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COSMO – a program to estimate spallation radioactivity produced in a pure substance by exposure to cosmic radiation on the earth

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A program is presented that calculates the production by nucleon-induced spallation of all radionuclides with halflives in the range 25 days–5 million years, from an initially pure substance.

PROGRAM SUMMARY

Title of program: COSMO

Catalogue number: ACJN

Program available from: CPC Program Library, Queen's University of Belfast, N. Ireland (see application form in this issue)

Licensing provisions: none

Computer: any with FORTRAN77 compiler

Programming language used: FORTRAN77

No. of lines in distributed program, including test data, etc.: 2279

Keywords: spallation, cosmogenesis, cosmic rays

Nature of the physical problem
Particularly in low-level counting applications (design of dark matter and neutrinoless ββ decay experiments), it is important to have estimates of the cosmogenic activity produced in detector and cryostat materials by interaction of cosmic rays. With straightforward modifications, the program would also be useful in computing induced radioactivity in accelerator components exposed to nucleon beams of energy greater than 50–100 MeV.

Method of solution
The variation of spallation, evaporation, fission, and peripheral reaction cross-sections with nucleon energy and target and product charge and mass numbers have been fitted to relatively simple analytic forms by Silberberg and Tsao [1]. The program COSMO augments these with approximations to the (p,xn) cross-sections of ref. [2] and the tritium production cross-sections of ref. [3]. A table containing all product radionuclides with lifetimes between 25 days and 5 million years is included, extracted from ref. [5]. An approximate energy spectrum for cosmic ray nucleons in the earth's atmosphere from the work of Lal and Peters [4] is used. The program permits the user to choose between three modes of calculation: an excitation curve showing production of any specified nuclide from any specified target nuclide as a function of beam energy; a mass yield curve showing total production of nuclides of a given mass number from a given target nuclide at a specified beam energy; or a list of all radionuclide activities produced from a specified target nuclide exposed to the approximate cosmic ray spectrum, for specified exposure time and decay time since exposure ended.

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Restrictions on the complexity of the problem
Only targets with atomic number less than 83 and mass number less than 210 are treated completely. Production of boron isotopes is not well represented by the Silberberg and Tsao fits. The treatment of (p, xn) reactions is based on very limited data. Nuclear energies from 100 MeV to 10 GeV are treated.

Overall accuracy of the Silberberg and Tsao fits for beam energies above 100 MeV is expected to be of the order of 20% in the cross-section, with the above noted exceptions. The assumption of charge independence is used to calculate production by cosmic ray neutrons using spallation cross-sections for proton induced reactions. This assumption is valid at the 25% level for beam energies above 75–100 MeV.

Typical running time
On an 80C88 microcomputer running at 8 MHz under DOS3.31, with Microsoft optimizing FORTRAN77 compiler, about 2 seconds for each medium mass product nuclide and each energy point.

References

[1] R. Silberberg, R. Tsao, Astrophys. J. Suppl. 220 (1973) 315, (1973) 335.
[2] L.B. Church and A.A. Caretto, Phys. Rev. 178 (1969) 1732.
[3] L.A. Currie, Phys. Rev. 110 (1959) 880; Phys. Rev. 114 (1959) 878.
[4] D. Lal and B. Peters, Handbuch der Physik 46/2 (1967) 567 (fig. 7).
[5] F.W. Walker, G.J. Kirouac and F.M. Rourke, eds., Chart of the Nuclides, (General Electric Company, San Jose, CA, 1977).

LONG WRITE-UP

1. Introduction

COSMO computes production cross-sections and activities for nuclides produced by nucleon-induced spallation of a specified set of target nuclides. Tabular data in the code permits automatic calculation of activity tables for all radioactive products produceable from the selected target nuclide. The program is intended to assist in materials selection and processing for ultra-low background experiments such as searches for galactic dark matter and neutrinoless $\beta\beta$ decay. The code runs on a microcomputer and has a simple interactive user interface.

2. Theory and numerical method

The theory of nuclear spallation, evaporation, fission, and peripheral reactions is briefly discussed in Silberberg and Tsao [1]. Mainly they give a set of decision rules and corresponding analytic formulae (fits to data) for calculating production of most of the radionuclides (Z,A) which can be produced by the high-energy bombardment of a target with (Z_t, A_t). Additional cross-section fits by the present authors to the data of Church [6] are used for (p, xn) reactions, and to the data of Currie [7] for tritium production.

The decision rules involve mainly the target and product atomic numbers and mass numbers. These rules permit one to determine which physical process (spallation, evaporation, fission, peripheral reaction, etc.) is responsible for a given production reaction. Once this is determined, the appropriate fitted formula from ref. [1] is used to calculate the production cross-section. Loops on product mass number, integration on beam energy, weighting by the cosmic ray spectrum [4] etc. are performed as requested by the user.

The program predictions have been compared by the authors to data from cosmic ray and reactor neutron activation of Ge [2–5]. Comparisons with literature data are difficult because published articles seldom give a thorough description of the samples' exposure histories. Some information about these comparisons is presented here. Exposure information can be gained by comparing activities for isotopes with similar (A, Z) but different halflives, for example the Co isotopes. Because of the guesswork involved in these comparisons, no detailed results are given here. However, the program is found to correctly predict which will be the most important radionuclides, and generally gives activities with an accuracy of the order of 50%.

3. Program structure

The code is supplied in nine files, each consisting of one major program unit, and associated FUNCTION program units. Some FUNCTION program units are used by several of the SUBROUTINES, and some of the major SUBROUTINES call each other, as required by the cross-section formulae to be computed. All data except for one lengthy table of product nuclide data is passed as arguments to subroutine calls. The product nuclide data is in a common block called ZATAU.

The main flow control and user interface is in SUBROUTINE COSMO. This prompts the user and accepts FORTRAN77 "free format" user inputs for target mass and atomic number, desired type of calculation (mass curve, excitation curve, activity calculation), energy range, etc. The structure of the input data is given in section 4. COSMO contains loops on product mass and beam energy. For activity calculations, all products listed in the table BLOCK DATA ZA having $Z \leqslant (Z_t + 1)$ are computed.

SUBROUTINE SELECT is called by COSMO to determine which physical process is involved in the production reaction under consideration. SELECT returns to COSMO an alphanumeric value coding for the relevant process. Next, subroutines MASSDEF and THR are called to check whether the current value of the bombarding energy exceeds the physical minimum energy required ("threshold") for the production reaction being calculated. The semiempirical mass formula of Seeger [8], modified to use the ^{12}C mass scale, is used for the threshold calculation.

If the energy is above the threshold, and depending on the value returned by SELECT, one or more of the cross-section calculation subroutines SLITE, SPALL, EVAP, FISS, PRPH are called. More than one call may be required because for some target–product pairs the cross-section prescribed by Silberberg and Tsao [1] is the maximum or a kind of geometric average of that calculated for two different physical processes.

The cross-section values are returned to COSMO, and either printed out directly or accumulated and weighted with the cosmic ray spectrum [9] to form an activity table. The activity tables are printed out separately for each target isotope, since this is often useful in applications. These ASCII tables can easily be summed and manipulated using a spreadsheet program.

4. Sample calculation

Sample input decks for Fe, with explanations. (Only the numbers should be put in the input deck). The output is given at the end of this paper.

a. Cosmic ray activity calculation: (option "a")

Input data	*Explanation*
45, 365	Exposure time, decay time (days)
26	Target element atomic number Z_t
4	Number of stable isotopes of target element
54, 0.058	Mass numbers A_t and abundances
56, 0.918	$f(A_t)$ of target isotopes (as many lines
57, 0.021	as stable isotopes exist)
58, 0.003	
1	Number of stable isotopes of $(Z_t + 1)$ element
59, 1	Mass number and abundances for each $(Z_t + 1)$ isotope
1	Number of stable isotopes of $(Z_t - 1)$ element
55, 1	Mass number and abundances for each $(Z_t - 1)$ isotope
a	Calculation option; *a* gives activity table from cosmic rays
40, 20, 23	Beginning bombarding energy, delta energy, number of energy steps

(end of input deck)

b. Single-energy, mass yield curve calculation (option "m")

Input data	*Explanation*
45, 365	Exposure time, decay time (days)
26	Target element atomic number Z_t
4	Number of stable isotopes of target element
54, 0.058	Mass numbers A_t and abundances
56, 0.918	$f(A_t)$ of target isotopes (as many lines
57, 0.021	as stable isotopes exist)

58, 0.003	
1	Number of stable isotopes of (Z_t+1) element
59, 1	Mass number and abundances for each (Z_t+1) isotope
1	Number of stable isotopes of (Z_t-1) element
55, 1	Mass number and abundances for each (Z_t-1) isotope
m	Calculation option; *m* gives mass yield curves at each energy
20	Up to 10 atomic masses at which
25	cross-section is to be calculated. Pro-
30	gram prints
35	$\Sigma_{Z_p,A_t} f(A_t)\,\sigma(A_t \to Z_p, A_p)$
40	
45	
50	
55	
0	Zero signifies end of mass entries
500, 20, 1	Beginning bombarding energy, delta energy, number of energy steps (end of input deck) Number of steps *must* be 1 for this option.

c. Single product, single energy option (option "z")

Input data	*Explanation*
45, 365	Exposure time, decay time (days)
26	Target element atomic number Z
4	Number of stable isotopes of target element
54, 0.058	Mass number and abundances of tar-
56, 0.918	get isotopes(as many lines as stable
57, 0.021	isotopes exist)
58, 0.003	
1	Number of stable isotopes of $(Z+1)$ element
59, 1	Mass number and abundances for each $(Z+1)$ isotope
1	Number of stable isotopes of $(Z-1)$ element
55, 1	Mass number and abundances for each $(Z+1)$ isotope
z	Calculation option; *z* gives activity table from cosmic rays
11, 23	Desired product Z_p, A_p (only one allowed)
500, 20, 1	Beginning bombarding energy, delta energy, number of energy steps (end of input deck) Number of energy steps *must* be 1 for this option. Program calculates production cross-section for desired product from each A_t.

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References

[1] R. Silberberg and R. Tsao, Astrophys. J. Suppl. Ser. 220 (1973) 315, 335.
[2] R.L. Brodzinski et al., Nucl. Instrum. Methods A 292 (1990) 337.
[3] E. Haller and E. Fiorini, private communication.
[4] B. Young, UCB-LBL, private communication.
[5] P. Fisher et al., Phys. Lett. 218 (1989) 257.
[6] L.B. Church and A.A. Caretto, Phys. Rev. 178 (1969) 1732.
[7] L.A. Currie, Phys. Rev. 110 (1959) 880; 114 (1959) 878.
[8] P.A. Seeger, Nucl. Phys. 25 (1961) 1.
[9] D. Lal and B. Peters, Handbuch der Physik 46/2 (1967) 567 (fig. 7).

TEST RUN OUTPUT

Using sample input deck from section 4a, calculate cosmic ray induced radioactivities in ^{nat}Fe target. Column 5 gives production rates in atoms per kg of ^{nat}Fe per day. Columns 6 and 7 give the activity in decays per kg of ^{nat}Fe per day, after the exposure time but respectively before and after the decay time specified in input deck.

```
 Cosmic Ray Spallation Program
 target atomic number=      26.000000 with           4 isotopes
 mass numbers and abundances       54.000000    5.800000E-02        56.000000
   9.180000E-01       57.000000    2.100000E-02        58.000000
   3.000000E-03
 centroid mass number=       56.250000 ezero=     2270.938000
 exposed for        45.000000 days, cooled down for        365.000000 days
option selected is a
  options are m for mass yield curve
              z for one product
              a for active nuclides
 E(start),delta(E),n(E)      40.000000        20.000000          23
```

Z(tgt)	A(tgt)	Z(pro)	A(pro)	Prd n /kg day	Initial Activity	Final Activty
26.	54.	1.	3.	.105E+01	.722E-02	.683E-02
26.	54.	4.	7.	.429E-01	.190E-01	.165E-03
26.	54.	4.	10.	.123E-01	.657E-09	.657E-09
26.	54.	5.	11.	.162E-02	.460E-11	.460E-11
26.	54.	6.	14.	.760E-03	.113E-07	.113E-07
26.	54.	10.	20.	.210E-02	.595E-11	.595E-11
26.	54.	11.	22.	.194E-02	.627E-04	.481E-04
26.	54.	13.	26.	.396E-02	.465E-09	.465E-09
26.	54.	14.	32.	.197E-02	.979E-06	.975E-06
26.	54.	15.	31.	.301E-01	.853E-10	.853E-10
26.	54.	15.	33.	.122E-01	.865E-02	.393E-06
26.	54.	16.	35.	.229E-01	.690E-02	.379E-03
26.	54.	17.	36.	.932E-01	.264E-07	.264E-07
26.	54.	18.	37.	.101E+00	.596E-01	.415E-04
26.	54.	18.	39.	.107E+00	.339E-04	.338E-04
26.	54.	18.	42.	.244E-02	.634E-05	.621E-05
26.	54.	20.	40.	.456E-01	.129E-09	.129E-09
26.	54.	20.	41.	.169E+00	.140E-06	.140E-06
26.	54.	20.	45.	.525E-01	.914E-02	.194E-02
26.	54.	21.	46.	.428E+00	.133E+00	.650E-02
26.	54.	22.	44.	.151E+00	.276E-03	.272E-03
26.	54.	23.	49.	.907E+01	.816E+00	.380E+00
26.	54.	23.	51.	.000E+00	.000E+00	.000E+00
26.	54.	24.	51.	.224E+02	.152E+02	.164E-02
26.	54.	25.	53.	.184E+01	.416E-07	.416E-07
26.	54.	25.	54.	.122E+01	.116E+00	.516E-01
26.	56.	1.	3.	.196E+02	.135E+00	.128E+00
26.	56.	4.	7.	.601E+00	.266E+00	.231E-02
26.	56.	4.	10.	.310E+00	.165E-07	.165E-07
26.	56.	5.	11.	.270E-01	.764E-10	.764E-10
26.	56.	6.	14.	.137E-01	.204E-06	.204E-06
26.	56.	10.	20.	.265E-01	.752E-10	.752E-10
26.	56.	11.	22.	.167E-01	.538E-03	.412E-03
26.	56.	13.	26.	.301E-01	.353E-08	.353E-08
26.	56.	14.	32.	.325E-01	.161E-04	.161E-04
26.	56.	15.	31.	.236E+00	.670E-09	.670E-09
26.	56.	15.	33.	.178E+00	.126E+00	.572E-05
26.	56.	16.	35.	.330E+00	.992E-01	.545E-02
26.	56.	17.	36.	.103E+01	.293E-06	.293E-06
26.	56.	18.	37.	.638E+00	.378E+00	.263E-03

26.	56.	18.	39.	.147E+01	.465E-03	.464E-03
26.	56.	18.	42.	.507E-01	.132E-03	.129E-03
26.	56.	20.	40.	.213E+00	.603E-09	.603E-09
26.	56.	20.	41.	.913E+00	.758E-06	.758E-06
26.	56.	20.	45.	.901E+00	.157E+00	.332E-01
26.	56.	21.	46.	.599E+01	.186E+01	.910E-01
26.	56.	22.	44.	.615E+00	.112E-02	.110E-02
26.	56.	23.	49.	.720E+02	.648E+01	.302E+01
26.	56.	23.	51.	.369E+02	.105E-06	.105E-06
26.	56.	24.	51.	.130E+03	.881E+02	.955E-02
26.	56.	25.	53.	.116E+03	.263E-05	.263E-05
26.	56.	25.	54.	.131E+03	.125E+02	.555E+01
26.	56.	26.	55.	.212E+03	.660E+01	.511E+01
26.	56.	27.	56.	.193E+02	.633E+01	.252E+00
26.	57.	1.	3.	.490E+00	.338E-02	.320E-02
26.	57.	4.	7.	.129E-01	.572E-02	.497E-04
26.	57.	4.	10.	.902E-02	.481E-09	.481E-09
26.	57.	5.	11.	.630E-03	.179E-11	.179E-11
26.	57.	6.	14.	.333E-03	.498E-08	.498E-08
26.	57.	10.	20.	.538E-03	.153E-11	.153E-11
26.	57.	11.	22.	.316E-03	.102E-04	.782E-05
26.	57.	13.	26.	.469E-03	.550E-10	.550E-10
26.	57.	14.	32.	.754E-03	.375E-06	.373E-06
26.	57.	15.	31.	.374E-02	.106E-10	.106E-10
26.	57.	15.	33.	.385E-02	.273E-02	.124E-06
26.	57.	16.	35.	.709E-02	.213E-02	.117E-03
26.	57.	17.	36.	.178E-01	.504E-08	.504E-08
26.	57.	18.	37.	.905E-02	.536E-02	.373E-05
26.	57.	18.	39.	.305E-01	.969E-05	.966E-05
26.	57.	18.	42.	.132E-02	.342E-05	.335E-05
26.	57.	20.	40.	.263E-02	.746E-11	.746E-11
26.	57.	20.	41.	.120E-01	.995E-08	.995E-08
26.	57.	20.	45.	.212E-01	.370E-02	.784E-03
26.	57.	21.	46.	.127E+00	.394E-01	.192E-02
26.	57.	22.	44.	.707E-02	.129E-04	.127E-04
26.	57.	23.	49.	.102E+01	.915E-01	.426E-01
26.	57.	23.	51.	.772E+00	.219E-08	.219E-08
26.	57.	24.	51.	.169E+01	.114E+01	.123E-03
26.	57.	25.	53.	.365E+01	.826E-07	.826E-07
26.	57.	25.	54.	.266E+01	.253E+00	.112E+00
26.	57.	26.	55.	.442E+00	.138E-01	.107E-01
26.	57.	27.	56.	.354E+00	.116E+00	.462E-02
26.	57.	27.	57.	.442E+00	.480E-01	.189E-01
26.	58.	1.	3.	.770E-01	.532E-03	.503E-03
26.	58.	4.	7.	.169E-02	.747E-03	.649E-05
26.	58.	4.	10.	.163E-02	.868E-10	.868E-10
26.	58.	5.	11.	.918E-04	.260E-12	.260E-12
26.	58.	6.	14.	.506E-04	.755E-09	.755E-09
26.	58.	10.	20.	.685E-04	.194E-12	.194E-12
26.	58.	11.	22.	.384E-04	.124E-05	.951E-06
26.	58.	13.	26.	.460E-04	.540E-11	.540E-11
26.	58.	14.	32.	.109E-03	.540E-07	.538E-07
26.	58.	15.	31.	.364E-03	.103E-11	.103E-11
26.	58.	15.	33.	.517E-03	.367E-03	.167E-07
26.	58.	16.	35.	.941E-03	.283E-03	.155E-04
26.	58.	17.	36.	.181E-02	.512E-09	.512E-09
26.	58.	18.	37.	.794E-03	.470E-03	.327E-06
26.	58.	18.	39.	.389E-02	.123E-05	.123E-05
26.	58.	18.	42.	.212E-03	.551E-06	.540E-06
26.	58.	20.	40.	.201E-03	.570E-12	.570E-12
26.	58.	20.	41.	.967E-03	.803E-09	.803E-09
26.	58.	20.	45.	.310E-02	.540E-03	.114E-03
26.	58.	21.	46.	.164E-01	.511E-02	.249E-03
26.	58.	22.	44.	.496E-03	.904E-06	.891E-06

26.	58.	23.	49.	.868E-01	.781E-02	.364E-02
26.	58.	23.	51.	.101E+00	.285E-09	.285E-09
26.	58.	24.	51.	.134E+00	.904E-01	.980E-05
26.	58.	25.	53.	.266E+00	.601E-08	.601E-08
26.	58.	25.	54.	.710E+00	.674E-01	.300E-01
26.	58.	26.	55.	.870E-01	.271E-02	.210E-02
26.	58.	27.	56.	.870E-01	.285E-01	.114E-02
26.	58.	27.	57.	.870E-01	.946E-02	.372E-02
26.	58.	27.	58.	.631E-01	.225E-01	.631E-03

```
****************************
****************************
Summary Table, Summed on Target Isotopes

target atomic number-      26.000000 with          4 isotopes
mass numbers and abundances
54.0000000    .0580000

56.0000000    .9180000

57.0000000    .0210000

58.0000000    .0030000

centroid mass number-      56.250000 ezero-     2270.938000
exposed for       45.000000 days, cooled down for      365.000000 days
E(start),delta(E),n(E)      40.000000        20.000000          23
```

ip	Z	A	t(1/2)	dndti	dndtf
1	1.	3.	.4500E+04	.1462E+00	.1382E+00
2	4.	7.	.5330E+02	.2916E+00	.2532E-02
3	4.	10.	.5840E+09	.1777E-07	.1777E-07
4	5.	11.	.1100E+11	.8310E-10	.8310E-10
5	6.	14.	.2090E+07	.2214E-06	.2214E-06
6	10.	20.	.1100E+11	.8290E-10	.8290E-10
7	11.	22.	.9494E+03	.6125E-03	.4692E-03
8	13.	26.	.2660E+09	.4053E-08	.4053E-08
9	14.	32.	.6280E+05	.1755E-04	.1748E-04
10	15.	31.	.1100E+11	.7672E-09	.7672E-09
11	15.	33.	.2530E+02	.1376E+00	.6254E-05
12	16.	35.	.8720E+02	.1085E+00	.5964E-02
13	17.	36.	.1100E+09	.3247E-06	.3247E-06
14	18.	37.	.3480E+02	.4431E+00	.3086E-03
15	18.	39.	.9820E+05	.5103E-03	.5090E-03
16	18.	42.	.1200E+05	.1419E-03	.1389E-03
17	20.	40.	.1100E+11	.7407E-09	.7407E-09
18	20.	41.	.3760E+08	.9086E-06	.9085E-06
19	20.	45.	.1630E+03	.1702E+00	.3606E-01
20	21.	46.	.8380E+02	.2040E+01	.9968E-01
21	22.	44.	.1710E+05	.1410E-02	.1390E-02
22	23.	49.	.3310E+03	.7393E+01	.3443E+01
23	23.	51.	.1100E+11	.1071E-06	.1071E-06
24	24.	51.	.2771E+02	.1045E+03	.1133E-01
25	25.	53.	.1380E+10	.2758E-05	.2758E-05
26	25.	54.	.3125E+03	.1291E+02	.5747E+01
27	26.	55.	.9855E+03	.6618E+01	.5120E+01
28	26.	59.	.4460E+02	.0000E+00	.0000E+00
29	26.	60.	.5470E+09	.0000E+00	.0000E+00
30	27.	56.	.7850E+02	.6479E+01	.2582E+00
31	27.	57.	.2710E+03	.5751E-01	.2261E-01
32	27.	58.	.7080E+02	.2250E-01	.6314E-03

Using sample input deck from section 4b, calculate mass yield curve from ^{nat}Fe target bombarded with 500 MeV protons.

```
 Cosmic Ray Spallation Program
 target atomic number=      26.000000 with           4 isotopes
 mass numbers and abundances      54.000000    5.800000E-02        56.000000
   9.180000E-01       57.000000    2.100000E-02        58.000000
   3.000000E-03
 centroid mass number=       56.250000 ezero=     2270.938000
 exposed for        45.000000 days, cooled down for       365.000000 days
option selected is m
  options are m for mass yield curve
              z for one product
              a for active nuclides
 E(start),delta(E),n(E)      500.000000       20.000000           1
Mass,sigma:
   20.      .443E+00 mb
   25.      .826E+00 mb
   30.      .204E+01 mb
   35.      .362E+01 mb
   40.      .651E+01 mb
   45.      .176E+02 mb
   50.      .508E+02 mb
   55.      .963E+02 mb
```

Using sample input deck from section 4c, calculate cross-sections for production of ^{23}Na from ^{nat}Fe target bombarded with 500 MeV protons.

```
 Cosmic Ray Spallation Program
 target atomic number=      26.000000 with           4 isotopes
 mass numbers and abundances      54.000000    5.800000E-02        56.000000
   9.180000E-01       57.000000    2.100000E-02        58.000000
   3.000000E-03
 centroid mass number=       56.250000 ezero=     2270.938000
 exposed for        45.000000 days, cooled down for       365.000000 days
option selected is z
  options are m for mass yield curve
              z for one product
              a for active nuclides
 E(start),delta(E),n(E)      500.000000       20.000000           1
 spallation of (ztgt,atgt)=       26.000000         54.000000
    producing (z,a,n/z)=      11.000000        23.000000          1.090909
  formula=lit4 ezero=     2270.938000
**********:sig(      500.000000 MeV)=   6.621197E-01 mb
 spallation of (ztgt,atgt)=       26.000000         56.000000
    producing (z,a,n/z)=      11.000000        23.000000          1.090909
  formula=lit4 ezero=     2270.938000
**********:sig(      500.000000 MeV)=   5.170147E-01 mb
 spallation of (ztgt,atgt)=       26.000000         57.000000
    producing (z,a,n/z)=      11.000000        23.000000          1.090909
  formula=lit4 ezero=     2270.938000
**********:sig(      500.000000 MeV)=   4.300104E-01 mb
 spallation of (ztgt,atgt)=       26.000000         58.000000
    producing (z,a,n/z)=      11.000000        23.000000          1.090909
  formula=lit4 ezero=     2270.938000
**********:sig(      500.000000 MeV)=   3.520810E-01 mb
```