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COMPARISON OF THE SANDYL MONTE-CARLO CODE
CALCULATIONS OF 20.9-MeV BREMSSTRAHLUNG
WITH PUBLISHED EXPERIMENTAL DATA

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The new flash x-ray facility constructed at Site 300 of the Lawrence Livermore National Laboratory has a nominal operating electron energy of 20 MeV. The bremsstrahlung photons from this accelerator will be used for a variety of radiographic investigations of both thick and thin objects under explosively driven conditions.

In order to properly design and interpret experiments, it is very useful to have a Monte-Carlo code to simulate the coupled electron-photon processes that occur both in the creation of the bremsstrahlung as well as in the collimation, the materials being radiographed and the detection system. One such code suitable for this purpose in many experimental situations is the SANDYL code¹, which has been used at this laboratory since 1974. This brief report is written to point out that if one uses the code's default values for some of the parameters involving the electron substep size, the code-predicted bremsstrahlung is higher than experimental data by about 60%. This report also shows that as this parameter is made finer, the code prediction approaches the experimental results to within about 10%.

This report compares the published data of O'Dell et al² for bremsstrahlung at 20.9 MeV with our SANDYL calculations. O'Dell et al² used linac-produced bremsstrahlung to irradiate a D₂O secondary target cell. Neutrons from photodisintegration of the deuterium were energy analyzed by time-of-flight at 90° to the photon direction, and the disintegration cross-section tables were used to infer the bremsstrahlung spectrum and strength. Our SANDYL calculations for the angular distribution of photon MeV are compared to the data of Sandifer and George³ for the same target.

Reference 3 shows that the photon angular distributions for electron energies ranging from 6.4 to 17.5 MeV can be superimposed into one curve if they are plotted as a function of MeV degrees. We have used their universal curve, assuming that it also applies at 20.9 MeV. The angular distribution depends upon the thickness of the target, but both refs. 2 and 3 used the same target.

SANDYL uses differential cross-sections for the production of bremsstrahlung photons recommended by Koch and Motz⁴ as adapted by Berger and Seltzer⁵. Different combinations of the formulae of ref. 4 are used for different ranges of the screening parameter (Eqn. 1 of ref. 5) which depends on the electron and photon energies and the atomic number of the bremsstrahlung target (tungsten in the present case). Both refs. 4 and 5 recommend using formulae 2CS of ref. 4. This allows one to calculate bremsstrahlung over a limited range of photon energies and angles analytically for a very thin tungsten target, where no electron-photon transport is needed.

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We have used formula 2CS(c) with intermediate screening to calculate the angular distribution of 10.2 MeV photons emitted from 20 MeV electron-induced bremsstrahlung over the region of validity which extends from 0.3° to 7° in photon angle. This calculation was done analytically for the purpose of checking the approximate formulae used in SANDYL (p.64 and 56) for the angular distribution of bremsstrahlung photons from a single atom. Figure 1 shows the comparison between the two calculations.

SANDYL uses an inherent angular distribution which is not dependent upon the photon energy. In formula 2CS, the angular distribution does depend slightly on photon energy. They agree rather well, and the slight difference is not important for tungsten targets with thicknesses comparable to the ones used on the FXR accelerator. The angular distribution in the latter case is a convolution of the inherent scattering of Fig. 1 with a half-intensity angle of about 0.9° with the angular distribution of electron scattering in the thick tungsten targets used on FXR. As will be shown later, the resultant angular distribution has a half-intensity angle of about 3.5° . Thus, small changes in the 0.9° inherent distribution do not change the thick-target results significantly. In fact, another Monte Carlo code⁶ called EGS assumes the inherent angular distribution is a delta function, where all created photons are emitted at a fixed angle (dependent only on electron energy) relative to the electron direction.

The SANDYL code was then used to calculate the angular distribution, spectral shape and strength of photons created in the geometry reported by O'Dell et al². The results are shown in Figs. 2 and 3. The geometry had axial symmetry about the direction of the electron beam. The SANDYL-7X version of the SANDYL code was used, and the problem required 188 minutes on a CDC7600 computer to run 200,000 source electrons. The running time is slow because special values were used for the electron substep size. The SANDYL code has a quantity called ISUB (p. 58 of ref. 1) which must be large enough, otherwise the calculation will be inaccurate. The larger ISUB is, the finer the electron energy grid in the calculation. We found that using the code's own default values for ISUB, the calculated photon strength is 60% higher than O'Dell et al's data². We tripled the values of ISUB, resulting in a tripling of computer time, but the discrepancy was reduced by a factor of three from 60% to 18%. Finally we made the ISUB values equal to 96 for tungsten and gold and 24 for aluminum, which is 6 times the default values. This made the computer time six times the original value, and the discrepancy is essentially gone, as Fig. 2 shows.

At the same time, the calculated angular distributions were too narrow compared to the data inferred from ref. 3, for the default values of ISUB. Increasing ISUB broadened the angular distribution to that shown in Fig. 3, which is a reasonable fit to the data. In summary, both the spectral strength and the width of the angular distribution match the calculations if ISUB is six times the default value, and presumably this is also true if ISUB is larger. It appears that if the energy grid is too coarse, the electrons in the code have not scattered in the tungsten to large enough angles, and thus the bremsstrahlung is directed too sharply in the forward direction. This causes the forward intensity to be too large. One sees from Fig. 3 that the half-intensity point of the data is at about 3.5° . This is much larger than the inherent 0.9° spread mentioned in Fig. 1 due to electron scattering in the tungsten before the creation of the bremsstrahlung. The other parameters such as zoning, energy cutoffs, etc., for the calculation are shown in Figs. 4, 5 and 6. ISUB is called IESBS in the card deck description of SANDYL.

References 5 and 6 also show comparisons between the data of O'Dell et al., and their calculations with ETRAN and EGS codes. The SANDYL comparison of our Fig. 2 matches best to the data. In plotting the data of O'Dell et al., in Fig. 2, I have noted the comment on page 627 of Berger and Seltzer that O'Dell's data must be divided by 1.12 if one wants the strength of the photon flux hitting their actual secondary D₂O target, which subtended a cone angle of about 1° as indicated in Fig. 2. O'Dell had multiplied his finite solid angle data by 1.12 to estimate what the flux at exactly 0° would be. We do not know if this was taken into account in the comparison made in ref. 6.

In summary, by using an electron subgrid sizes six times finer than the SANDYL default values, good agreement is obtained with published data for the strength, spectral shape, and angular distribution of 20.9-MeV induced thick-target bremsstrahlung.

References

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4. H. W. Koch and J. W. Motz, "Bremsstrahlung Cross-Section Formulas and Related Data," Rev. Mod. Phys. 31 (1959), p. 920.
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BARNs

ATOM-MEV-STERADIAN

COMPARISON OF TWO FORMULAE
USED TO CALCULATE THE PHOTON
ANGULAR DISTRIBUTION FROM A
SINGLE TUNGSTEN TARGET ATOMFORMULA 2CS(c) FOR $KE_E =$
20.0 MEV AND
 $E_{\text{PHOTON}} = 10.2 \text{ MEV}$ FORMULA USED IN SANDYL
FOR $KE_E = 20.0 \text{ MEV}$
FOR ALL PHOTON ENERGIES
NORMALIZED AT ZERO DEGREES

PHOTON ANGLE IN DEGREES

Fig. 2

PHOTONS IN THE $0-1^\circ$ CONE
MEV · STERADIAN · ELECTRON

SANDYL MONTE-CARLO CALCULATION

O-DELL ET AL. MEASUREMENTS

Fig. 3

COMPILE DATE: 01/21R 16.48.50
BOX 801 HANDYL76 VERSION=X

SMALL CORE MEMORY USED=0134375
LARGE CORE MEMORY USED=0272460

BOX 809 GOOSMAN
20.9 MEV ON 0.254 CM W AND .0127 CM AU + 2.86 CM AL IESBS=96 + TARGET
20.9 MEV ON 0.254 CM W AND .0127 CM AU + 2.86 CM AL IESBS=96 + TARGET

NUMBER OF ZONES

IESBS = 24 for aluminum

7 INSIDE

96 for gold

10 TOTAL

96 for tungsten

SURFACES 2 QUADRICS

7 PLANES

-0 X PLANES

-0 Y PLANES

SOURCE

20 SAMPLES

10000 HISTORIES PER SAMPLE

SOURCE ZONE SET TO 1

REACTION WEIGHTS RWT1

2.5000E-01 2.5000E-03 2.5000E-05 2.5000E-06 1.0000E+00 1.0000E+00 1.0000E+00

FLUORESCENCE AND AUGER (IONIZATION) NOT FOLLOWED

IN ZONE 1

TYPE 1000= 1

REFERENCE DIRECTION 1ANG= -0

TIME DIST 1TH= 1

TYPE 1SPEC= -0

PHOTON EDIT 1TN= 3

SPECTRUM OPTION 1SENT= 1

PHOTON EDIT TIMES 1M= 0

JDBUG= -0

1BTST= 2

1CU = 1

1BZ = -0

1JO = -0

1JM = -0

1JMPSEC= 1

1NGBIN= L

1UNITS= -0

1DBO = -0

1NDRY= -0

RANDOM NUMBER SEQUENCE 1

REACTION WEIGHTS -0

DEPOSITION SPECTRUM -0

CHANGE TALLY ENERGIES -0

CHANGE ANGULAR TALLY ENERGIES 1

NUMBER OF MATERIALS 4

Fig. 4

-9-

UPPER ANGLES FOR EMT BINS

1.000	2.000	3.000	4.000	5.000
6.000	7.000	8.000	9.000	10.000
11.000	12.000	13.000	14.000	15.000
16.000	17.000	18.000		

ENERGY GRID INDICES--ITAP

33	34	35	36	37	38	41	43	45	47	49	51	53	55	57	59	61	63
55	57	59	71	73	75	77	79	81	83	85	87	89	91	93	95	97	99

ANGULAR ENERGY GRID INDICES--ILAP

25	26	27	28	29	30	31	32	33	34	35	36	37
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ZONE BOUNDARY DATA

ZONE	JP	B	JP	B	JP	B	JP	B	JP	B	JP	B	JP	B	JP	B	JP	B
1	2	-2	-10	-1	9	9	9	9	9	9	9	9	9	9	9	9	9	9
2	3	-3	-1	-2	9	9	9	9	9	9	9	9	9	9	9	9	9	9
3	4	-4	-2	-3	9	9	9	9	9	9	9	9	9	9	9	9	9	9
4	5	-5	-3	-4	9	9	9	9	9	9	9	9	9	9	9	9	9	9
5	6	-6	-4	-5	9	9	9	9	9	9	9	9	9	9	9	9	9	9
6	7	-7	-5	-6	9	9	9	9	9	9	9	9	9	9	9	9	9	9
7	8	-8	-6	-7	9	9	9	9	9	9	9	9	9	9	9	9	9	9
8	9	-9	-7	-8	9	9	9	9	9	9	9	9	9	9	9	9	9	9
9	10	-10	-8	-9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
10																		

FUDGE XN 0. YN 0. ZN 0. GPPP 0. GPXP 1.00000E+00

SOURCE TNER S8 0. S9 0. S10 0. S11 0. S12 0.

MIN ENERGY INITIAL TIME 0. BZ 0. ACC 0. S15 0. PROB MULT 0.

QUADRIC DATA

SURFACE	X-ZERO	Y-ZERO	Z-ZERO	C	K	K SQUARED
1	0.	0.	0.	0.	4.4680000E-01	1.9953024E-01
2	0.	0.	0.	0.	5.0000000E+00	2.5000000E+01

PLANE DATA

1	-1.00000000E-01
2	1.00000000E+00
3	1.02540000E+00
4	1.03810000E+00

5 3.89610000E+00
 6 2.66100000E+01
 7 2.66100000E+01

MAT NO	ELE NO	Z	A	APCT	1	1	1.000E+00	1.000E+00	1.000E+00
MAT NO	ELE NO	Z	A	APCT	2	2	7.400E+01	1.838E+02	1.000E+00
MAT NO	ELE NO	Z	A	APCT	3	3	1.300E+01	2.637E+01	1.000E+00
MAT NO	ELE NO	Z	A	APCT	4	4	7.900E+01	1.972E+02	1.000E+00

ZONE	MATERIAL	IELTR	LTYPE	ECUT	VOFL	WGT	ETA	PCT	CC	VOLUME	MASS
1	-1	1	-0	3.000E+00	-2.000E-01	1.000E+00	1.000E+00	0.	0.	8.639E+01	8.639E+02
2	-2	1	-0	3.000E+00	-2.000E-01	1.000E+00	1.000E+00	0.	0.	1.995E+00	3.850E+01
3	-4	1	-6	3.000E+00	-2.000E-01	1.000E+00	1.000E+00	0.	0.	9.975E-01	1.927E+01
4	-3	1	-6	3.000E+00	-2.000E-01	1.000E+00	1.000E+00	0.	0.	2.246E+02	6.065E+02
5	-1	1	-6	3.000E+00	-2.000E-01	1.000E+00	1.000E+00	0.	0.	1.783E+03	1.783E+03
6	-1	1	-6	3.000E+00	-2.000E-01	1.000E+00	1.000E+00	0.	0.	6.272E-03	6.272E-06
7	-1	1	-6	3.000E+00	-2.000E-01	1.000E+00	1.000E+00	0.	0.	7.654E-01	7.854E-04
TOTAL VOLUME =				2.09780477E+03	CC.	TOTAL WEIGHT =				6.66127283E+02	GRAMS

ELECTRON SOURCE
 ELECTRON TRANSPORT REQUESTED ETA SET TO 1.0

MATERIAL MASS
 1 1.870189E+00
 2 3.850179E+01
 3 6.064845E+02
 4 1.927084E+01

MAT/L ATOM/CM-B FRACTIONS ISOTOPES
 4
 1 0.00059769 1.000000 1.
 2 0.06322156 1.000000 74.
 3 0.06031422 1.000000 13.
 4 0.05902515 1.000000 79.