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Techniques for Efficiency Calibration of Photon Detectors for X-Rays and Low Energy Gamma Rays

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TECHNIQUES FOR EFFICIENCY CALIBRATION OF PHOTON DETECTORS FOR X-RAYS AND LOW ENERGY GAMMA RAYS

In atomic-nuclear physics, information about internal structure is contained in the x-rays and γ-rays emitted. Semiconductor photon detectors like Si(Li), HpGe efficiently detect and quantize the yield of emitted photons. In order to normalize these yields and convert them to cross section for production of the photons, it is essential to know the efficiency of the detector used. Measured cross section can then be compared with cross section values predicted by the theoretical models (Duggan, *et al*., 1985). This comparison is more meaningful if the uncertainties in the data are small. In measuring x-ray and γ-ray production cross section experimenters strive to reduce errors to a few percent. A large part of the error comes from uncertainties in the efficiency. To make accurate measurement of x-ray and x-ray production cross sections it is imperative that efficiency be known to a high degree of accuracy. Using several techniques to measure or calculate the efficiency in a region of photon energy and then averaging these results minimize the overall uncertainties in the determined efficiency value.

In the present work, techniques for measuring efficiency of detector will be reviewed from the stand point of the type of the detector, the energy range of the photons to be studied with the detector and the uncertainties that arise. Origin of the uncertainties and their effect on the overall uncertainty in the efficiency values will be explored.

The primary method of measuring efficiency utilizes calibrated radioactive sources (Gallagher and Cipolla, 1974). The calibration gives their activities and standard tables provide rates of emission of the x-rays and γ-rays from the source. The energies of these photons should also be known to a high degree of accuracy. Ideally a point source is preferred for the geometry to be used with the source and the detector. From the activity of the source and a knowledge of half-life of the radioactive decay involved, the disintegration rate of the source isotopic nuclei on any date can be calculated. Uncertainty comes in the calculation via both the half-life and the activity quoted. The efficiency of the detector, ε, at the energy of the photon, E, is then given by

$$\varepsilon = \frac{(d\Omega/4\pi)\ (\#\text{photons measured/time})}{\text{Activity.}\ (x \text{ or } \gamma \text{ emission rate/disintegration})} \qquad (1)$$

where $d\Omega$ is the geometrical factor related to the solid angle subtended by the point source at the detector position. The limitation of this technique is the non-availability of a calibrated source for < 3 keV energy region that is being studied. Among the available sources, the 3.3 keV M-shell x-ray line in an open/(unshielded) ^{241}Am source is the lowest energy line available for efficiency determination studies (Campbell and McNelles, 1974). This line has a comparatively large (9%) uncertainty quoted for its emission rate. Most of the higher energy lines in this source (e.g. 13.9 keV, 26.5 keV, 59.6 keV) are well suited for accurate efficiency determination as their emission rates are known to uncertainties of 1-2%. For energy regions above ~5 keV, assuming activity uncertainties are below 5% and other parameters in eq. (1) can be measured to accuracies of 1-2%, the overall uncertainty is < 8%. But for regions at 3 keV errors propagate to at least 14%. Figure 1 was determined with a calibrated source of ^{241}Am. The efficiency(ε) is above 5 x 10^{-5} between 10 and 30 keV and falls off at other energies.

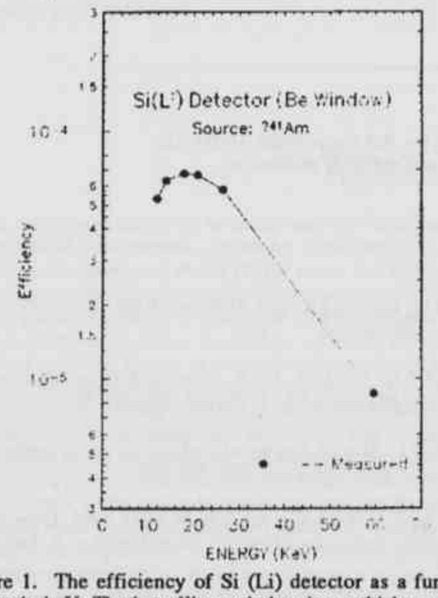

Figure 1. The efficiency of Si (Li) detector as a function of photon energy in keV. The berryllium window has a thickness of7.62 µm. The resolution of the detector at 5.9 keV is 165 eV.

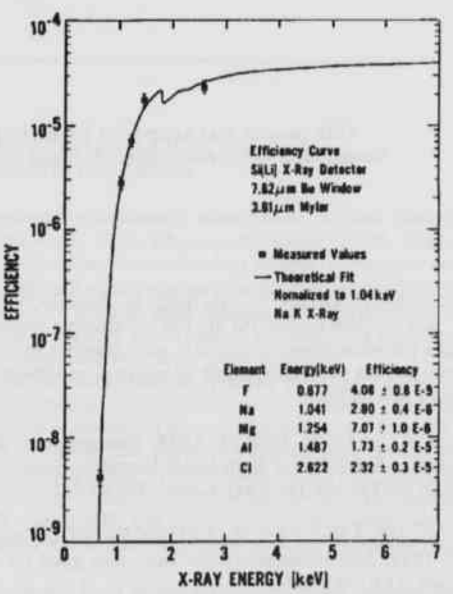

Figure 2. Efficiency of the Si(li) dector vs. the x-ray energy.

The method of determining the yield of the x-ray or the γ-ray yield from the measured spectrum is another crucial aspect in reducing uncertainties. The basic procedure here is to subtract a properly drawn background and fit the resulting spectrum with peaks of appropriate line shapes. The fitting algorithm has to take into account whether the peak represents a x-ray or an γ-ray (Gunnink, 1977). The line-shapes of the peaks representing x-ray or γ-rays are dependent on their origin, atomic for x-rays and nuclear for γ-rays. The x-ray shapes are non-gaussian because of their long tails and hence described better by Voight function while x-rays have a natural line shape given by Lorentzian function (Debertin and Pessara, 1981). The resolution of the detector also affects the fitting procedure as peaks become resolved or not depending on the resolution. Then there is the question of the detector response to the photons (Yacout, *et al* 1986). Basically the interaction of the photon in the active region of the detector is via photoelectric effect. Compton effect adds to the overall shape of the spectrum and for low energies (<150 keV) the other mechanisms that contribute are the Auger electrons and the escape peaks generated by the element of the detector (Silicon for Si(Li) and Germanium for HpGe). MonteCarlo calculations (He *et al*., 1988) of the detector response function allows one to have a better understanding of these mechanisms.

The second technique (Gallagher and Cippolla, 1974) is based on the calculation of attenuation of photon intensities in traversing the various layers before the photon reaches the active region (active silicon in a Si(Li) and the active Germanium in a HpGe detector) of the detector. A typical set of layers is comprised of, starting from outside, a thin mylar film ($C_{10}H_8O_4$), beryllium window, gold contact layer and dead layer (No electrical pulses are generated from this region of the crystal and hence the terminology dead). The attenuation depends on the thickness (x) of the layer and its mass absorption coefficient (μ) at the photon energy. The intensity attenuation is given by the exponential law

$$I = I_0 e^{-\mu x} \quad \text{.......... (2)}$$

The intrinsic efficiency, ε, as a function of the energy of photon, E, in terms of a ε_0, the geometrical factor, is given by

$$\varepsilon = \varepsilon_0 \cdot e^{\alpha E^\beta} \cdot [1 - \exp(\gamma E^\delta) \quad \text{.......... (3)}$$

where α, β, γ and δ are the parameters. The efficiency curve determined from eq. (3) is normalized via efficiency numbers generated from the method of calibrated sources at a common point in energy. This normalized curve then allows one to read efficiency values at energies of photons below 3 keV. The uncertainties also arise from absorption edges of Si-K shell and Au-M shell. The photon absorption at these edges result in abrupt changes in the efficiency curve at the energies of these edges. The typical efficiency curve, at 1 keV and below, shows a sharply dropping efficiency with decreasing energy. Starting with ~14% at 3.3 kev the uncertainties only keep increasing with decreasing energy. It becomes essential in the region below 3.3 kev, especially below 1 keV, to use another method for determination of efficiency that would allow one to average efficiency and reduce uncertainties.

The technique proposed by Lennard and Phillips (1979) allows one to determine efficiency accurately in 0.5 - 8.4 keV range. In this method K-shell x-rays from targets of low Z elements (Z= 8-29) is measured for incident proton and helium ions. The x-ray yield is normalized to the theoretical cross section for K-shell x-ray production and efficiency determined. The efficiency for Kshell x-rays of each element is given by

$$\epsilon = \frac{Y_{KX} \cdot DT_X \cdot \sigma_R(\theta) \cdot \Delta\Omega}{Y_R \cdot DT_R \cdot \sigma_{KX} \cdot S} \quad \text{.......... (4)}$$

where Y_{KX} is the net yield of K-shell x-ray, DT_X is the dead time correction for x-ray detector, $\sigma_R(\theta)$ is the differential Rutherford cross section, ΔΩ is the solid angle subtended by the particle detector, Y_R is the net yield of the scattered particles, DT_R is the dead time correction for the particle detector, ε is the efficiency of the x-ray detector at Kα x-ray energy, S is the correction for self-attenuation of the x-rays in the target foil. Figure 2 shows efficiency of Si(Li) detector for x-ray energies below 3 keV determined following this procedure (Duggan *et al.*, 1985). The solid curve was determined by attenuation method as described by eq.(2) and eq.(3). Good agreement is seen between the efficiency determined by the two methods. Even with this good agreement and overall reduction in the uncertainty in efficiency, there is still >10% uncertainty. Equation (4), when rearranged and solved for σ_{KX}, allows one to calculate photon production cross section. The uncertainty in the efficiency is then propagated to σ_{KX} according to eq. (4). It turns out that uncertainties in all other parameters in eq. (4) can be reduced to <5% most of the times. Hence the largest uncertainty in cross sections comes due to uncertainty in the efficiency. Therefore it is essential that uncertainty be known to a great degree of accuracy.

In order to determine efficiency of a windowless Si(Li) detector to a high degree of accuracy, down to 600 eV, researchers have successfully used the measurement of atomic field bremsstrahlung (Weathers *et al.*, 1991). Bremsstrahlung spectrum is a slowly varying function of energy. This radiation was measured from targets of Al, Ag and Au for incident beam of 66.5 kev electrons. The measured Bremsstrahlung Spectra was compared to the theoretically predicted Bremsstrahlung distribution and an intrinsic efficiency was generated. The efficiency determined with a calibrated radioactive source at 5.4 keV allowed for absolute normalization of the efficiency curve.

To summarize, the efficiency of a detector, an important parameter in determination of photon production cross section, can be determined by different techniques. The choice of technique depends on photon energy. Some of these techniques allow one to extend the range of energies covered while the overlapping energy regions covered in these techniques provide for reduction of uncertainty in the efficiency.

In conclusion, efficiency plays an important role in determination of photon production cross section and the uncertainty there in. The overall uncertainty in the efficiency can be reduced by combining efficiency determined via various techniques.

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