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CALIBRATION STANDARDS FOR PHOTON SPECTROSCOPY BETWEEN 20-200 Kev

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INTRODUCTION

The discovery of extraterrestrial x-rays from discrete sources in 1962 (1) has spurred the development of > 1 keV photon detectors for space research. X-ray astronomy above ~ 1 keV is possible from satellites and rockets, but photon spectroscopy from balloons is restricted to energies > 30 keV because of the few g/cm^2 of residual atmosphere which preclude analysis at lower energies.

All of the detection devices employed use the photoelectric effect in the detection medium to perform the spectral analysis. Each has its relative advantages and disadvantages in different applications, as will be discussed below. Similarly, each requires its own calibration techniques. While this study was undertaken expressly for the purpose of calibrating a Ge(Li) system, the general principles apply to any detection technique.

In particular, radioactive sources provide the means by which the calibration can be accomplished. In studying the response of our own system, it was found that the available literature was often vague and contradictory regarding the details of the photon emission from a good

fraction of our source folio. For this reason, we have tabulated relative line strengths from 11 representative sources in the hope that this quick reference list will provide an alternative to exhaustive (and often fruitless) literature searches.

DETECTOR

Three basic types of detectors have been used in space research for photons above 30 keV.

(1) Alkali halide scintillators

(2) Gas proportional counters

(3) Solid-state crystals

Alkali halide spectroscopy has been the most successful to date (2); the remaining techniques are still in their infancy with regard to high-energy x-ray astronomy. Alkali halides detectors have no dead layer, are extremely efficient (the photoelectric cross-section is much larger than the Compton cross-section over the whole range), have large (and linear) light outputs, and can be grown to relatively large areas (devices up to 400 cm^2 (3) have been successfully used). The main disadvantage is that the energy resolution is typically $\sim$ 30% FWHM or worse, while the other two techniques can do considerably better. A second, less serious, disadvantage is the long recovery time of the scintillators ($\sim$ several μsec even for small pulse amplitudes) — this

limits the detector areas which can be employed. Escape peaks are a further complication, which can sometimes be considerable (4).

Of the three techniques, proportional counters constitute the oldest, by far, for x-ray analysis. Their application to high-energy x-rays for astronomy is still developmental, however (5). With a multi-anode chamber filled with a gas as dense as Xenon at a few atmospheres, it is possible to get energy resolution of 10% FWHM (6) with areas approaching 1 m^2. While there is no dead layer problem, even a few atmospheres of Xenon are not sufficient to keep the efficiency high at energies approaching 100 keV. The photo-efficiency is further reduced by Compton interactions, and escape radiation is generally a more pronounced effect than in alkali halides.

The newest technique, and that which provides the motivation for this study, is that involving the use of solid-state crystals. Lithium-drifted germanium, when cooled to liquid nitrogen temperatures, can provide energy resolution of $\sim$2 keV FWHM (electronics-noise-limited) almost independent of energy. With a cooled FET preamplifier input, a resolution of 1 keV FWHM is not overly optimistic. The photoelectric cross-section exceeds the Compton cross-section up to $\sim$150 keV, and crystal depths of $>$ 1 cm are obtainable so that the net photoelectric efficiency above $\sim$100 keV is lower than that in alkali halides, but is

considerably more than that in proportional chambers. Escape radiation is less of a problem than with the other techniques. The most serious drawbacks are the liquid-nitrogen temperatures required, and the fact that individual detectors with areas larger than ~ 20 cm^2 cannot be made without a degradation of the resolution due to the increased detector capacitance.

DETECTOR RESPONSE

If there existed a perfect detector, i.e. one for which edge effects and interactions other than photoelectric could be neglected, the efficiency could be deduced immediately. If the probability for photointeraction in a depth dx is μ:

$$\frac{dI}{I} = -\mu\, dx \tag{1}$$

the absorption probability in a depth d is therefore:

$$\chi_0 = 1 - e^{-\mu d} \tag{2}$$

For a real detector, of course, there are many complicating factors:

(1) energy resolution

(2) competing interactions

(3) edge effects

(4) variation with energy of all of the above

The energy resolution of any device is determined primarily by the statistics of the energy loss in the detection medium. A system such as Ge (Li), with less than 3 ev/ion-pair, will have an inherent energy resolution which is three times better than a gas proportional counter, since the specific ionization in the gas is an order of magnitude higher. There is no internal multiplication (or low noise amplification) in such a device, however, making the energy resolution electronics-limited. Inefficient conversion and collection can degrade the resolution as well. Resolution can easily be measured as a function of energy with monochromatic sources, so that the area in the peak can then be related to the photoelectric efficiency.

The Compton interaction is generally the most important competing interaction with the photoelectric effect. We can make a first-order correction to equation (2) by considering that probability of a photon having a photoelectric interaction in its initial encounter in the medium. If the probability for a Compton interaction in dx is η, then this first-order expression can be written:

$$\chi_1 = \frac{\mu}{\mu + \eta} \left(1 - e^{-(\mu + \eta) d}\right) \qquad (3)$$

For a thick detector, however, the simpler expression χ_0 is closer to reality, since Compton interactions followed by photoelectric interactions are indistinguishable from initial photoelectric interactions. The total photoelectric response for a given geometry may be calculated by means of a Monte Carlo calculation, but a fairly good approximation can be obtained from summing contributions from all Compton effects ending with a photo-interaction in a depth d:

$$\chi_2 = \frac{\Gamma}{1 - \eta/\mu \Gamma} \tag{4}$$

where

$$\Gamma = \chi_1 = \frac{\mu}{\mu + \eta} \left(1 - e^{-(\mu+\eta) d}\right) \tag{5}$$

This expression represents the total photoelectric interaction probability, i.e. not the probability of an event falling within the resolution peak. Some of these true photo-events will be recorded at lower energies or will not be recorded at all because of edge effects.

Some detectors (in particular Ge (Li)), have a thin "dead layer" in which photons may be converted without having the energy collected. Since this layer is generally thin and important at lower energies,

where the photo-effect dominates, this correction can generally be made with a zero-order term. For a dead layer of thickness t in front of a detector d deep:

$$\chi_4 = e^{-\mu t} \chi_3 \tag{6}$$

Another class of edge effect arises from photons which convert in the active detection medium but do not give rise to total energy collection because a converted x-ray photon gets out or an electron leaves the active medium. This effect is detector-geometry dependent and can best be determined from a Monte Carlo calculation. It may be possible to measure the photon escape if the energy resolution of the detector is good enough so that the primary and escape peaks may be resolved. Inefficient collection is very difficult to measure experimentally, however, since at energies much lower than incident the Compton interactions mask the poorly collected photo-interactions. In most detectors the edge-effects (excluding escape) form at most a few percent of the total photo-interactions, and can be neglected.

CALIBRATION STANDARDS

Radioactive sources provide an ideal tool for the measurement of energy resolution, system linearity, and escape-to-primary ratio. The

energies of the source lines are generally well known. Unfortunately, however, the absolute intensities of the lines are not well known. This is not only because source strengths are generally uncertain but also because relative line strengths are not usually available in the literature for most sources. Knowing relative line strengths in a given source is extremely useful in the determination of detector depth and dead layer.

This study was undertaken expressly for the purpose of determining the depth and dead layer of a Ge (Li) detector. It was found that the published relative intensities of lines from Cd^{109} and Ba^{133} could be consistently reconciled with a detector depth of 1 cm masked by a 30 micron dead layer.

The following source catalogue has been compiled with this detector. The quoted relative intensities have been escape- and resolution- as well as depth- and dead-layer-corrected. Previously published intensities are included where we have been able to find them (detailed reference list can be found in (7)). No attempt has been made to estimate the absolute error in our measurements since we cannot be sure that we have correctly taken systematic effects into account (although the relatively good agreement with Cd^{109} and Ba^{133} would indicate that we have not done badly in this respect). Where a line

has been reported in the literature which we have been unable to resolve, an approximate upper limit is indicated.

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Source	Decay Mode	$T_{\frac{1}{2}}$	Energy	Ident.	Publ. Intensity	Meas. Intensity
Co^{57}	EC	267d	121.9	γ Fe^{57}	1.0	1.0
			136.3	γ Fe^{57}	.07	.12
Cd^{109}	EC	470d	22.2	Kα Ag^{109}	} 23.8±.7	20.8 } 23.6
			25.0	Kβ Ag^{109}		2.8
			87.5	γ Ag^{109}	1.0	1.0
Sn^{119}	IT	250d	24	γ Sn^{119}		1.0
			25.3	Kα Sn^{119}		.82
			28.5	Kβ Sn^{119}		.10
			65	γ Sn^{119}		~.004

Source	Decay Mode	$T_{\frac{1}{2}}$	Energy	Ident.	Publ. Intensity	Meas. Intensity
Te^{127}	IT	105d	27.2	$K\alpha_2 Te^{127}$		
	β-	9.3h	27.5	$K\alpha_1 Te^{127}$		
			28.3	$K\alpha_2$ I^{127}		~ 18
			28.6	$K\alpha_1$ I^{127}		
			31.0	$K\beta_1 Te^{127}$		
			31.7	$K\beta_2 Te^{127}$		
			32.3	$K\beta_1$ I^{127}		~ 2.2
			33.0	$K\beta_2$ I^{127}		
			58.5	γ I^{127}	.776	~ .5
			88.7	γ Te^{127}	.13	~ .1
			*122			~ 1.4
			*136			~ .17
			145	γ I^{127}	.008	~ .03
			203	γ I^{127}	.11	< .1
			215	γ I^{127}		< .1
			360	γ I^{127}	.15	< .3
			418	γ I^{127}	1.0	1.0

* These lines can be attributed to Co^{57} contamination in our sample

Source	Decay Mode	$T_{\frac{1}{2}}$	Energy	Ident.	Publ. Intensity	Meas. Intensity	Calc.* Intensity
Ba^{133}	EC	7.2y	30.6	$K\alpha_2 Cs^{133}$		.12	
			31.0	$K\alpha_1 Cs^{133}$		.70 } 1.04	} .98
			35.0	$K\beta_1 Cs^{133}$		.17	
			35.8	$K\beta_2 Cs^{133}$		.05	
			53	$\gamma\ Cs^{133}$	.015-.073	.021	.029
			79	$\gamma\ Cs^{133}$	<.07	< .01	< .10
			81	$\gamma\ Cs^{133}$	.32 -.55	.55	.56
			160	$\gamma\ Cs^{133}$	.004-.02	< .01	.023
			220	$\gamma\ Cs^{133}$	<.005	< .005	< .005
			274	$\gamma\ Cs^{133}$	.02 -.1	.09	.071
			302	$\gamma\ Cs^{133}$	.22 -.45	.26	.28
			355	$\gamma\ Cs^{133}$	1.0	1.0	1.0
			380	$\gamma\ Cs^{133}$	.10 -.20	.17	.1

* Calculated from available x-ray conversion coefficients and available information about unconverted gamma ray relative intensities. Enough information was present only for Ba^{133} to perform this computation.

Source	Decay Mode	$T_{\frac{1}{2}}$	Energy	Ident.	Publ. Intensity		Meas. Intensity	
Eu^{155}	β^-	1.81y	26	γ Gd^{155}	.04		< .01	
			31	γ Gd^{155}			< .01	
			39.5	γ Gd^{155}			.08	
			42.3	$K\alpha_2 Gd^{155}$	}		.12	}
			43.0	$K\alpha_1 Gd^{155}$	}		.26	}
			45	γ Gd^{155}	} .023	.98	.026	} .47
			48.7	$K\beta_1 Gd^{155}$	}		.074	}
			50.0	$K\beta_2 Gd^{155}$			.017	
			60	γ Gd^{155}	.05		.025	
			85.9	γ Gd^{155}			< .05	
			86.5	γ Gd^{155}	1.0		1.0	
			100.0	γ Gd^{155}			< .02	
			102.3	γ Gd^{155}			< .02	
			105	γ Gd^{155}	.63		.66	
			118	γ Gd^{155}			< .005	
			125	γ Gd^{155}			.026	
			132	γ Gd^{155}			~ .001	
			137	γ Gd^{155}			< .002	

Source	Decay Mode	$T_{1/2}$	Energy	Ident.	Publ. Intensity	Meas. Intensity
Tm^{170}	β-	127d	* ~ 48			12
			51.3	$K\alpha_2 Yb^{170}$		30
			52.4	$K\alpha_1 Yb^{170}$		91
			59.4	$K\beta_1 Yb^{170}$		32
			61.0	$K\beta_2 Yb^{170}$		4.9
			* 66.7			31
			84.2	γ Yb^{170}		1.0
Au^{195}	EC	192d	30.8	γ Pt^{195}	.01- .014	< .005
			65.1	$K\alpha_2 Pt^{195}$	1.0	.20
			66.8	$K\alpha_1 Pt^{195}$		.55
			75.7	$K\beta_1 Pt^{195}$		.20
			77.9	$K\beta_2 Pt^{195}$		.05
			98.8	γ Pt^{195}	.096- .14	.13
			129	γ Pt^{195}	.007- .037	.008

1.0

* It is assumed that the presence of the 66.7 keV line in our samples of Tm^{170} is due to contamination by Tm^{171}. Our measured relative intensity of K x-rays should therefore be higher than that for a pure Tm^{170} source. We can not plausibly explain the presence of the line at 48 keV.

Source	Decay Mode	$T_{\frac{1}{2}}$	Energy	Ident.	Publ. Intensity	Meas. Intensity	
Hg^{203}	β-	47d	70.8	$K\alpha_2 Tl^{203}$		~ .064	.193
			72.9	$K\alpha_1 Tl^{203}$		~ .088	
			82.6	$K\beta_1 Tl^{203}$		~ .029	
			84.9	$K\beta_2 Tl^{203}$		~ .012	
			279.	γ Tl^{203}		1.0	
*Bi^{207}	EC	~ 304	72.8	$K\alpha_2 Pb^{207}$		~ .38	
			75.0	$K\alpha_1 Pb^{207}$		~ 1.0	
			84.9	$K\beta_1 Pb^{207}$		~ .35	
			87.3	$K\beta_2 Pb^{207}$		~ .09	

* Lowest energy gamma is 570 keV

Source	Decay Mode	$T_{\frac{1}{2}}$	Energy	Ident.	Publ. Intensity	Meas. Intensity
*Am^{241}	α	460y	26.4	γ Np^{237}	.0825- .10	.06
			33.2	γ Np^{237}	.005	< .01
			43.4	γ Np^{237}	.006	< .01
			55.5	γ Np^{237}		.09
			59.6	γ Np^{237}	1.0	1.0
			97.0	$K\alpha_2 Np^{237}$		< .001
			101.0	$K\alpha_1 Np^{237}$		~ .001
			103.	γ Np^{237}	.001	~ .001

* Higher energy gammas could not be resolved (see reference 8)