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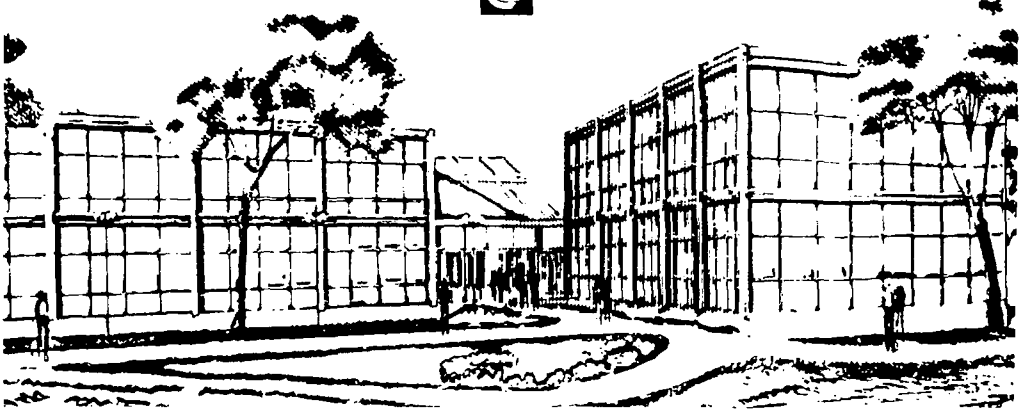

FILTER FLUORESCER EXPERIMENT ON THE ARGUS LASER

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ABSTRACT

A filter fluorescer experiment has been installed and operated on the Argus laser system of the Lawrence Livermore Laboratory. X-ray spectra have been measured between 20 and 116 keV from laser produced plasmas. Three spectral cuts were made in this region (20-29, 47-61 and 80-116 keV) with an additional channel providing a measure of the high energy response (> 116 keV) of the 3rd. channel. We have measured x-ray spectra from laser shots of 600-900 J in 1 ns with intensities of $3 \times 10^{14} - 3 \times 10^{15}$ W/cm^2 incident on Au disks.

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Filter Fluorescer Exp. On Argus Laser

H. N. Kornblum, B. L. Pruett, K. G. Tirsell, and V. W. Slivinsky

A filter-fluorescer experiment has been designed and used on the Argus laser system of Lawrence Livermore Laboratory (LLL) to measure x-ray spectra between 20 and 116 keV from laser produced plasmas. Three spectral cuts were made in this region (20-29, 47-61, and 80-116 keV) with an additional channel providing a measure of the high energy response (>116 keV) of the 3rd channel.

Previous to the present experiment, our active x-ray spectral measurements consisted primarily of a series of K-edge absorption filters used with various x-ray detectors, e.g., Si PIN diodes and NaI scintillators with photomultipliers, to provide appropriate spectral response functions. This technique gives well defined, relatively narrow spectral cuts for spectra which are falling sufficiently rapidly with increasing photon energy. However, if this is not the case, i.e., if the x-ray spectrum is relatively flat, the technique becomes progressively less usable. This is due to the fact that the transmission of the filter begins to increase again immediately after the sudden drop at the absorption edge and if an appreciable amount of spectral energy is present where the transmission becomes significant, this will contribute to the signal recorded for the channel. Thus, the channel data will no longer represent spectral energy found in a narrow band below the K-edge of the filter material. This effect is demonstrated in Fig. 1. Shown here is a typical K-edge filter channel using a 20 mil Sn filter, with an absorption edge at 29 keV, in combination with a Si PIN diode (Fig. 1[a]). Fig. 1(b) and 1(c) show the result of folding this response function with bremsstrahlung spectra from 10 keV and 50 keV Maxwellian distributions respectively. In the case of the less quickly falling spectrum, a significant fraction of the total integrated response is due to the spectrum above the K-edge of Sn. An additional weakness in the K-edge filter technique is that the use of the filter to provide the low energy cutoff inherently results in a response function that is much more sensitive at the high energy side of the channel than the low energy side. Therefore, any spectral structure within the effective energy band of the channel, such as x-ray lines, can result in invalid conclusions about the spectral energy content in the band.

In order to avoid these problems we have changed to the filter-fluorescer experimental arrangement shown schematically in Fig. 2(a). Briefly, the experiment works in the following way:

The incident x-ray beam, whose spectrum is to be measured, is first transmitted through the prefilter material. The spectrum is thus modified by being strongly absorbed in the energy region just above the characteristic K-edge of the preabsorbing material (Fig. 2[b]). This new spectrum, which now has a high-energy cutoff at the preabsorber K-edge, is then incident upon the fluorescer foil, chosen to have a K-edge below that of the prefilter. All incoming photons not transmitted through the foil are involved in either a photoelectric or scattering interaction. The photoelectric process dominates in this case because the photoelectric cross section in the energy region of interest is much larger than the cross section for scattering (Fig. 2 [c]). Thus the x-ray fluence, seen by the detectors that are located at 90° to the primary beam, consists largely of fluorescent photons resulting from photoelectric interactions. An interaction of this type can be caused only by an incident photon of greater energy than that of the K-edge of the fluorescing material. Therefore, each channel responds most efficiently to those primary photons having energies between the K-edges of the prefilter and fluorescer materials (Fig. 2[d]). Some slight improvement in the response function can be obtained by inserting an additional filter between the fluorescer and the detector. The purpose of the postfilter is to minimize both L-shell and scattered radiation incident on the detector. Typically, the postfilter is of the same material as the fluorescer so that the fluorescent photons are preferentially transmitted with respect to photons of other energies. For the sake of simplicity, postfiltering was not used in the present experiment.

The problems associated with the use of K-edge filters alone are lessened considerably with this technique. First, the response of the channel above the energy band of interest is minimized due to the rapidly falling photoelectric cross section of the fluorescer. Second, appropriate selection of channel width and prefilter thickness can provide a reasonably flat response within the energy band. Fig. 2(d) demonstrates both of these effects. There remains, however, an inherent uncertainty in results obtained from channels measuring the high energy end of the relevant spectral range which is relatively bigger than the uncertainty for lower energy channels. In the latter case, the contribution of the channel response above the band-pass can be accounted for in a mathematical unfolding process since the higher energy channels provide spectral information in this region. This is not the case for the few channels measuring the spectrum at the highest photon energies since one has no real knowledge of the spectral shape above this limit.

The following technique appears to be useful in alleviating this problem. For a particular channel, a matching one can be designed with very little response in the nominal band of photon energies to be measured, but with nearly the same response outside of that band. This is done by using an identical prefilter as the channel in question but a fluorescer of the same material as the prefilter. In this way we match the absorption cross section of the original prefilter without providing a transmission window in the nominal energy band of the original channel. Fig. 3 shows an example of this technique. Plotted here is the response of a FF channel using a 15 mil U prefilter and a 0.5 mil Au fluorescer, intended to measure x-ray fluence between 80-115 keV. One finds, however, that more than 50% of the total integrated response of such a channel occurs outside the energy band of interest. Curve A in Fig. 3 shows the response of a channel using 15 mil U prefilter and a 1 mil U fluorescer. This channel nearly duplicates the previous one outside the 80-115 keV band of interest but has an insignificant response within this band. Thus, in this case, the technique provides a very good way of correcting for the undesired response.

A filter-fluorescer experiment has been used to measure x-ray spectra from Au disks irradiated with 3×10^{14} - 3×10^{15} W/cm^2 by the LLL Argus laser. A summary of the channel parameters for this experiment is given in Table I and a plot of the three response functions in Fig. 4. Prefilter and fluorescer thicknesses and channel widths were chosen to provide some compromise between response function shape, resolution, and expected signal.

Calculations of response functions are done using the LLL FLUORESCER CODE[1] written for the CDC 7600. As seen in Fig. 2(a) the first element of the response function is simply the x-ray transmission of the prefilter. Transmission, scattering, and fluorescence calculations employ an LLL compilation of x-ray cross sections.[2] Referring to Fig 5, the fluorescer foil calculation is done by first dividing the foil into thin slabs. These slabs act as volume sources of fluoresced or scattered photons. In addition to the probability of fluorescence and coherent and incoherent scattering, the code also calculates the transmission of incident photons into and fluoresced or scattered photons out of the foil. After transmitting the exit photons through a postfilter, if used, the sensitivity function of the detector is then folded into the result. This is a single-scattering code and assumes only single incident and exit angles for calculating photon interactions in the fluorescer. These angles are specified by the user and care must be taken in the design of the geometry of the experiment to insure that the actual spread of angles encountered does not deviate too strongly from those used in the calculation.

A schematic of the experimental arrangement is shown in Fig. 6. The magnets shown are 6" long and provide a field of 1200 gauss. Detectors consist of 1- or 3- mm thick NaI crystals and Amperex XP2020 photomultipliers. These detectors have been calibrated from 8-97 keV with a Picker x-ray machine and a series of filtered fluorescers. A typical calibration curve is shown in Fig. 7. Data were recorded on LeCroy 2249 integrators or Tektronix R7903 oscilloscopes.

In designing a filter-fluorescer experiment, great care must be taken to shield detectors, as well as material which can be viewed by the detectors, from direct irradiation by any significant x-ray fluence. These precautions are necessary because the fluorescence process reduces the signal observed by a factor of 10^3 or more below what would be produced by the same portion of the source spectrum impinging directly on the detector. In order to check the effectiveness of our shielding a number of laser shots were fired at Au disks with no fluorescer foils installed. These results provided a measure of the background due to direct radiation of the detectors and/or indirect radiation from pipe walls, prefilters, collimators, etc. These measurements indicated that less than 10% of our total signal (for the low energy channels, less than 1%) was originating from these extraneous sources.

RESULTS

As mentioned previously, analysis of the data requires a mathematical unfolding process in order to account for the contribution of the channel response above the bandpass. This process is described in Appendix A.

We have used the filter-fluorescer technique to measure x-ray spectra produced by Argus laser shots with intensities of 3×10^{14} - 3×10^{15} W/cm^2 incident on Au disks. Results are shown in Fig. 8. For these conditions, x-ray intensity decreases with increasing photon energy similarly to bremsstrahlung spectra from Maxwellian electron distributions with kT = 10 - 35 keV.

APPENDIX A

For data analysis, spectrum unfolding is carried out with a code called UNSPEC.[3] The unfolding uses the following algorithm:

$$S_j^{n+1} = S_j^n \left[\frac{\sum_i W_i \, X_i \, F_{ij}}{\sum_i F_{ij}} \right] \qquad i = 1, m$$

= corrected value in the j^{th} zone of the n+1 iterated spectrum

M_i = experimental measurement of the i^{th} channel

S_j^n = energy in zone j of the n^{th} iteration for the spectrum

E_{ij} = response of the i^{th} channel to unit energy in the j^{th} zone of the spectrum

R_i = $\sum_j S_j^n E_{ij}$ = calculated value of the i^{th} channel to the n^{th} iteration for the spectrum S_j

X_i = M_i/R_i = ratio of the measured value for the unknown spectrum to the calculated value for spectrum S^n.

F_{ij} = $S_j^n E_{ij}/R_i$ = fractional contribution of zone j in channel i to the total calculated response

W_i = relative weight given to the measured signal value in channel i

n = iteration number

Due to the shapes of the response functions, E_{ij}, the result of this calculation normally has a number of sharp discontinuities present. Therefore, after each iteration a smoothing procedure is used. Several smoothing techniques are available in UNSPEC but the one chosen here is the "smoothing cubic spline".[4,5]

Briefly, one chooses a series of "anchor points", energy values which are selected, one per channel, at a suitable energy value for each response function. The smooth curve produced, made up of a series of cubic polynomials, is forced to miss the unsmoothed result at the anchor points by less than a specified amount, which may be different for each point. In addition, an adjustable parameter is available which controls the amount of curvature allowed between anchor points. One might reasonably conclude from this description that the smooth curves produced depend somewhat on the personal preferences of the code operator. Indeed this is true and in using an unfolding code of this type it is always necessary to determine the effects of these choices on the final result. For a filter-fluorescer experiment in which attention has been paid to the response function characteristics mentioned previously, the spectral energy content inferred for each channel from the measured data is quite insensitive to the smooth curve used. In any case, error estimates should include the uncertainty due to the unfolding procedure. For the present experiment this is about a 10% effect.

ACKNOWLEDGMENTS

We would like to acknowledge the contributions of Mary Cunningham and William McMaster, both of LLL, who did much of the original development of the filter-fluorescer technique. Dr. Cunningham was responsible for the first successful fielding of the experiment to measure x-ray spectra from nuclear devices at the Nevada Test Site. Dr. McMaster wrote the original versions of both the FLUORESCER and UNSPEC codes. Thanks are also due to T. L. Harper and R. D. Neifert for maintaining and improving these codes. We would also like to thank G. R. Leipelt for his help in assembling the present experiment and in calibrating detectors and foils.

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2. W. H. McMaster, et. al., Compilation of X-Ray Cross Sections, LLL Rept. UCRL-50174, Sections 1-4 (1970).

3. R. D. Neifert, UNSPEC-Revisited, LLL Rept. DAG 75-39 (1975).

4. L. F. Shampine and R. C. Allen, "An Introduction to Numerical Computing," Saunders and Company (1973).

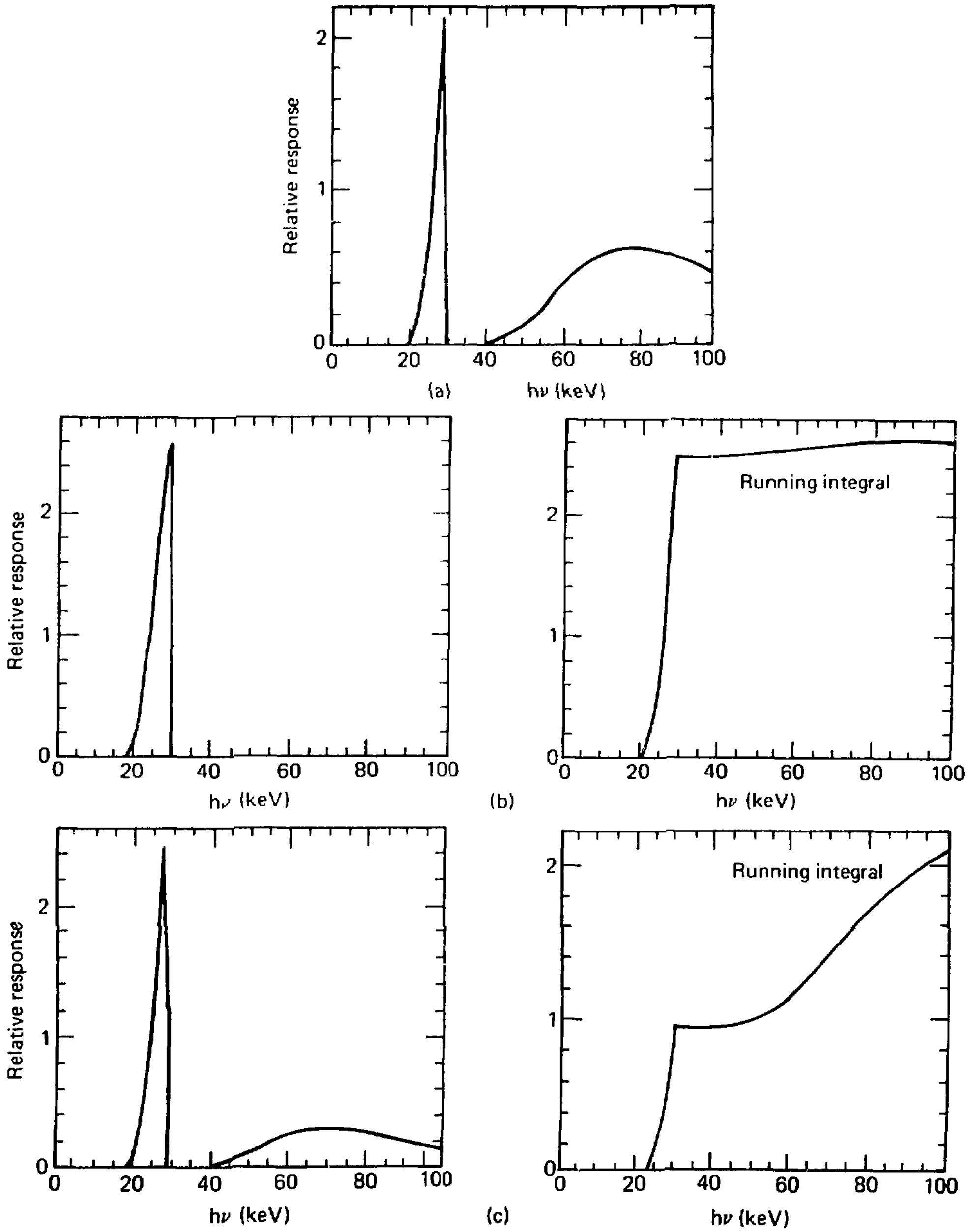
5. C. H. Reinsch, "Smoothing by Spline Functions," Numerique Mathematik 10, 177-183 (1967).

-Table 1-

Channel	Energy band (keV)	Prefilter		Fluorescer		Fluoresced response / Scattered response	Band response / Total response	Flatness of response function in band*
		(mat)	(mils)	(mat)	(mils)			
1	20-29.2	Sn	2.7	Mo	1.0	6.2	0.47	1.20
2	46.8-61.3	Yb	6.0	Sm	1.0	14.3	0.38	1.10
3	80.7-115.6	U	15.0	Au	0.5	6.3	0.36	2.4
4	> 115.6	U	15.0	U	1.0	–	–	–

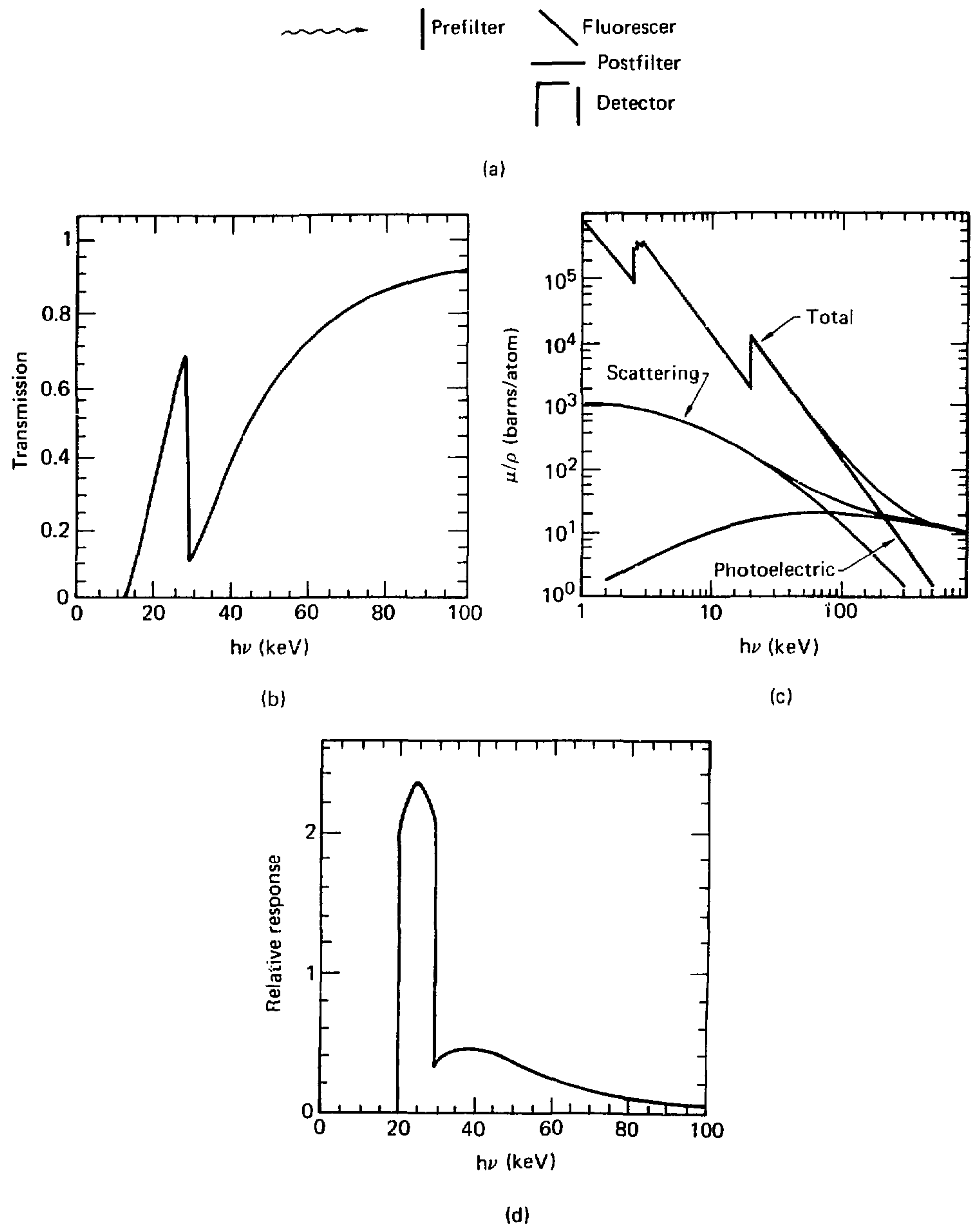
*Ratio of maximum to minimum response within band.

-Figure 1-



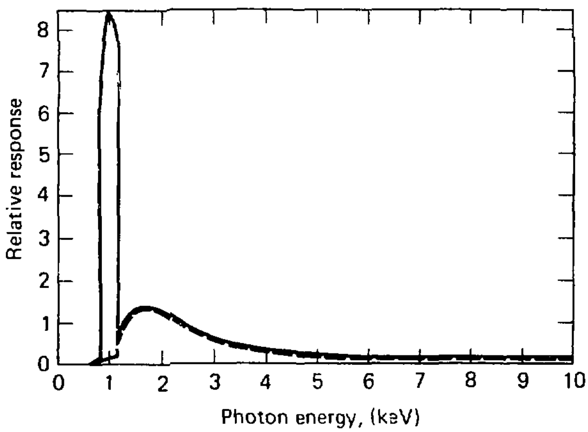
Relative response
0
1
2
0
20
40
60
80
100
(a)
hν (keV)
Relative response
hν (keV)
(b)
Running integral
hν (keV)
Relative response
hν (keV)
(c)
Running integral
hν (keV)

-Figure 2-

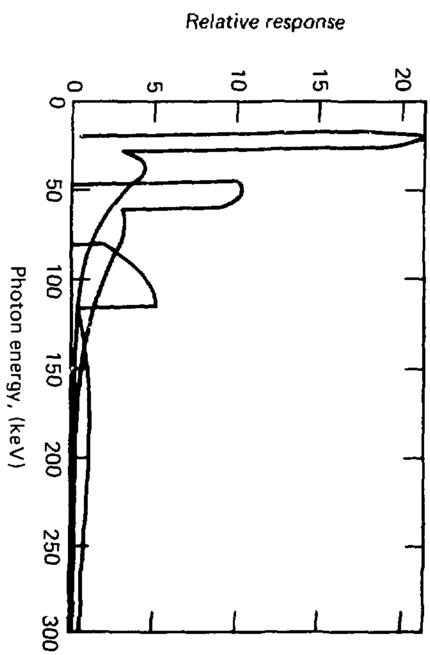


Prefilter
Fluorescer
Postfilter
Detector
(a)
Transmission
0
0.2
0.4
0.6
0.8
1
0
20
40
60
80
100
hν (keV)
(b)
μ/ρ (barns/atom)
10^0
10^1
10^2
10^3
10^4
10^5
1
10
100
hν (keV)
Total
Scattering
Photoelectric
(c)
Relative response
0
1
2
0
20
40
60
80
100
hν (keV)
(d)

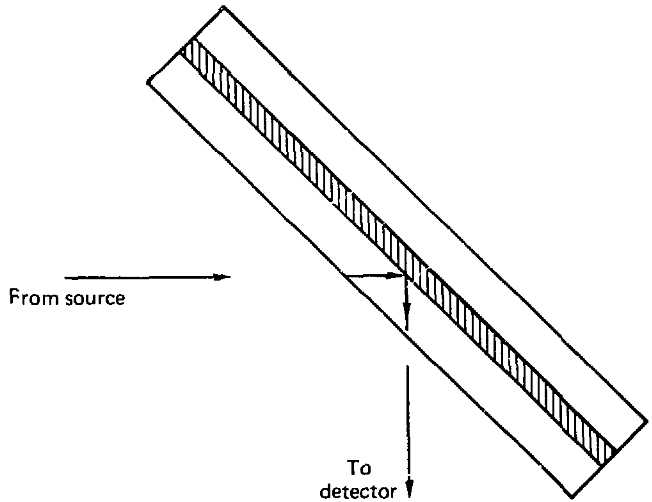
-Figure 3-



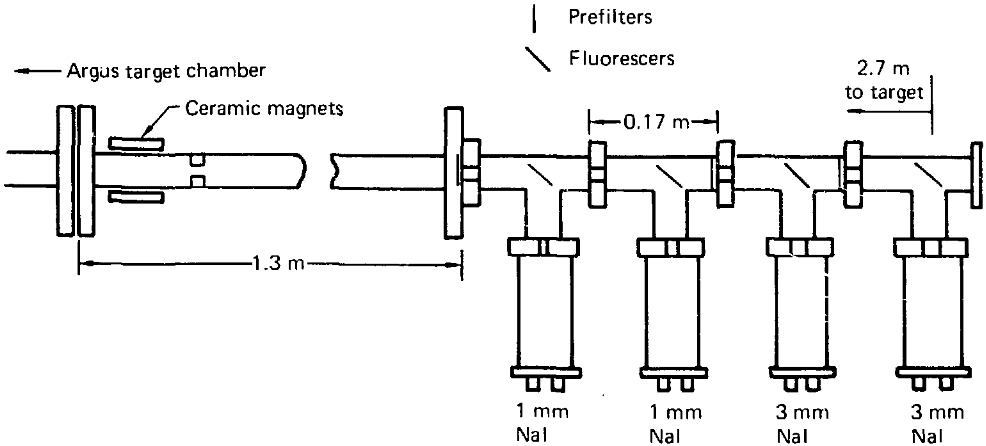
Relative response
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
Photon energy, (keV)


Relative response
0
5
10
15
20
0
50
100
150
200
250
300
Photon energy, (keV)

-Figure 4-

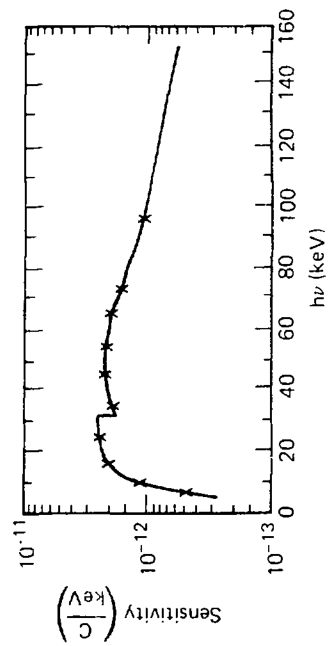


-Figure 5-

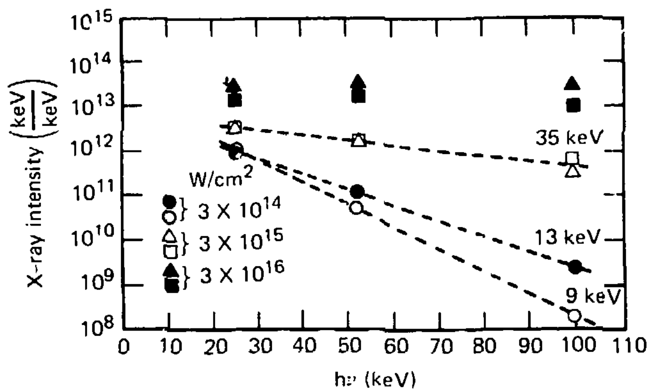

Prefilters
Fluorescers
Argus target chamber
Ceramic magnets
2.7 m
to target
0.17 m
1.3 m
1 mm
NaI
1 mm
NaI
3 mm
NaI
3 mm
NaI

-Figure 6-

-Figure 7-



Sensitivity (C/keV)
10^{-11}
10^{-12}
10^{-13}
0
20
40
60
80
100
120
140
160
hν (keV)


X-ray intensity (keV/keV)
10^15
10^14
10^13
10^12
10^11
10^10
10^9
10^8
0 10 20 30 40 50 60 70 80 90 100 110
hν (keV)
W/cm^2
3 X 10^14
3 X 10^15
3 X 10^16
35 keV
13 keV
9 keV

-Figure 8-