Nuclear Instruments and Methods in Physics Research B40/41 (1989) 1189–1192
North-Holland, Amsterdam

NUCLEAR ACTIVATION TECHNIQUES FOR MEASURING DIRECT AND BACKSCATTERED COMPONENTS OF INTENSE BREMSSTRAHLUNG PULSES *

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High-voltage electron accelerators used for bremsstrahlung generation can produce intense pulses of radiation with different endpoint energies. The energy spectrum can be changed by varying the charging voltage or by softening the photons with Compton scattering in a low atomic number material. The high dose rate and the flexible spectrum capabilities of the Aurora accelerator have been used to investigate the potential for measuring the bremsstrahlung spectrum by photoactivation of nuclear isomeric states. Recent success in calibrating lower intensity sources has shown that gram-sized targets of isotopes, such as ^{115}In, can be used to sample the incident X-rays at several discrete gateway energies. When irradiated at these energies the targets are excited to metastable states with lifetimes suitable for conventional counting after the flash.

1. Introduction

Recent gamma-ray laser studies have shown the synergism between the search for energy gateways to excite nuclear isomeric states and the measurement of photon energy spectra from flash X-ray machines. The flash X-ray machines are optimized to produce very intense X-ray pulses ideal for the generation of measurable populations of isomeric states, some of which decay very rapidly. In turn, the presence of known isomeric states can in principle be used to measure the spectral content of the X-ray pulses. This paper discusses both applications in the context of a recent experiment performed at the Aurora flash X-ray facility.

Since 1971 the Aurora accelerator [1] has been the largest flash X-ray simulator in the world. Its main use is laboratory testing of electronic devices for their hardness to radiation from a nuclear explosion, but over time the machine has acquired additional capabilities. Besides X-rays with photon energies up to 10 MeV, Aurora can now generate pulses of photons around 0.1 MeV with very large dose–area products. Electrons from Aurora may also be used for direct irradiation and for the production of microwaves [2].

* Research supported by SDIO/IST through NRL and DNA through Harry Diamond Laboratories.

The accelerator consists of a 5 MJ Marx generator which drives four parallel oil-filled coaxial Blumleins. Each Blumlein connects to a vacuum transmission line terminating in a diode. The charging voltage of the Marx capacitors determines the total electron energy delivered to each diode; the maximum is 0.5 MJ. On stopping in a tantalum slab the electron energy is converted into bremsstrahlung with a dose–area product of ~ 60 Gy m^2 (1 gray = 0.1 krad) in silicon. Since the four diodes are in parallel, the total dose–area product is ~ 240 Gy m^2. This produces a dose of 400 Gy over the "hot spot", a volume of about 0.1 m^3 centered near the intersection point of the four transmission lines.

Aurora can also produce a softened X-ray environment. By Compton backscatter, the flash X-rays are converted into moderate-energy photons with a spectrum similar to bremsstrahlung from 1 MeV electrons. Photons from the diodes are scattered many times in a material with low atomic number, which then serves as a secondary source of softer X-rays. Fig. 1 shows the geometry of a recent experiment [3] which produced a dose–area product of 25 Gy m^2. Only two diodes are shown.

In both environments, the dose produced by the radiation is routinely and accurately measured, but it is more difficult to determine the spectrum of the X-rays. Spectral measurements for the hard X-rays using the

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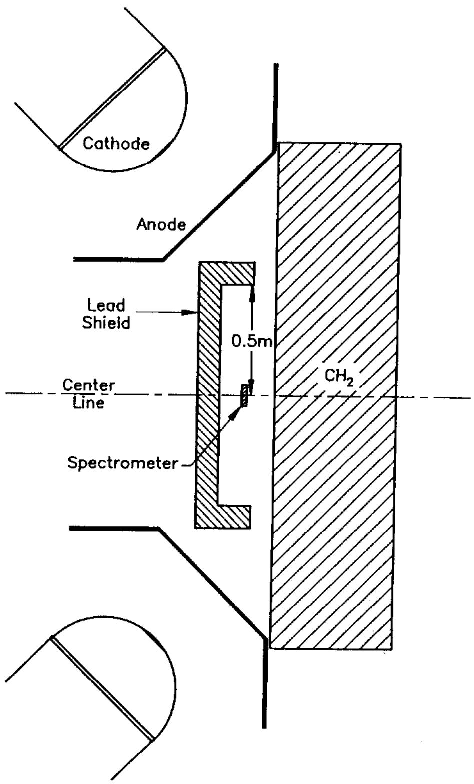

Fig. 1. Geometry of the Compton backscattering device. Only two of the four Aurora transmission line diodes are shown.

energy spectrum of Compton electrons [4] are cumbersome, and a differential absorber method [5] was used for the soft X-rays. With this technique it is impossible to infer the shape of the spectrum above 1 MeV, as all absorbers are equally gray for these photons. The few measurements that have been done agree well with computations [6]. The solid line in fig. 2 shows an unmodified bremsstrahlung spectrum computed for a 90 kV charging voltage, and fig. 3 shows a backscattered or softened spectrum. In the latter figure, the computed spectrum, depicted by the dashed line, falls off rapidly for photons exceeding 1 MeV, but the spectrum measured with differential absorbers shows some supra-1-MeV photons with an indeterminate spectral shape.

An alternative technique to determine the gamma-ray spectrum is based on activation of suitable nuclei by (γ,γ') reactions. This technique, called X-ray activation of nuclei (XAN), has been previously reported [7] and has been successfully validated [8] as a means of calibrating nuclear simulators with end point energies $E_m < 1.5$ MeV.

A key to the development of this technique was the use of many shots to activate test samples to resolve experimentally the level of self-consistency among values of basic nuclear parameters in the current database.

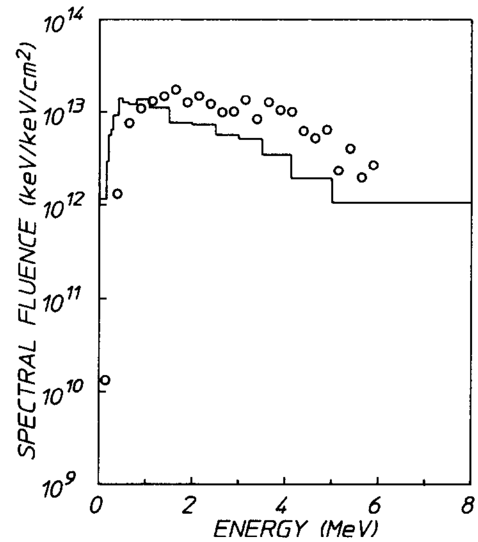

Fig. 2. Data points record the loci of the spectral intensity of Aurora measured at one energy by nuclear activation calibrated in the linac in comparison with the computed spectrum normalized by a dosimeter measurement. The computed spectrum is represented by the solid line. The energy to which the activation procedure is most sensitive is not known but loci record possible values and corresponding intensities. The bremsstrahlung was produced by Aurora charged to 90 kV.

This is relatively straightforward below about 1.5 MeV, but at higher energies ($E_m < 6$ MeV) the situation becomes more complex, and the accepted database is severely flawed. Recent experiments [9] with the bremsstrahlung from a medical linear accelerator (linac) have shown the importance of high-energy gateways. These

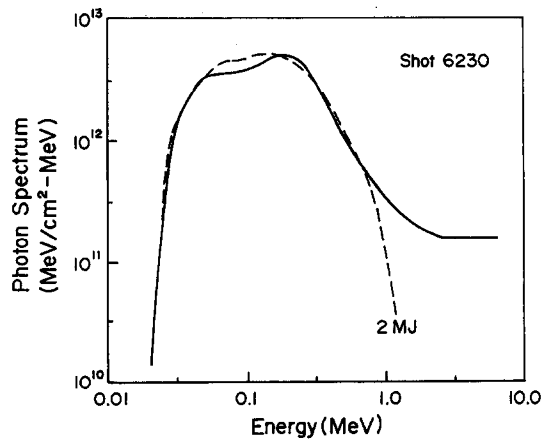

Fig. 3. Compton-scattered photon spectrum of the bremsstrahlung produced by Aurora shot 6230, with a charge voltage of 110 kV. The solid line represents the spectrum determined from differential absorber measurements. The dashed line indicates the computed spectrum which corresponds to a delivered energy of 2 MJ.

provide paths for selective excitation about 1000 times greater than anything found earlier.

2. Experimental objectives

Conceptually, XAN differs from standard activation techniques used to sample particle fluxes in one important respect: there can be no significant transfer of momentum. As a result, threshold energies for a reaction do not occur in XAN. Instead, narrow energy windows exist through which photons can be absorbed to induce (γ, γ') reactions [3]. Quantitatively described in terms of integrated cross sections having units of nuclear target area times the width of the energy window, these resonances provide a means to sample very narrow slices in energy of the incident X-ray spectrum.

The recent discovery [10] of giant gateways for sampling bremsstrahlung fluences above 1.5 MeV motivates the attempt to determine the relevant nuclear parameters and energies, E_i, for a number of test nuclei. One objective of this work was to determine if Aurora's hard X-rays could be cross-calibrated with those from the linac in terms of relative fluorescence yield from a target material. A second was to survey a selected group of materials for evidence of any individually distinctive dependence of fluorescence efficiency upon bremsstrahlung endpoint, information needed to extend the XAN procedure for calibrating pulse X-ray sources to the 2–6 MeV range.

3. Experimental approach and results

To resolve the first issue, a thin foil target of naturally abundant indium was irradiated with approximately 140 Gy (Si) of Aurora's X-rays. After irradiation, the fluorescence was measured with both NaI(Tl) and high-purity Ge spectrometers. The activation induced by the reaction ^{113}In(γ, γ')^{113}In^m was so intense that usable levels were observed 6 h after irradiation. A typical NaI fluorescence spectrum is shown in fig. 4. From these data the number of activated nuclei in the sample was obtained.

The spectral fluence was obtained by assuming that one (γ, γ') channel at an undetermined energy E_1 dominated the excitation. Values for the integrated cross-section as a function of possible E_1 values were taken from the linac experiments. This data gave the values of spectral fluence shown in fig. 2. The points define the loci of the single measurement of intensity which would result if the precise energy of the dominant gateway were known.

For the survey study, targets of BaF_2, Hg_2Cl_2, SrF_2, Cd and In were held in individual plastic vials. These were irradiated at the position of the indium foil and

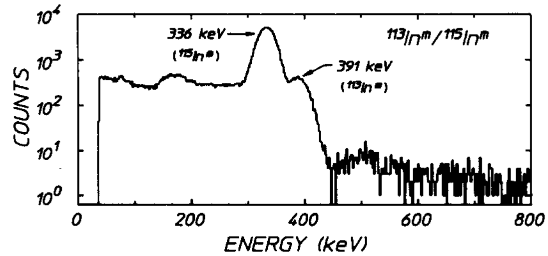

Fig. 4. Typical NaI(Tl) spectrum of the fluorescence detected over the range of energies shown for an indium sample. The sample contains natural abundances of ^{113}In and ^{115}In.

counted with a NaI(Tl) spectrometer. The target package was backed with an array of thermoluminescent dosimeters, TLDs, to determine the radiation pattern.

The endpoint energy of the bremsstrahlung from Aurora could be varied over a limited range to support a search for the gateway energy at which a window is reached for turning on the activation of an irradiated sample. As an example, fig. 5 shows the normalized activation per delivered dose as a function of the Aurora charging voltage for ^{111}Cd. Extrapolating the data back to zero excitation suggests a possible onset of excitation near 60 kV simulator voltage charge.

Use of the XAN technique for measuring spectra [8] was attempted in the softened X-ray environment. Two indium foils were exposed. One foil was encased in a cadmium cover to protect against potential photoneutrons from deuterium, ^{13}C and ^{17}O in the scatterer.

All features in both spectra were due to ^{116}In, produced by neutron capture. From the difference in the activations of the covered and bare foils, it was possible to calculate by standard methods the thermal and epithermal neutron fluxes. Normalized to the dosage, these were found to be Φ_{th}/dose = $(4.20 \pm 0.28) \times 10^5$ n/(cm^2 Gy), and Φ_{ep}/dose = $(9.53 \pm 0.65) \times 10^3$ n/(cm^2 Gy).

In each backscattering experiment a cadmium foil and a mixed Se/LiBr sample were also irradiated at the target position. Spectra from these samples showed strongly the presence of neutron capture products, al-

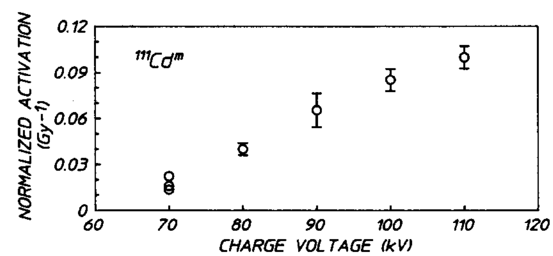

Fig. 5. Isomeric activation per gray of dose normalized to the activation at ^{110}kV, as a function of the Aurora charging voltage for ^{111}Cd^m. Where no error bars are shown the error is commensurate with the symbol size.

though peaks representing photoactivated isomers were also present. Preliminary results were obtained by correcting the measured photoactivation for the neutron interference and by employing known integrated cross sections for the ^{111}Cd pump state at 1.19 MeV of $\sigma = 9.8 \times 10^{-29}$ cm^2 keV, and for the ^{79}Br pump state at 0.761 MeV of $\sigma = 6.2 \times 10^{-29}$ cm^2 keV. The photon fluxes per unit dose were found to be $\Phi = (3.44 \pm 0.88) \times 10^9$ photons/(cm^2 keV Gy) at 1.19 MeV, and $\Phi = (3.89 \pm 0.32) \times 10^9$ photons/(cm^2 keV Gy) at 0.761 MeV.

The difference between these values and the expected photon fluxes illustrated in fig. 3 can be reconciled by considering the effect of the unresolved high-energy tail detected in the absorption spectrometer. Since the activation cross sections near 3 MeV would be about three orders of magnitude larger than those near 1 MeV, the observed activation could be accounted for by this tail.

4. Conclusions

The general agreement between the calculated and measured values of spectral fluence shown in fig. 2 is surprisingly good for such preliminary results. Since the dominant gateway energies of ^{115}In and ^{113}In in the target are not known, deviations between theory and experiment of less than an order of magnitude are most heartening. The survey results are interesting for the appearance of individual gateways at the lower charging voltages.

For the softened environment, further analysis is necessary. The preliminary results are encouraging as there is support for the premise of a high energy tail even in the backscattered spectrum. The present data do not allow detailed mechanisms for the production of observed activation to be determined. It is clear that there is a strong case for calibrating large accelerators such as Aurora with the XAN technique proven at lower X-ray energies.

References

[1] B. Bernstein and I.B. Smith, IEEE Trans. Nucl. Sci. NS-20 (1973) 294.

[2] A. Bromborsky et al., Proc. SPIE paper 873-06 (1988); recently, G.A. Huttlin has obtained 309 J per pulse, private communication (1988) and to be published (1989).

[3] D.A. Whittaker, K.G. Kerris, M.S. Litz, S.G. Gorbics and N.R. Pereira, J. Appl. Phys. 58 (1985) 1034;
K.G. Kerris, F.J. Agree, D.A. Whittaker, S.G. Gorbics and N.R. Pereira, J. Appl. Phys. (January 1989).

[4] J.G. Kelly, L.D. Posey and J.A. Halbleib, IEEE Trans. Nucl. Sci. 18 (1971) 131;
J. Lee, private communication (1988).

[5] T.L. Johnson and S.G. Gorbics, Health Phys. 41 (1981) 859.

[6] J.A. Halbleib and T.A. Mehlhorn, ITS: The integrated TIGER series of coupled electron/photon Monte Carlo transport codes, Sandia National Laboratories, SAND84-0573 (1984).

[7] J.A. Anderson and C.B. Collins, Rev. Sci. Instr. 58 (1987) 2157.

[8] J.A. Anderson and C.B. Collins, Rev. Sci. Instr. 59 (1988) 414.

[9] J.A. Anderson, C.D. Eberhard, J.F. McCoy, K.N. Taylor, J.J. Carroll, M.J. Byrd, C.B. Collins, E.C. Scarbrough and P.P. Antich, in: Center for Quantum Electronics Report GRL/8704, University of Texas at Dallas (1988) unpublished, pp. 11–35.

[10] C.B. Collins, C.D. Eberhard, J.W. Glesener and J.A. Anderson, Phys. Rev. C37 (1988) 2267.