
1.00E-06
1.00E-04
1.00E-02
1.00E+00
1.00E+02
1.00E+04
Th(232)
Th(232)+Be(9)

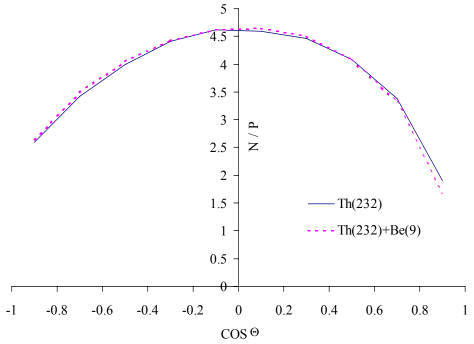
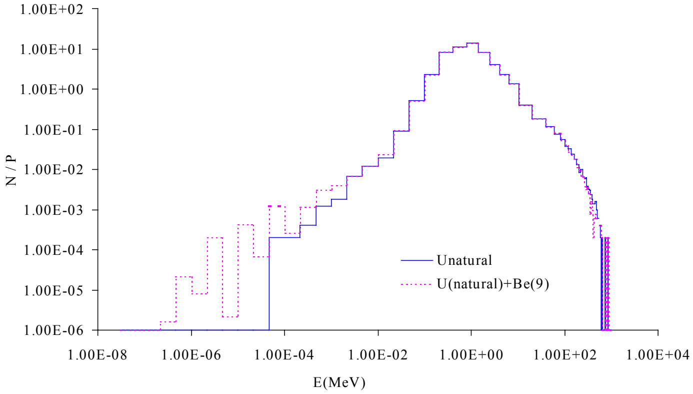
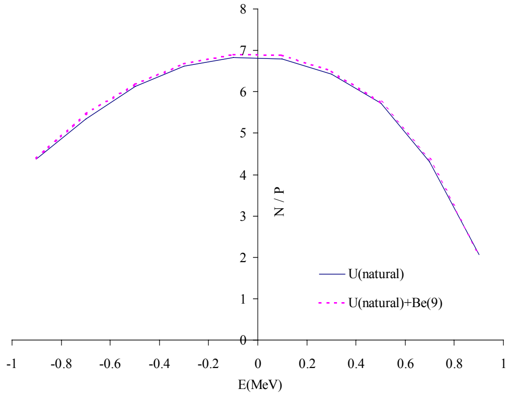

N / P
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
COS Θ
Th(232)
Th(232)+Be(9)

fig. 5 b)


N / P
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-08
1.00E-06
1.00E-04
1.00E-02
1.00E+00
1.00E+02
1.00E+04
E(MeV)
Unatural
U(natural)+Be(9)


N / P
8
7
6
5
4
3
2
1
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
E(MeV)
U(natural)
U(natural)+Be(9)

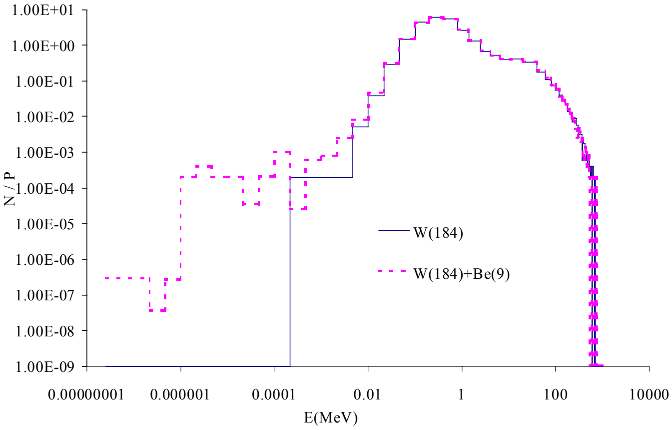
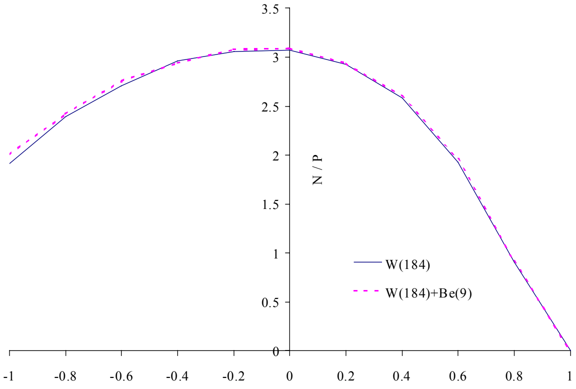

N / P
1.00E+01
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
1.00E-07
1.00E-08
1.00E-09
0.00000001
0.000001
0.0001
0.01
1
100
10000
E(MeV)
W(184)
W(184)+Be(9)

fig. 7 a)


N / P
3.5
3
2.5
2
1.5
1
0.5
0
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
W(184)
W(184)+Be(9)

2.2 HEAT CONTRIBUTIONS OF VARIOUS PROCESSES

Dubna Cascade Code provides estimate of heat contributions of following different atomic and sub-atomic processes taking place in side the targets. Table 2 gives comparative study of these processes in five sets of the targets in cases of with and without Be- reflector.

Following salient features may be revealed from the data in table 2,

i) contribution of ionization energy is very high ~ 44-49% of the beam energy in all the cases,

ii) fission energy contribution is only in case of Th- and U- targets and it works as the multiplicative factor of energy.

iii) contribution of (n, γ) process is very high in case of W-,Th- and U- than Pb- and Pb+Bi .

iv) energy of the escaped neutrons is about 50% higher in case of Th- target than U-, Pb and Pb+Bi while we also know that the average number of neutrons is about 80% more in U- than Th-. This implies that neutrons from the Th- source carry on an average very high energy than that from the U- source. This also means that for the Th- based ADSS one needs high moderation if fissile fuel is used in second part of the reactor.

v) The last but not the least important observation is that average energy of the neutrons is very high from the spallation sources therefore reactor size will increase because of requirement of high moderation for spallation neutrons of energy >50 MeV

Table 2. Average heat contributions of different atomic and sub-atomic processes, Q_i inside various targets (2R x L=20 x 60 cm^2) on collision of 1 GeV proton . Relative heat contribution from the ionization process, q = Q_{ion} / E (%) and total heat produced by each colliding proton is also given.

Heat (MeV) \ Targets	Pb	Pb+Be	Pb+Bi	Pb+Bi+Be	W	W+Be	Th	Th+Be	U	U+Be
Q_1 Ionization losses $q=Q_1 / E$ (%)	440 44	460 46	428 42.8	434 43.4	506 50.6	502 50.2	465 46.5	466 46.6	481 48.1	485 48.5
Q_2 Stopped hadrons and nuclei	11. 2	13. 2	10. 6	11.1	17.7	18.7	16. 3	16. 9	15.0	15. 2
Q_3 Low energy fission	0	0	0	0	0	0	118	117	1200	1200
Q_4 High energy fission	30.7	31.7	36.9	36.7	4.89	4.45	488	491	726	730
Q_5 Energy in (n, γ) reactions	.244	.319	.128	.231	31.1	31.6	16	18.1	47	47
Q_6 γ- ray de excitation by fission and inelastic collisions	13.7	15.6	12.9	13.1	21	21.2	32.1	32.3	86.7	87.1
Q_7 Gamma ray energy from pion decay	27.4	28.2	26.8	24.4	32.2	32.4	27.9	30	29.5	27
Q_8 Recoil nuclei energy in (n, γ) reactions	.0313	.0334	.0226	.0606	2.4	2.44	2.16	2.24	4.49	4.55
Q_9 Recoil nuclei energy in (n, n') reactions	17.5	21.5	15.4	15.5	50.1	50.7	45.8	45.7	79.8	80.4
Q_{10} Recoil nuclei energy in low energy elastic scattering	.589	.957	.494	.694	1.04	1.05	.486	.722	1.41	1.46
Q_{11} Recoil nuclei energy in high energy elastic scattering	.0147	.0422	.0134	.0403	.0308	.0338	.0163	.047	.0208	.024
Q_{12} Energy of the escaped neutrons $q_n=Q_{12}/E$(%)	137 13.7	153 15. 3	136 13. 6	137 13.7	97.9 9. 8	97.7 9. 8	183 18. 3	181 18.1	137 13.7	132 13. 2
Q_{13} Escaped charge particles	11.9	9.65	22.2	18.6	1.49	.823	19	14.2	1.66	1.47
Q_{14} Recoil energy of the residual cascade nuclei	218	252	204	202	318	320	274	270	291	292
Q (Total)	908	986	894	893	1084	1083	1688	1685	3101	3103

2.3 ISOTOPIC YIELD

Dubna Cascade Code provides estimates of the isotopic yield of produced nuclei in collision of beam proton with the target . The yield distribution can be easily divided in three categories viz. i) $A < 5$ ii) $5 < A < 150$ and iii) $A > 150$. In case of fissile targets fission fragments over populate the middle mass range . Yield of Polonium ($_{84}$Po) isotopes in case of p+ Pb comes out to be 1.469×10^{-7} (reactions /gm.cm^{-2} .p) and in case of p + (Pb+Bi) reactions it is much higher ~ 0.9576×10^{-4} (reactions /gm.cm^{-2} .p) . It is well known that isotopes of Po- are strong alpha emitters hence Pb+Bi target gets much higher radio-activity than Pb- so Pb+Bi is not favored in comparison of Pb . On the other hand from the point of neutron multiplication Pb+Bi+Be combination may be favored because alphas emission by Po- and that may react with Be- to produce neutrons . In this situation when Pb+Bi target is used as spallation target then after couple of days it may produce significant number of Po-nuclei which help in enhancing neutron yield. It seems Dubna Code has not taken care of this point of view in its present version.

Similarly, yield of $_{81}$Tl- isotopes is about 5.895×10^{-4} in Pb- which is comparable to 3.143×10^{-4} (reactions /gm.cm^{-2} .p) in case of Pb+Bi target .

3. CONCLUSIONS

From the aforesaid analytical study following conclusions may be drawn,

1. Neutron multiplicity data from the experiments and Dubna Cascade Code in proton collision with the block of Pb- up to 1.2 GeV energy agree very well . This suggests that dimensions of spallation source may be d x L = 20 x 60 cm^2 with out loosing significant number of neutrons.

On adding Be- layer enhancement of neutron yield as well as their scattering at larger angles is revealed from the Code calculations. This effect is favorable to the ADSS design.

2. Although Pb- seems to be better neutron source from the point of cost and radio-activity, nevertheless other considerations of molten phase, handling of the spallation source in ADSS suggest Pb+Bi eutectic to be better source. If the spallation source has to be exposed heavily to high current proton beam or for longer period with even moderate currents then Pb+Bi eutectic with Be layer will prove to be better neutron source.
3. Polonium yield is about 1000 times higher in Pb+Bi than Pb- target and other heavy mass products are almost comparable. Effects of production of Po- in enhancement of neutron yield may further be studied.

ACKNOWLEDGEMENTS

Authors are thankful to I.L.T.P. between India and Russia for the grant of the project and one of the author (V.S.B.) is also thankful to the Russian Foundation of Fundamental Researches for the financial support. Authors H.K and U.G. are thankful to C.S.I.R., New Delhi for granting them research fellowships.

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