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Test Calculations with IAEA Photonuclear Data Library

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Abstract

As a result of an international cooperation a recommended file of photonuclear reactions of 164 isotopes becomes available [1]. The formal and practical quality of these data are examined by using them for calculation of photoneutron production. A modified version [2] of MCNP code [3] is used for this purpose.

1 Representation of data in the IAEA Photonuclear Data Library

The IAEA Photonuclear Data Library is consisted of files originated from five laboratories. In spite of the earlier recommendations [4] the representation of data in files of different laboratories are different. (Some files contain trivial format errors, see later.) Only the files from LANL and KAERI are fully compatible and the BOFOD and CNDC files exhibit some similarity. Files from JENDL use MT=201-207 for photonuclear productions though this is not recommended in [4].

Nevertheless the utilization of files for photonuclear calculation with MCNP code could be attempted. Features of files relevant from this point of view are summarized below.

a) BOFOD representation

In BOFOD files (γ,n), (γ,2n) and (γ,fission) cross-sections (MF=3 MT=4, 16, 18) and ν (MF=1, MT=456) for fissionable isotopes can be found. The ν may be absent for some fissionables. In this case the ν values given in neutron table are used where the projectile energy is decreased by the threshold energy of (γ,fission) reaction. The CNDC data are of similar format except those for Be.

Upper energy bound for projectile: 20MeV for BOFOD, 30MeV for CNDC.

b) LANL representation

(γ,absorption) cross-section (MF=3, MT=5), yields and double differential cross-sections (MF=6, MT=5) are given. KAERI data are also given in this form. In certain files (C12 and O16) the total photoproduction is coming from reaction MT=5 and 50.

Upper energy bound for projectile: 150MeV for LANL, 140 MeV for KAERI.

c) JENDL representation

(γ,absorption) cross-section (MF=3, MT=5) and neutron production cross-sections (MF=3, MT=201) are given.

Upper energy bound for projectile: differs from file to file but generally over 100MeV.

2 Handling upper energy bound problem of libraries

If a photon energy is higher than the last energy point of photoneutron cross-section given in the data file then the following extrapolation procedure is applied: if below the upper energy bound the cross-section is decreasing then it will be linearly extrapolated down to zero, after this point it is always taken to zero, otherwise its last value is used for higher energies.

3 Energy and angular distribution of photoneutrons

The specification of energy and angular distribution of secondaries is the most differently specified data items in the files. Therefore, in the case BOFOD and JENDL representations the application of these data to the calculation of secondary angle-energy distribution of photoneutrons is given up. Instead an isotropic angular distribution is assumed and the photoneutron energy is calculated from the formula given below.

$$E_n = \frac{A-1}{A}(E_g - Q - \frac{E_g^2}{2m_n c^2 (A-1)} + \frac{E\,g}{A}\sqrt{\frac{2(A-1)}{m_n c^2 A(E_g - Q)}\cos q})$$

where
A = mass of the target nucleus,
$E\gamma$ = energy of photon
E_n = energy of neutrons
Q = threshold energy
m_n = neutron mass,
c = velocity of light,
θ = angle between photon and neutron flight direction.

In the case of (γ,2n) for the first neutron the threshold energy of (γ,2n) reaction is taken, and the energy of second neutron is calculated also from the above formula using the threshold energy of (γ,n) reaction.

For neutrons from (γ,fission) the energy is sampled from fission spectrum which is taken from the table specified for neutron projectile at energy which is the difference in energy of incident γ and the threshold energy of photofission reaction.

These method can be applied consequently in the case of BOFOD files, where reactions MT=4,16,18 are given explicitly. However, in the case of JENDL files the number of photoneutrons are calculated from the ratio of photoneutron production cross-section to photoabsorption cross-section. From this ratio the number of secondary neutrons is sampled (like to the number of fission neutrons). If this number greater the 2 and the isotope is not fissionable then a warning message is issued and the number of secondary neutron is taken to 2. In some cases the number of photoneutrons occured unphysically high which **may refer to the inaccuracy of data in the file.**

In the case of LANL representation the prescrition given for Kalbach parameters is followed. For reaction MT=50, the formula given above is used.

4 Formal errors of files and their elimination

The highest energy point in all KAERI files is 1.4E14 instead of 1.4E8. This error could easily be eliminated by our processing code. In Tables 1. errors (or possible errors) in individual files are enlisted. Three types of errors are noted:

1. File begins with no tape label and NSUB=10 is used. NJOY [5] routines are not able to process such file; This should be corrected by hand.
2. No dictionary is included. This is fatal for NJOY but our processing routine could scope with it.
3. To many secondaries at photonuclear process. This may refer to data of questional quality and requires further investigation.

Table 1. Errors in files

Isotope	Laboratory	type of error
H2	JAERI	1
N14	JAERI	1
Fe54	JAERI	2, 3
Fe56	JAERI	2, 3
Ni58	JAERI	2
Cu65	JAERI	2, 3
Zn64	JAERI	2
Ta181	JAERI	2, 3
W182	JAERI	1, 3
W186	JAERI	1, 3

5 Test calculations

In order to asses the applicability of photonuclear data simple test calculations have been accomplished.

For each isotope two targets are bombarded with photons of 20, 30, 50 and 80 MeV energy, respectively. The atomic density of targets was 3.3e-2 (x10e24) atom/cm^3 disregarding from the real density of actual material. (This density approximately corresponds to the real density of lead). First target is small: 6cm diameter and 4 cm thick, the second one is large: 50 cm diameter and 100 cm thick. In the Tables 1. the number of photoneutrons/incident photons are given.

From the point of view of physical consequences the isotopes with the same atomic order are interesting because for these the non-nuclear photon transport is taking place in the same way and the differences in photoneutrons are comming only from photonuclear data. It can be noted that in most of case the number photoneutrons increases with increasing number of neutrons in nucleus. Though, an exceptional case is the Ti46-48 for 20Mev gammas.

6 Verification with experimental data

Experimental data of photoneutron yields from electron induced bremstrahlung are used for a more physical verification of the applied calculational procedure and data. Such experimental data are found in paper [6], where measured neutron yields gained from bremstrahlung photons are given. We tried to reproduce the values given for natural lead making use the LANL photonuclear and high energy nuclear data available for isotopes of lead.

There are two natural lead targets of 11.5x11.5 cm^2 cross-section, 0.52 and 3.02 cm thickness, respectively. They are irradiated with 19, 28, 34, 60, 100, 150 MeV electrons, respectively. Calculations with MCNPX [7] have been carried out both with TTBR approximations (i.e. without detailed electron transport) and with detailed electron transport and the results are shown in Table 3. This verification seems to be successfull as no dramatic deviation from the experimental results is experienced.

Table 2a. Target dimension: 6cm diam. 4cm thick

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
H2	JAERI	3.100E-03	2.400E-03	2.100E-03	2.000E-03
Be9	CNDL	1.280E-02	1.960E-02	1.040E-02	6.000E-04
C12	LANL	7.470E-02	2.280E-02	2.100E-02	2.170E-02
C13	KAERI	2.580E-02	2.210E-02	2.870E-02	4.280E-02
N14	JAERI	2.450E-02	6.940E-02	1.630E-02	1.740E-02
N15	KAERI	2.590E-02	2.520E-02	3.700E-02	6.060E-02
O16	LANL	1.437E-01	1.397E-01	1.397E-01	1.150E-01
O17	KAERI	2.790E-02	3.510E-02	6.400E-02	8.950E-02
O18	KAERI	5.520E-02	6.850E-02	7.000E-02	8.430E-02
Na23	KAERI	3.890E-02	5.740E-02	1.014E-01	1.820E-01
Mg24	KAERI	6.750E-02	2.760E-02	8.790E-02	1.820E-01
Mg25	KAERI	1.863E-01	7.750E-02	1.685E-01	2.090E-01
Mg26	KAERI	6.800E-02	7.920E-02	1.322E-01	2.493E-01
Al27	LANL	1.349E-01	6.170E-02	1.018E-01	1.440E-01
Si27	KAERI	2.580E-02	3.420E-02	1.154E-01	2.130E-01
Si28	KAERI	1.199E-01	2.870E-02	1.097E-01	2.255E-01
Si29	KAERI	1.427E-01	7.390E-02	1.321E-01	2.500E-01
Si30	KAERI	2.589E-01	8.670E-02	1.597E-01	2.744E-01
S32	KAERI	1.141E-01	4.910E-02	1.383E-01	3.198E-01
S33	KAERI	5.900E-02	9.830E-02	1.979E-01	3.409E-01
S34	KAERI	8.520E-02	9.390E-02	2.123E-01	4.702E-01
S36	KAERI	2.597E-01	1.747E-01	2.938E-01	4.934E-01
Cl35	KAERI	2.570E-01	1.114E-01	2.313E-01	4.031E-01
Cl37	KAERI	1.482E-01	1.652E-01	2.338E-01	3.711E-01
Ar36	KAERI	1.090E-02	5.390E-02	1.845E-01	3.796E-01
Ar38	KAERI	7.000E-02	1.323E-01	2.682E-01	4.555E-01
Ar40	KAERI	2.446E-01	2.504E-01	3.521E-01	6.034E-01
K39	KAERI	2.433E-01	1.064E-01	2.092E-01	3.574E-01
K40	KAERI	9.870E-02	1.366E-01	2.545E-01	4.291E-01
K41	KAERI	1.674E-01	1.714E-01	2.810E-01	4.531E-01
Ca40	LANL	1.138E-01	5.470E-02	1.207E-01	2.165E-01
Ca42	KAERI	4.076E-01	1.500E-01	2.935E-01	4.810E-01
Ca43	KAERI	5.975E-01	1.882E-01	3.193E-01	5.257E-01
Ca44	KAERI	7.115E-01	2.512E-01	3.577E-01	5.738E-01
Ca46	KAERI	1.033E+00	3.025E-01	3.831E-01	6.318E-01
Ca48	KAERI	1.094E+00	3.364E-01	4.108E-01	6.678E-01
Ti46	KAERI	2.022E-01	1.454E-01	3.445E-01	7.026E-01
Ti47	KAERI	1.797E-01	1.853E-01	4.021E-01	7.504E-01
Ti48	KAERI	1.635E-01	2.436E-01	4.212E-01	7.848E-01
Ti49	KAERI	1.922E-01	2.434E-01	4.569E-01	8.360E-01
Ti50	KAERI	2.495E-01	2.889E-01	4.783E-01	8.568E-01
V51	CNDL	0.000E+00	5.287E-01	1.994E-01	2.308E-01
Cr50	CNDL	0.000E+00	5.619E-01	2.131E-01	2.414E-01
Cr52	CNDL	0.000E+00	5.632E-01	2.139E-01	2.437E-01

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
Cr53	CNDL	3.558E-01	5.641E-01	2.156E-01	2.495E-01
Cr54	CNDL	4.993E-01	5.677E-01	2.193E-01	2.585E-01
Mn55	KAERI	2.815E-01	2.979E-01	4.972E-01	9.382E-01
Fe54	JAERI	3.205E-01	8.810E-02	2.160E-01	3.888E-01
Fe56	JAERI	1.841E-01	2.812E-01	3.885E-01	5.261E-01
Fe57	KAERI	2.859E-01	3.331E-01	6.266E-01	1.063E+00
Fe58	KAERI	4.231E-01	3.948E-01	7.103E-01	1.092E+00
Co59	KAERI	2.277E-01	3.510E-01	6.282E-01	1.107E+00
Ni58	JAERI	1.386E-01	2.026E-01	2.971E-01	4.570E-01
Ni60	KAERI	1.811E-01	2.387E-01	5.295E-01	8.640E-01
Ni61	KAERI	2.210E-01	3.082E-01	6.595E-01	1.157E+00
Ni62	KAERI	3.380E-01	3.946E-01	6.726E-01	1.148E+00
Ni64	KAERI	5.927E-01	4.939E-01	8.506E-01	1.342E+00
Cu63	LANL	1.975E-01	3.113E-01	5.391E-01	8.364E-01
Cu65	JAERI	3.439E-01	3.716E-01	5.494E-01	6.469E-01
Zn64	JAERI	2.098E-01	2.384E-01	3.762E-01	5.777E-01
Zn66	KAERI	2.341E-01	2.986E-01	5.510E-01	9.328E-01
Zn67	KAERI	1.149E+00	4.125E-01	6.809E-01	1.142E+00
Zn68	KAERI	6.249E-01	4.895E-01	6.821E-01	1.118E+00
Zn70	KAERI	2.018E+00	6.433E-01	8.162E-01	1.348E+00
Ge70	KAERI	2.393E-01	3.622E-01	8.094E-01	1.301E+00
Ge72	KAERI	4.072E-01	4.294E-01	7.617E-01	1.177E+00
Ge73	KAERI	3.831E-01	4.143E-01	7.126E-01	1.132E+00
Ge74	KAERI	5.153E-01	4.725E-01	7.945E-01	1.221E+00
Ge76	KAERI	5.749E-01	4.934E-01	8.027E-01	1.247E+00
Sr84	KAERI	2.660E-01	3.607E-01	6.506E-01	1.148E+00
Sr86	KAERI	2.987E-01	4.345E-01	7.244E-01	1.224E+00
Sr87	KAERI	2.865E-01	4.330E-01	7.387E-01	1.236E+00
Sr88	KAERI	3.167E-01	4.535E-01	7.197E-01	1.230E+00
Sr90	KAERI	6.620E-01	6.092E-01	1.022E+00	1.608E+00
Zr90	KAERI	3.333E-01	5.825E-01	1.041E+00	1.711E+00
Zr91	CNDL	1.009E+00	1.084E+00	4.471E-01	5.905E-01
Zr92	CNDL	1.295E+00	1.091E+00	4.767E-01	6.625E-01
Zr93	KAERI	8.613E-01	9.454E-01	1.484E+00	2.478E+00
Zr94	KAERI	8.616E-01	9.280E-01	1.462E+00	2.269E+00
Zr96	CNDL	9.410E-01	1.094E+00	4.789E-01	6.787E-01
Nb93	KAERI	5.845E-01	5.744E-01	9.858E-01	1.579E+00
Nb94	KAERI	5.780E-01	6.171E-01	1.048E+00	1.640E+00
Mo92	KAERI	2.520E-01	2.914E-01	5.683E-01	1.088E+00
Mo94	KAERI	6.033E-01	6.050E-01	1.023E+00	1.612E+00
Mo95	KAERI	6.006E-01	6.479E-01	1.115E+00	1.687E+00
Mo96	KAERI	7.162E-01	6.783E-01	1.275E+00	1.874E+00
Mo97	KAERI	7.680E-01	7.798E-01	1.311E+00	1.958E+00
Mo98	KAERI	8.278E-01	8.224E-01	1.389E+00	2.143E+00
Mo100	KAERI	8.640E-01	9.006E-01	1.493E+00	2.233E+00
Pd102	KAERI	4.974E-01	5.777E-01	1.075E+00	1.788E+00
Pd104	KAERI	6.747E-01	6.919E-01	1.294E+00	2.021E+00
Pd105	KAERI	7.817E-01	8.329E-01	1.423E+00	2.222E+00
Pd106	KAERI	9.037E-01	8.501E-01	1.488E+00	2.266E+00
Pd107	KAERI	9.108E-01	9.762E-01	1.635E+00	2.524E+00
Pd108	KAERI	9.319E-01	8.992E-01	1.492E+00	2.292E+00
Pd110	KAERI	1.008E+00	1.049E+00	1.781E+00	2.664E+00
Ag107	KAERI	6.857E-01	6.582E-01	1.317E+00	2.101E+00

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
Ag108	KAERI	6.489E-01	7.471E-01	1.282E+00	1.985E+00
Ag109	KAERI	7.159E-01	7.295E-01	1.263E+00	1.996E+00
Cd106	KAERI	3.616E-01	6.212E-01	1.167E+00	2.024E+00
Cd108	KAERI	5.561E-01	6.336E-01	1.092E+00	1.770E+00
Cd110	KAERI	7.436E-01	7.137E-01	1.228E+00	1.956E+00
Cd111	KAERI	7.866E-01	8.349E-01	1.384E+00	2.235E+00
Cd112	KAERI	8.274E-01	7.780E-01	1.305E+00	2.060E+00
Cd113	KAERI	8.267E-01	9.020E-01	1.494E+00	2.334E+00
Cd114	KAERI	8.610E-01	8.379E-01	1.399E+00	2.170E+00
Cd116	KAERI	9.589E-01	9.439E-01	1.578E+00	2.421E+00
Sn112	KAERI	5.133E-01	6.384E-01	1.075E+00	1.821E+00
Sn114	KAERI	7.412E-01	8.232E-01	1.526E+00	2.498E+00
Sn115	KAERI	8.970E-01	1.001E+00	1.692E+00	2.801E+00
Sn116	KAERI	8.819E-01	8.562E-01	1.089E+00	1.453E+00
Sn117	KAERI	9.856E-01	8.699E-01	1.667E+00	3.282E+00
Sn118	KAERI	9.487E-01	9.977E-01	1.559E+00	2.527E+00
Sn119	KAERI	1.097E+00	1.219E+00	2.108E+00	3.414E+00
Sn120	KAERI	9.368E-01	1.063E+00	1.736E+00	2.799E+00
Sn122	KAERI	1.037E+00	1.059E+00	1.728E+00	2.782E+00
Sn124	KAERI	1.026E+00	1.080E+00	1.752E+00	2.724E+00
Sb121	KAERI	7.960E-01	8.236E-01	1.434E+00	2.319E+00
Sb123	KAERI	8.218E-01	8.311E-01	1.446E+00	2.329E+00
Te120	KAERI	7.911E-01	7.983E-01	1.552E+00	2.364E+00
Te122	KAERI	9.088E-01	8.712E-01	1.560E+00	2.473E+00
Te123	KAERI	9.597E-01	1.093E+00	1.817E+00	2.949E+00
Te124	KAERI	9.770E-01	9.873E-01	1.668E+00	2.704E+00
Te125	KAERI	1.048E+00	1.217E+00	2.002E+00	3.238E+00
Te126	KAERI	1.055E+00	1.074E+00	1.784E+00	2.857E+00
Te128	KAERI	1.027E+00	1.109E+00	1.851E+00	2.957E+00
Te130	KAERI	1.066E+00	1.159E+00	1.959E+00	3.164E+00
I127	KAERI	9.939E-01	1.018E+00	1.792E+00	2.898E+00
I129	KAERI	1.061E+00	1.093E+00	1.885E+00	3.053E+00
Cs133	KAERI	8.173E-01	8.402E-01	1.534E+00	2.447E+00
Cs135	KAERI	9.534E-01	9.944E-01	1.757E+00	2.774E+00
Cs137	KAERI	1.031E+00	1.090E+00	1.891E+00	2.974E+00
Pr141	KAERI	9.522E-01	9.264E-01	1.584E+00	2.566E+00
Sm144	KAERI	5.976E-01	8.233E-01	1.560E+00	2.407E+00
Sm147	KAERI	1.134E+00	1.013E+00	1.704E+00	2.833E+00
Sm148	KAERI	1.180E+00	1.223E+00	1.956E+00	3.090E+00
Sm149	KAERI	1.286E+00	1.357E+00	2.206E+00	3.773E+00
Sm150	KAERI	1.321E+00	1.529E+00	2.585E+00	4.038E+00
Sm151	KAERI	1.316E+00	1.558E+00	2.633E+00	4.251E+00
Sm152	KAERI	1.324E+00	1.538E+00	2.590E+00	4.182E+00
Sm154	KAERI	1.433E+00	1.713E+00	2.950E+00	4.769E+00
Tb158	KAERI	1.169E+00	1.431E+00	2.405E+00	3.945E+00
Tb159	KAERI	1.220E+00	1.365E+00	2.324E+00	3.836E+00
Ho165	KAERI	1.176E+00	1.246E+00	2.039E+00	3.350E+00
Ta181	JAERI	1.102E+00	1.266E+00	1.680E+00	2.389E+00
W180	CNDL	1.095E+00	1.710E+00	8.106E-01	1.272E+00
W182	JAERI	1.187E+00	1.385E+00	2.008E+00	3.128E+00
W183	CNDL	1.140E+00	1.734E+00	8.922E-01	1.438E+00
W184	LANL	1.090E+00	1.658E+00	2.653E+00	4.160E+00
W186	JAERI	1.191E+00	1.296E+00	1.748E+00	2.558E+00

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
Au197	KAERI	1.001E+00	1.294E+00	2.167E+00	3.640E+00
Pb206	LANL	1.124E+00	1.721E+00	2.744E+00	4.353E+00
Pb207	LANL	1.135E+00	1.764E+00	2.830E+00	4.489E+00
Pb208	LANL	1.097E+00	1.646E+00	2.880E+00	4.688E+00
Bi209	CNDL	1.154E+00	1.787E+00	8.919E-01	1.446E+00
Th232	BOFOD	1.861E+00	3.607E-01	1.111E+00	2.300E+00
U233	BOFOD	1.854E+00	3.322E-01	9.125E-01	1.836E+00
U234	BOFOD	1.823E+00	2.889E-01	9.332E-01	1.984E+00
U235	BOFOD	1.871E+00	3.913E-01	1.025E+00	2.072E+00
U236	BOFOD	1.833E+00	3.282E-01	1.021E+00	2.155E+00
U238	BOFOD	1.859E+00	3.703E-01	1.044E+00	2.102E+00
Pu238	BOFOD	1.850E+00	2.900E-01	9.539E-01	2.056E+00
Pu239	BOFOD	1.876E+00	3.715E-01	1.104E+00	2.294E+00
Pu241	BOFOD	1.903E+00	4.354E-01	1.255E+00	2.562E+00

Table 2b. Target dimension: 50 diam 100 thick

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
H2	JAERI	7.360E-02	5.830E-02	4.870E-02	4.290E-02
Be9	CNDL	3.521E-01	4.980E-01	3.538E-01	1.663E-01
C12	LANL	1.251E+00	4.897E-01	5.098E-01	6.145E-01
C13	KAERI	4.379E-01	3.952E-01	5.306E-01	8.728E-01
N14	JAERI	3.621E-01	1.066E+00	3.018E-01	4.051E-01
N15	KAERI	3.871E-01	4.183E-01	6.098E-01	1.090E+00
O16	LANL	1.863E+00	1.878E+00	1.964E+00	1.821E+00
O17	KAERI	4.896E-01	6.419E-01	1.177E+00	1.865E+00
O18	KAERI	7.151E-01	9.558E-01	1.038E+00	1.412E+00
Na23	KAERI	3.750E-01	5.318E-01	1.054E+00	1.807E+00
Mg24	KAERI	5.571E-01	2.318E-01	7.573E-01	1.555E+00
Mg25	KAERI	1.613E+00	7.454E-01	1.724E+00	2.231E+00
Mg26	KAERI	5.986E-01	7.387E-01	1.366E+00	2.414E+00
Al27	LANL	1.043E+00	4.770E-01	8.165E-01	1.215E+00
Si27	KAERI	1.734E-01	2.206E-01	7.771E-01	1.439E+00
Si28	KAERI	8.185E-01	2.007E-01	7.595E-01	1.583E+00
Si29	KAERI	1.039E+00	5.704E-01	1.077E+00	2.065E+00
Si30	KAERI	1.850E+00	6.499E-01	1.284E+00	2.242E+00
S32	KAERI	6.542E-01	2.826E-01	7.960E-01	1.825E+00
S33	KAERI	3.743E-01	6.209E-01	1.288E+00	2.279E+00
S34	KAERI	5.059E-01	5.771E-01	1.369E+00	2.832E+00
S36	KAERI	1.543E+00	1.149E+00	2.035E+00	3.452E+00
Cl35	KAERI	1.383E+00	6.162E-01	1.293E+00	2.267E+00
Cl37	KAERI	7.978E-01	9.495E-01	1.357E+00	2.276E+00
Ar36	KAERI	4.550E-02	2.521E-01	8.424E-01	1.744E+00
Ar38	KAERI	3.392E-01	6.591E-01	1.322E+00	2.224E+00
Ar40	KAERI	1.226E+00	1.327E+00	1.855E+00	3.166E+00
K39	KAERI	1.127E+00	4.763E-01	9.535E-01	1.655E+00
K40	KAERI	4.615E-01	6.694E-01	1.276E+00	2.194E+00
K41	KAERI	7.657E-01	8.154E-01	1.375E+00	2.268E+00
Ca40	LANL	4.767E-01	2.195E-01	5.020E-01	8.738E-01
Ca42	KAERI	1.734E+00	6.558E-01	1.294E+00	2.194E+00
Ca43	KAERI	2.571E+00	8.665E-01	1.573E+00	2.707E+00
Ca44	KAERI	3.029E+00	1.116E+00	1.673E+00	2.893E+00
Ca46	KAERI	4.393E+00	1.401E+00	1.898E+00	3.325E+00
Ca48	KAERI	4.635E+00	1.542E+00	2.036E+00	3.550E+00

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
Ti46	KAERI	7.685E-01	5.407E-01	1.298E+00	2.499E+00
Ti47	KAERI	6.958E-01	7.565E-01	1.600E+00	2.975E+00
Ti48	KAERI	6.180E-01	9.521E-01	1.635E+00	2.937E+00
Ti49	KAERI	7.699E-01	1.023E+00	1.912E+00	3.503E+00
Ti50	KAERI	9.570E-01	1.152E+00	1.945E+00	3.484E+00
V51	CNDL	0.000E+00	1.847E+00	7.665E-01	1.093E+00
Cr50	CNDL	0.000E+00	1.819E+00	7.197E-01	9.751E-01
Cr52	CNDL	0.000E+00	1.831E+00	7.381E-01	9.913E-01
Cr53	CNDL	1.200E+00	1.841E+00	7.785E-01	1.099E+00
Cr54	CNDL	1.689E+00	1.872E+00	8.509E-01	1.275E+00
Mn55	KAERI	9.081E-01	9.972E-01	1.642E+00	3.055E+00
Fe54	JAERI	9.772E-01	2.811E-01	6.751E-01	1.227E+00
Fe56	JAERI	5.772E-01	8.712E-01	1.230E+00	1.772E+00
Fe57	KAERI	9.119E-01	1.098E+00	2.076E+00	3.490E+00
Fe58	KAERI	1.350E+00	1.221E+00	2.192E+00	3.474E+00
Co59	KAERI	6.705E-01	1.023E+00	1.858E+00	3.245E+00
Ni58	JAERI	4.079E-01	5.645E-01	8.483E-01	1.336E+00
Ni60	KAERI	4.961E-01	6.730E-01	1.431E+00	2.398E+00
Ni61	KAERI	6.412E-01	9.366E-01	1.969E+00	3.412E+00
Ni62	KAERI	9.405E-01	1.102E+00	1.915E+00	3.212E+00
Ni64	KAERI	1.663E+00	1.403E+00	2.425E+00	3.925E+00
Cu63	LANL	5.214E-01	8.275E-01	1.438E+00	2.260E+00
Cu65	JAERI	9.417E-01	1.002E+00	1.537E+00	2.015E+00
Zn64	JAERI	5.394E-01	6.105E-01	9.843E-01	1.581E+00
Zn66	KAERI	5.932E-01	7.644E-01	1.375E+00	2.347E+00
Zn67	KAERI	2.858E+00	1.163E+00	2.038E+00	3.564E+00
Zn68	KAERI	1.592E+00	1.270E+00	1.852E+00	3.228E+00
Zn70	KAERI	4.959E+00	1.716E+00	2.435E+00	4.411E+00
Ge70	KAERI	5.588E-01	8.555E-01	1.834E+00	2.940E+00
Ge72	KAERI	9.764E-01	1.010E+00	1.794E+00	2.871E+00
Ge73	KAERI	9.538E-01	1.018E+00	1.786E+00	2.954E+00
Ge74	KAERI	1.243E+00	1.105E+00	1.904E+00	3.036E+00
Ge76	KAERI	1.380E+00	1.185E+00	1.967E+00	3.194E+00
Sr84	KAERI	5.104E-01	6.986E-01	1.246E+00	2.224E+00
Sr86	KAERI	5.778E-01	8.369E-01	1.421E+00	2.473E+00
Sr87	KAERI	5.618E-01	8.579E-01	1.498E+00	2.614E+00
Sr88	KAERI	6.108E-01	8.799E-01	1.443E+00	2.547E+00
Sr90	KAERI	1.324E+00	1.252E+00	2.200E+00	3.681E+00
Zr90	KAERI	5.955E-01	1.035E+00	1.851E+00	3.116E+00
Zr91	CNDL	1.798E+00	1.850E+00	8.373E-01	1.315E+00
Zr92	CNDL	2.272E+00	1.884E+00	9.699E-01	1.600E+00
Zr93	KAERI	1.629E+00	1.755E+00	2.807E+00	4.872E+00
Zr94	KAERI	1.642E+00	1.733E+00	2.781E+00	4.628E+00
Zr96	CNDL	1.730E+00	1.905E+00	1.003E+00	1.655E+00
Nb93	KAERI	1.049E+00	1.055E+00	1.874E+00	3.145E+00
Nb94	KAERI	1.052E+00	1.145E+00	2.023E+00	3.334E+00
Mo92	KAERI	4.315E-01	4.925E-01	9.883E-01	1.879E+00
Mo94	KAERI	1.038E+00	1.037E+00	1.789E+00	2.934E+00
Mo95	KAERI	1.067E+00	1.169E+00	2.036E+00	3.279E+00
Mo96	KAERI	1.241E+00	1.176E+00	2.153E+00	3.315E+00
Mo97	KAERI	1.374E+00	1.417E+00	2.406E+00	3.851E+00
Mo98	KAERI	1.494E+00	1.518E+00	2.609E+00	4.283E+00
Mo100	KAERI	1.573E+00	1.653E+00	2.786E+00	4.464E+00

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
Pd102	KAERI	7.741E-01	8.722E-01	1.656E+00	2.763E+00
Pd104	KAERI	1.058E+00	1.059E+00	2.007E+00	3.211E+00
Pd105	KAERI	1.276E+00	1.356E+00	2.316E+00	3.819E+00
Pd106	KAERI	1.424E+00	1.324E+00	2.304E+00	3.673E+00
Pd107	KAERI	1.477E+00	1.586E+00	2.685E+00	4.287E+00
Pd108	KAERI	1.477E+00	1.402E+00	2.329E+00	3.712E+00
Pd110	KAERI	1.603E+00	1.639E+00	2.788E+00	4.352E+00
Ag107	KAERI	1.059E+00	9.965E-01	2.021E+00	3.265E+00
Ag108	KAERI	1.036E+00	1.164E+00	2.064E+00	3.347E+00
Ag109	KAERI	1.111E+00	1.111E+00	1.946E+00	3.171E+00
Cd106	KAERI	5.564E-01	9.312E-01	1.768E+00	3.124E+00
Cd108	KAERI	8.365E-01	9.422E-01	1.646E+00	2.693E+00
Cd110	KAERI	1.120E+00	1.064E+00	1.861E+00	3.015E+00
Cd111	KAERI	1.262E+00	1.374E+00	2.385E+00	3.947E+00
Cd112	KAERI	1.257E+00	1.172E+00	2.000E+00	3.245E+00
Cd113	KAERI	1.324E+00	1.451E+00	2.487E+00	4.064E+00
Cd114	KAERI	1.311E+00	1.242E+00	2.116E+00	3.402E+00
Cd116	KAERI	1.453E+00	1.420E+00	2.382E+00	3.819E+00
Sn112	KAERI	7.373E-01	9.200E-01	1.556E+00	2.659E+00
Sn114	KAERI	1.089E+00	1.182E+00	2.173E+00	3.643E+00
Sn115	KAERI	1.371E+00	1.548E+00	2.685E+00	4.606E+00
Sn116	KAERI	1.289E+00	1.241E+00	1.673E+00	2.417E+00
Sn117	KAERI	1.495E+00	1.367E+00	2.592E+00	5.087E+00
Sn118	KAERI	1.391E+00	1.449E+00	2.288E+00	3.852E+00
Sn119	KAERI	1.642E+00	1.814E+00	3.173E+00	5.301E+00
Sn120	KAERI	1.378E+00	1.538E+00	2.580E+00	4.211E+00
Sn122	KAERI	1.520E+00	1.561E+00	2.588E+00	4.256E+00
Sn124	KAERI	1.515E+00	1.581E+00	2.595E+00	4.229E+00
Sb121	KAERI	1.165E+00	1.202E+00	2.118E+00	3.446E+00
Sb123	KAERI	1.192E+00	1.209E+00	2.138E+00	3.497E+00
Te120	KAERI	1.118E+00	1.109E+00	2.081E+00	3.257E+00
Te122	KAERI	1.280E+00	1.222E+00	2.176E+00	3.578E+00
Te123	KAERI	1.464E+00	1.744E+00	2.973E+00	5.019E+00
Te124	KAERI	1.371E+00	1.394E+00	2.339E+00	3.940E+00
Te125	KAERI	1.567E+00	1.893E+00	3.201E+00	5.371E+00
Te126	KAERI	1.488E+00	1.526E+00	2.514E+00	4.167E+00
Te128	KAERI	1.466E+00	1.572E+00	2.659E+00	4.345E+00
Te130	KAERI	1.560E+00	1.712E+00	2.964E+00	4.931E+00
I127	KAERI	1.386E+00	1.426E+00	2.463E+00	4.139E+00
I129	KAERI	1.491E+00	1.556E+00	2.682E+00	4.469E+00
Cs133	KAERI	1.113E+00	1.156E+00	2.111E+00	3.500E+00
Cs135	KAERI	1.348E+00	1.450E+00	2.612E+00	4.318E+00
Cs137	KAERI	1.449E+00	1.556E+00	2.749E+00	4.526E+00
Pr141	KAERI	1.253E+00	1.184E+00	2.037E+00	3.357E+00
Sm144	KAERI	7.338E-01	1.010E+00	1.888E+00	3.032E+00
Sm147	KAERI	1.404E+00	1.278E+00	2.169E+00	3.730E+00
Sm148	KAERI	1.450E+00	1.509E+00	2.411E+00	3.881E+00
Sm149	KAERI	1.607E+00	1.719E+00	2.812E+00	4.889E+00
Sm150	KAERI	1.636E+00	1.855E+00	3.162E+00	5.081E+00
Sm151	KAERI	1.664E+00	1.949E+00	3.363E+00	5.538E+00
Sm152	KAERI	1.633E+00	1.855E+00	3.153E+00	5.182E+00
Sm154	KAERI	1.874E+00	2.255E+00	3.942E+00	6.465E+00
Tb158	KAERI	1.584E+00	1.987E+00	3.462E+00	5.725E+00

Isotope	Laboratory	20MeV	30MeV	50MeV	80MeV
Tb159	KAERI	1.606E+00	1.851E+00	3.204E+00	5.406E+00
Ho165	KAERI	1.402E+00	1.467E+00	2.404E+00	4.015E+00
Ta181	JAERI	1.259E+00	1.445E+00	1.970E+00	2.968E+00
W180	CNDL	1.222E+00	1.846E+00	9.060E-01	1.512E+00
W182	JAERI	1.371E+00	1.613E+00	2.472E+00	3.965E+00
W183	CNDL	1.276E+00	1.879E+00	1.023E+00	1.742E+00
W184	LANL	1.228E+00	1.852E+00	2.980E+00	4.812E+00
W186	JAERI	1.365E+00	1.478E+00	2.039E+00	3.128E+00
Au197	KAERI	1.096E+00	1.413E+00	2.411E+00	4.095E+00
Pb206	LANL	1.225E+00	1.847E+00	2.942E+00	4.808E+00
Pb207	LANL	1.248E+00	1.911E+00	3.072E+00	5.017E+00
Pb208	LANL	1.196E+00	1.785E+00	3.110E+00	5.165E+00
Bi209	CNDL	1.219E+00	1.868E+00	9.751E-01	1.631E+00
Th232	BOFOD	1.956E+00	4.475E-01	1.299E+00	2.723E+00
U233	BOFOD	1.956E+00	4.160E-01	1.101E+00	2.178E+00
U234	BOFOD	1.912E+00	3.523E-01	1.077E+00	2.334E+00
U235	BOFOD	1.984E+00	4.834E-01	1.256E+00	2.433E+00
U236	BOFOD	1.923E+00	3.905E-01	1.180E+00	2.521E+00
U238	BOFOD	1.962E+00	4.559E-01	1.241E+00	2.462E+00
Pu238	BOFOD	1.922E+00	3.440E-01	1.090E+00	2.347E+00
Pu239	BOFOD	1.956E+00	4.473E-01	1.272E+00	2.642E+00
Pu241	BOFOD	1.990E+00	5.152E-01	1.433E+00	2.964E+00

Table 3. Values of yield*10^3 are given for lead targets bombarded by electrons with different energies

MeV	0.52 cm		3.02 cm		experiment	
	ttbr	electron transp.	ttbr	electron transzp.	0.52	3.02
19	0.50	0.59	1.60	1.98	≈0.75	≈2.5
28	1.50	1.34	4.71	5.44	≈1.7	≈6.8
34*	2.15	1.66	6.85	7.59	2.1	9.0
60	4.89	2.36	15.86	15.98		
100	8.58	3.16	28.99	27.65		
150	12.77	4.01	45.22	41.31		

*Only values for this energy are given explicitly in [6] others are estimated from curves.

References

[1] Handbook on photonuclear data for applications, IAEA TECDOC Draft No3, March 2000.

[2] http://judit.aeki.kfki.hu/~vertes/mcnp-photo/

[3] J. F. Breismeister, MCNP™ A General Monte Carlo N-Particle Transport Code, LA-12625-M

[4] INDC(NDS)-384

[5] R. E. MacFarlane, D.W. Muir, The NJOY Nuclear Data Processing System, *LA-12740-M* (1994))

[6] W. C. Barber, W. D. George, Phys. Rev. Vol. 116, p. 1551

[7] http://mcnpx.lanl.gov/

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