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ABSTRACT

During radiographic experiments involving explosives, it is valuable to have a method of monitoring the X-ray flux ratio between the dynamic experiment and an X-ray taken of a static object for comparison. The standard method of monitoring with thermoluminescent detectors suffers the disadvantages of being sensitive to temperature, shock, UV radiation, cleanliness and saturation. We are studying an additional flux monitoring system which is not subject to any of the above disadvantages and is based upon the 63Cu(photon,n)62Cu reaction. The 62Cu has a 10 min half life and is counted by a nuclear pulse counting system within a few minutes of an explosive test. 170 microcoulomb of 19.3 MeV electrons hitting 1.18 mm of Ta produces X-rays which illuminate a 0.8mm thick by 1.6 cm diameter Cu disk placed 46 cm from the Ta. The activated Cu is placed in a counting system with a window between 400-600keV and produces about 42500 counts in the first 100 sec. counting period. Less than 0.2% of the initial activity is due to other reactions. Photo-induced neutrons in Be parts of the system are shown to produce a negligible effect in the Cu. The main disadvantage of the Cu activation is its sensitivity to electron energy. Monte-Carlo calculations of the excitation function for our accelerator are shown, along with excitation functions for three other configurations.

INTRODUCTION

Flash radiography has been used at the Lawrence Livermore National Laboratory (LLNL) to study the physics of hydrodynamic phenomena driven by explosives and other sources. The recent construction of the 20-MeV linear induction accelerator has increased this capability considerably. The forward-directed X-ray flux at 1 meter ranges from 400-500 rads in CaF2 and at the same time has a gaussian electron spot size with a full width at half maximum of 2.7 mm.

In some experiments with explosives, one wants to compare radiographs of the dynamic experiment with that of a non-dynamic assembly in order to be able to infer quantitative information from the former. To do this one needs to monitor any variation in the X-ray flux produced by the electron accelerator between the dynamic and static events.

The normal thermolumiscent detectors (TLD'S) are difficult to use in these explosive events, because when placed inside the accelerator protection materials, they obscure the image and may saturate if placed directly in the beam, and otherwise must monitor perhaps unreliable scattered flux if placed elsewhere. They also may be subjected to severe shock and temperatures reaching several hundred degrees C.

Therefore we are studying copper activation as an additional method of flux monitoring. Being a nuclear process, the production of Cu62 by the photoneutron reaction on Cu63, this technique promises several advantages. It is insensitive to temperature, shock, UV radiation, cleanliness and saturation which can affect CaF2 dosimeters. It is not sensitive at all to large numbers of low energy scattered X-rays, since the threshold is 10.8 MeV. It is sensitive enough to use with a 20 MeV 20 ampere beam lasting 60 nsec.

THE TECHNIQUE

Figure 1 shows a simplified configuration for production of X-rays for radiography of explosively-driven events. Approximately 2000 Amperes of electrons with a half-angular convergence of about 6 degrees make bremmstrahlung in a 1 mm thick Ta disk oriented at 30 degrees from normal incidence. They slow down in the Ta and Be plug, enter air and stop in a second Be piece. The X-rays are collimated by tungsten and uranium pieces before traversing a disk of copper 0.8 mm thick and 16 mm in diameter placed usually at 46 cm from the Ta. The tapered Be plug and ceramic cone provide blast protection from the explosive which is located to the right of the figure. X-rays above 10.8 MeV produce 62Cu in the disk which is recovered shortly after the dynamic event and counted at a remote station. The purpose of the Cu disk is to monitor the X-ray flux leaving the collimators, since the converging electron beam does not always hit the same spot on the Ta target. The size of the air opening in the tungsten collimator is determined by the focal size of the electron spot and its change in position from pulse to pulse.

Figure 2 shows a simplified schematic for the counting system. After the X-rays activate the Cu, it can be recovered and placed into the counting station within 4 minutes. The principal activity is 62Cu with a half life of 9.76 minutes, along with a very small amount of 64Cu (with a half life of 10.8 hours) made by the photoneutron reaction on the 65Cu in the disk. The 64Cu activity is small because of the long halflife and because only 31% of natural Cu is 65Cu. Also, each decay of 64Cu makes only 0.38 0.51-MeV photons, while each 62Cu makes almost two. The Cu disk is attached to an aluminum positron stopper and positioned close to a 1.2 cm diameter by 5 cm long NaI(Tl) detector. A conventional nuclear pulse counting system records the pulses in the NaI crystal between 400 and 600 keV in pulseheight for successive 100 sec intervals. The count rate is enhanced by the annihilation of positrons in the aluminum, which results in two .51 MeV photons. The pulse-height analyser provides a check on the gain and position of the discriminator gates, by using a few microCurie source of 137Cs in place of the Cu.

Figure 3 shows a measured decay curve for a single electron burst of the accelerator. The uncorrected data are as counted, and the corrected curve was generated by continuing the count for two days to extract the 64Cu activity. In addition, a measured constant background rate of 4 counts per 100 sec was subtracted. The resulting corrected curve is shown with a straight line of the accepted half life, 9.76 minutes. Only 0.17% of the initial counting rate at t=0 is due to 64Cu. The initial 100 sec count is 42500.

The two activities were compared with calculations. Resistive wall current beam monitors for the accelerator pulse indicated that 170 microcoulomb of 19.3 MeV electrons were aimed towards the Ta target with a half-angular convergence of 6 degrees. Then bremsstrahlung calculations(1,2,3) done with the SANDYL coupled electron-photon Monte Carlo computer code(4) were scaled down from 20 to 19.3 MeV and the resulting X-ray spectrum convolved with the published cross-section(5) for photo-activation of 62Cu. The initial counting rate measured for the Cu disk was within 20% of this precalculated value. A calculation was also made for the initial 64Cu activity. It predicted 50 counts during the first 100 second period, compared to the 71 counts actually inferred by decomposition of the data of Fig. 3. The difference may be due to thermal neutron capture of 63Cu. The latter is difficult to estimate.

It is possible that the 62Cu activity has contributions other than from X-rays emanating from the Ta and Be. Calculations were carried out to estimate these other sources. The photon spectrum illuminating the tapered Be plug adjacent to the Cu disk produces a spectrum of photo-induced neutrons. These can produce 62Cu in the disk by the n,2n reaction. A calculation was done by convolving all the relevant cross-sections together showing that this source of 62Cu is roughly .04% of the expected activity from direct photo-activation of the Cu. An estimate was similarly made of the photo-induced neutrons from the Uranium collimator producing 62Cu via the n,2n reaction. The result was less than 1 part in 100000. Also it was shown that photo-induced neutrons from the two Be pieces closest to the Ta target produce roughly .0001 of the direct 62Cu activity.

The Cu disks were made of commercial grade oxygen-free copper and were kept free of salt from finger marks by occasional cleaning. This kept the 15O and 34Cl activities to a negligible level.

The above calculations and decay curve were for 10.3 MeV electrons. The threshold for the gamma, 2n reaction on 63Cu is close to 20 MeV. For electron energies below 24 MeV, the latter reaction is negligible for the counting system of Fig. 2. The decay shown in Fig. 2 is of a sufficiently single half life that if the Cu is counted within 24 minutes of irradiation, the count during the first 100 sec period may be used, correcting only for the 62Cu decay. The result will be statistically accurate within 1% even with no correction for the 64Cu activity. In practice we have found that a single 100 sec count is sufficient to infer the yield. After one day, the old Cu disks can be reused with negligible background accumulation.

THE COUNT RATE VS. ELECTRON ENERGY

With all the advantages of the Cu counting system for monitoring of X-ray flux leaving the collimators, the most serious disadvantage is its sensitivity to the electron beam energy. It will serve as a useful beam current monitor only if the accelerator has a very stable energy, or if there is some independent method of monitoring relative energy changes from pulse to pulse. On the LLNL linear induction accelerator, the voltages of each of the 54 cavities are monitored by fixed capacative pickup probes, read onto a computer data base and then added. Small changes of the order of 0.5-1.0% in this summed voltage from pulse to pulse are used to correct the data from the Cu counting system.

In order to do this, one needs to have available a plot of count rate vs. electron energy for the configuration being used. If the accelerator's energy can be easily changed, the most practical method is to measure the excitation function, using open-enough collimation that the current indicated by the normal beam monitors will all hit the target close-enough to the axis so that beam position variations dont affect the Cu count.

For the flash X-ray (FXR) accelerator configuration shown in Fig. 1, no excitation function could be found in the literature, so we have carried out calculations with the SANDYL code to provide this information. As explained in Refs. 2 and 3, the SANDYL code is a coupled electron photon Monte Carlo transport code, used for calculating the bremsstrahlung from the incident electrons. It is capable of calculating for the geometry of Fig. 1 the photon flux vs. photon energy vs. angle entering any of the parts shown in that figure. The code's ability to calculate bremsstrahlung correctly has been checked by comparing its results with the experimental results of O'Dell et al. (6) for 20.9 MeV electrons with little angular divergence onto a target of 0.49 gm/cm2 W plus 0.245 gm/cm2 Au with 7.7 gm/cm2 Al absorber. Photons were detected within one degree of the axis of the electron beam. References 2 and 3 show the agreement of SANDYL with these measurements for photon energies between 4 and 12 MeV.

In addition, we have recently carried out the comparison of their measurements with SANDYL predictions for the high-energy part of the photon spectrum from 10-20 MeV, and the agreement is still within about 10% except above 18 MeV near the endpoint of the spectrum. Nevertheless, it is still very difficult to measure the photon spectrum near the endpoint and also difficult to calculate it. The Monte-Carlo code method is slow, and restricting the editing angle to with 1 degree of the electron beam axis provides poor statistical accuracy. As pointed out in Refs. 2 & 3, the electron substep used in SANDYL had to be decreased in size by a factor of 6 from the standard default values in the code in order to make it fine enough to provide agreement to within 10%. Otherwise, with coarse electron steps, the angular distributions of the photons are too narrow and forward intensities too high, when compared with measurements.

To estimate the excitation function for copper activation on the FXR, SANDYL problems were run at nine electron energies between 13.3 MeV and 23.7 MeV. For each of these runs, the electron substep size was six times the default value which increased running time by a factor of six. A point source of 400000 parallel electrons was incident upon 1.18 mm of Ta. The two Be parts on the left of Fig. 1 and the U collimator and the Cu disk were zoned into the calculation. Fluxes of photons were edited entering the Cu disk as well as those leaving the second Be part as a function and photon energy and angle, for each of the 9 beam energies. Each run with SANDYL required about 6.5 hours of central processing unit time on a CDC 7600 computer. An electron and photon energy cutoff of 7.5 MeV was used to keep this computation time to a minimum, since the threshold for the Cu activation is 10.8 MeV. Photons from 7.5 to 10 MeV were edited even though they are below threshold in order to allow the spectrum which appears as a histogram to be better estimated above 10 MeV by curve fitting.

The real FXR configuration uses an electron convergence angular range from zero to 6 degrees. The SANDYL calculations were for parallel incident electrons. To account for the electron convergence, the SANDYL photon flux from zero to six degrees was summed for parallel electrons. This is a simple way to estimate the photon flux on axis. This works because an electron at six degrees produces the same on-axis photon flux per steradian as an axial electron produces at 6 degrees photon angle. It works if the incident electrons are uniformly distributed per steradian from zero to six degrees. This proceedure is slightly in error due to the slightly longer path length of the electron incident at 6 degrees within the Ta, but the effect is completely negligible here. Another way to calculate the effects of electron divergence was described in Ref. 2.

For each of the nine electron energies, the 0-6 degree photon flux exiting the second Be part was plotted vs. photon energy. For the run at 23.7 MeV electron energy, about 7000 photons above 10.8 MeV were tallied into six photon energy bins. These nine histograms were then fit to a smooth curve of the expected bremsstrahlung shape. This smooth curve was then convolved in 200 keV photon energy steps with the Cu activation cross section given in Ref. 5. The resultant estimate of the excitation function is shown as curve C in Fig. 4. This represents the SANDYL estimate of the Cu count rate vs beam energy if the Cu disk samples the photon flux at 0 degrees and the electron angles fill a six degree cone. The Cu disk in Fig. 1 samples photons within 1 degree of the axis. The flux at exactly 0 degrees is about 12% higher than that averaged from 0 - 1 degrees for 21 MeV electrons. At 13.3 MeV electron energy the ratio is closer to 1.08. So the estimated excitation function for the geometry of Fig. 1 is a curve 12% lower at 21 MeV and 8% lower at 13.3 MeV than curve C of Fig. 4.

Curve C's accuracy is limited by at least one restriction within SANDYL. As explained in detail in Ref. 3, the code uses an angular distribution of photons which, for a given incident electron energy, is independent of photon angle. In reality, the photon spectrum does depend (7) slightly on photon angle even for angles less than 6 degrees. The distinction would be most evident for thin bremsstrahlung targets and less for targets such as the one used in Ref. 6, which was 0.73 gm/cm2 thick. As discussed in Ref. 3, for this target the electron angles introduced by scattering within the target are about 4 times the angular width of the bremsstrahlung from very thin targets. This dependence of photon spectrum vs. angle is even less important for the 2 gm/cm2 thick target used in Fig. 1 and in curve C of Fig. 4. The statistical uncertainties of curve C are evident from their scatter of the nine points from the smooth curve. Unfortunately, we have not been able to vary the energy of the FXR accelerator to experimentally check curve C.

Curve A of Fig. 4 is the excitation function (8) for nearly parallel electrons incident upon a very thin 37mg/cm2 Au target, for electron energies ranging between 14.5 and 16.9 MeV. The actual electron convergence was not stated, but the Cu disk subtended a half-angle of 5.7 degrees at the target position.

Curve D of Fig. 4 is the excitation function (9) measured for 14 - 21 MeV nearly parallel electrons incident upon a 330 mg/cm2 Cu target, and the X-rays emitted into a very large unstated solid angle were used to activate a thinner Cu foil. The large collection solid angle was used because Ref. 9 compared with a theory integrated over angle.

Curve B of Fig. 4 is a mixture of experiment and calculations. The bremsstralung data of Ref. 6 for 4 electron energies were convolved by us with the gamma,n cross section of Ref. 5 to produce this curve. The smooth curve representations of the data were taken with unstated but probably nearly parallel electrons incident upon a 735mg/cm2 thick W-Au target. Although unstated in Ref. 6, the discussion in Ref. 9 states that the photons were sampled in a cone subtending a half angle of about 1 degree from the beam axis, and that the raw data were multiplied by 1.12 in order to estimate the flux at exactly 0 degrees, which is what is plotted in Ref. 6. It is not clear whether the 1.12 factor was used for all the electron energies or not. Ref. 9 implies that it was at least for 10 and 20.9 MeV electron energies. The uncertainty bars for curve B are our estimates based upon the uncertainties in the X-ray spectra quoted in Ref. 6.

It is to be emphasized that the four curves of Fig. 4 represent different physical situations, since there is quite a variation in target thickness from 37 to 2000 mg/cm2 as well as differences in incident electron convergence and photon collection solid angles. Curve

D was included because it extended to 24 MeV, although it is for a Cu radiator rather than for high-Z elements as are the other 3 curves. It is also to be emphasized that Fig. 4 cannot be used to infer the relative strength of the Cu yield between any two of the four curves, only the relative strength vs. energy for a given curve is determined.

The four curves apparently have different shapes. Curve D shows clearly that for Cu radiators and for large photon collection angles, the excitation function slope decreases significantly above 20 MeV. The measured curve A and the mixed curve B are both for thinner targets and smaller electron convergences and collection angles than for the SANDYL calculations of curve C. A SANDYL calculation of the photons within the first two degrees was done similar to the 6 degree edits mentioned above. Its corresponding curve is similar in shape to that of curve C, but of larger statistical uncertainty. This shape is the same because of the independence of photon spectrum with photon energy which is built into the SANDYL code. We were not able to find a published excitation function close to the configuration of Fig. 1 to compare with the SANDYL runs. However, the SANDYL code does correctly predict the shape and magnitude of the photon spectrum used in the 20.9 MeV point of curve B.

Despite the differences in the curves, for the 18 MeV beam used with the FXR, a 1% beam energy difference is expected to make a change in the Cu yield of about 7.5%. In a TLD with a flat dose response, the increase in TLD reading would be about 3%. The accuracy of the excitation functions is sufficient for our purposes, since the beam energy variations between radiographs of a static model and the dynamic mock usually differ by less than 1%.

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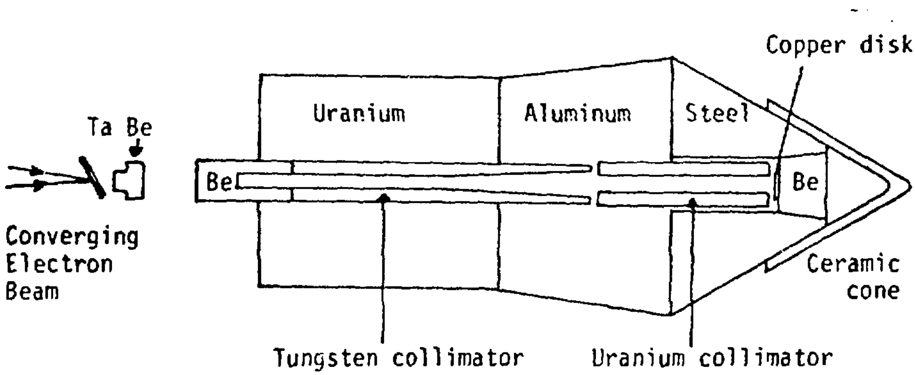

FIGURE 1. Simplified target configuration

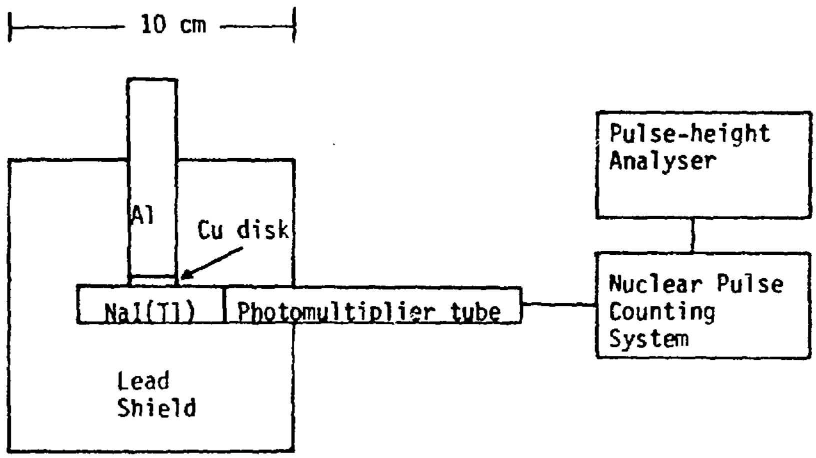

FIGURE 2. Block diagram of counting station

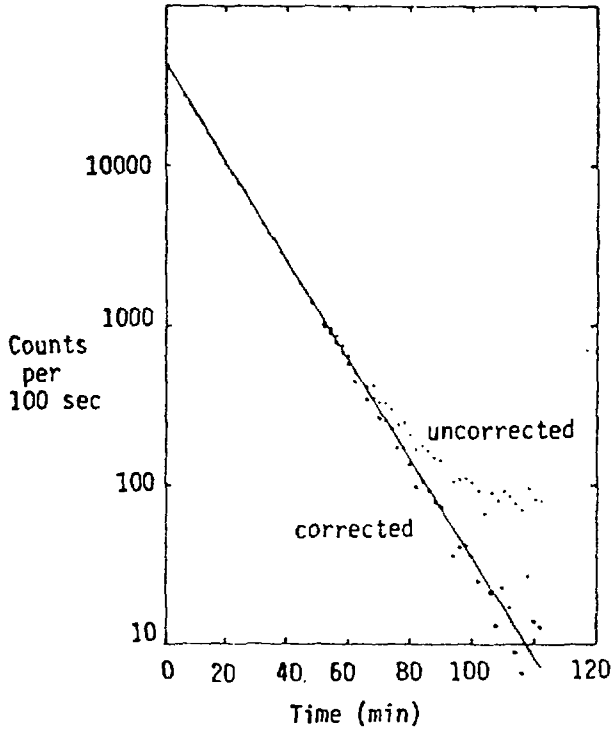

FIGURE 3. Time dependence of the count rate

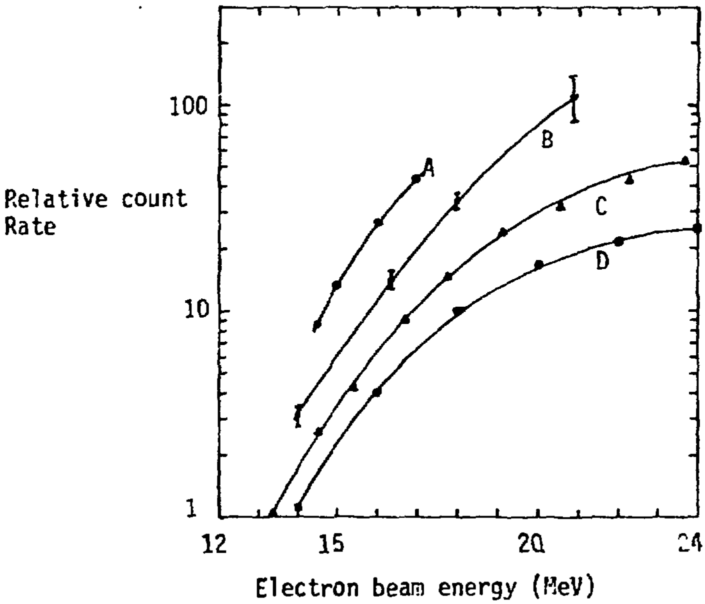

FIGURE 4. Count rate vs. electron beam energy