

GAMMA-RAY SPECTRA

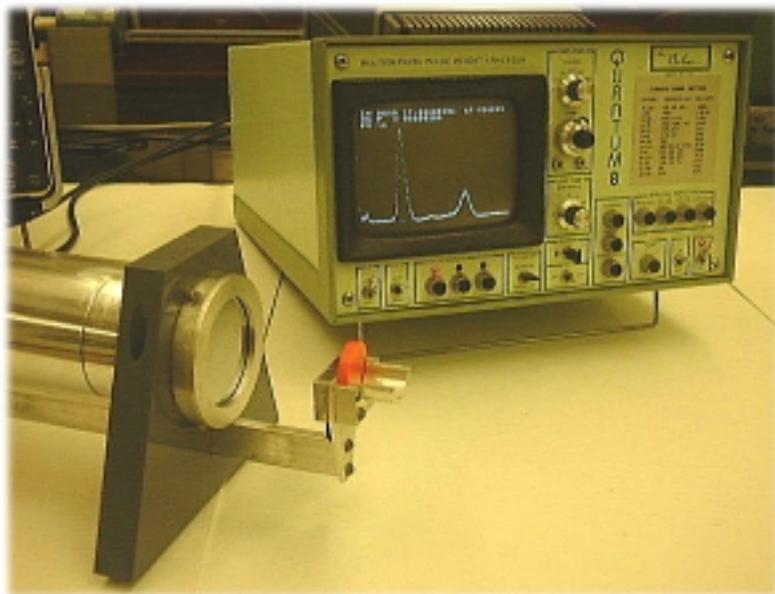
REFERENCES

1. K. Siegbahn, *Alpha, Beta and Gamma-Ray Spectroscopy*, Vol. I, particularly Chapt. 5, 8A.
2. *Nucleonics Data Sheets*, Nos. 1-45 (available from the **Resource Centre**)
3. H.E. Johns & Cunningham, *The Physics of Radiology*, 3rd edition
4. H. Enge, *Introduction to Nuclear Physics*, Chapt. 7
5. INSTRUCTION MANUAL for "THE NUCLEUS" model Quantum 8 Multichannel Analyzer (available from the **Resource Centre**)

SPECIAL NOTE ON SAFETY:

See *HEALTH AND SAFETY IN THE LABORATORY* in the **Laboratory Manual** with regard to handling radioactive materials and lead. In particular, note the following cautions on radiation: The sources we use in the lab are weak, so that when properly used, they subject the user to a small fraction of the radiation one receives in every-day life. However, as with any toxic material, it is important that you minimize the exposure you receive as any exposure does damage (be it small) to your body. Thus, place the sources you are using in a location away from yourself and other persons. Total radiation exposure is proportional to the source strength, the time you are exposed and a distance factor which for gamma rays drops off as the inverse square of the distance, and for alphas and betas, even faster.

INTRODUCTION



In this experiment you will investigate the properties of gamma-ray spectra as observed with scintillation counter (a sodium iodide, NaI(Tl) scintillation counter and a multichannel analyzer). You will calibrate the detection system using radioactive sources (available at the **Resource Centre**) with gamma-rays of known energy and then you will measure the energy of a gamma-ray from an unknown source.

SCINTILLATION SPECTRA

The Photopeak

If you were to place a monoenergetic source of gamma-rays (*e.g.*, ^{137}Cs) near a scintillation detector, you expect, ideally, a spectrum which is a single photopeak caused by the photoelectric effect in the NaI crystal as in Figure 1. However, other processes take place by which the gamma-ray energy is absorbed, thus altering the spectrum shape.

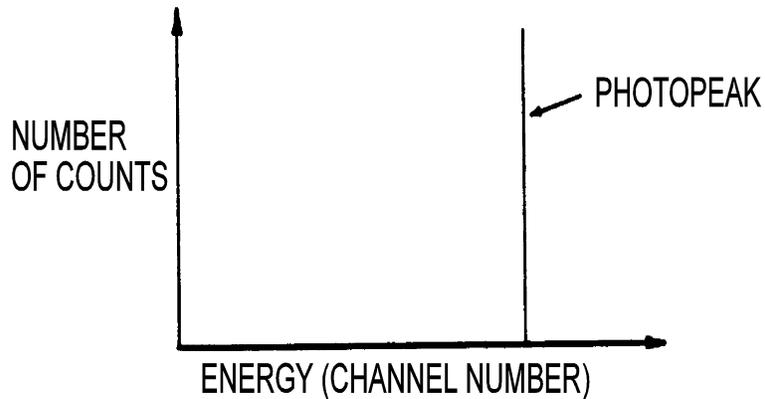


Figure 1. - Idealized Picture of Gamma-Ray Spectrum Showing Only the Photopeak

The Compton Plateau

When a gamma-ray enters the crystal, instead of ejecting an electron from an atom, it may collide with a (more or less) free electron giving up only a part of its energy to the electron. If the scattered gamma ray escapes from the crystal then only part of the energy of the original gamma ray is left with the electron in the crystal. This results in a smaller amount of light and it is as if a gamma ray of smaller energy were completely absorbed in the crystal. Simple kinematics (conservation of energy and momentum) forbids the electron from receiving more kinetic energy than

$$E_{max} = \frac{2E_{\gamma}^2}{m_0c^2 + 2E_{\gamma}}$$

This is called the Compton edge. E_{γ} is the energy of the gamma-ray and $m_0 c^2$ is the rest energy of the electron. This maximum energy transfer corresponds to an angle of scattering of the gamma-ray through 180° . A 0° scatter transfers no energy. Compton scattering is a fairly slowly varying function of angle and so there will be a distribution of Compton events of energy less than the Compton edge. As a result of the photoelectric effect and the Compton effect, an idealized gamma-ray spectrum should have the form shown in Figure 2. (Note that the photopeak (or full-energy peak) can still be seen as resulting from the absorption of all the incident gamma-ray energy. However this total absorption may also result from a compton scattering followed by photo-electric absorption of the compton scattered gamma-ray).

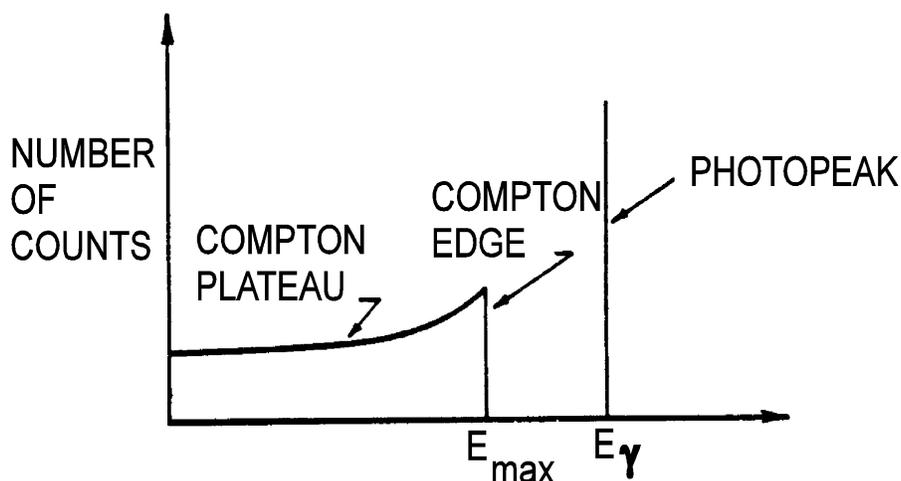


Figure 2. - Idealization of gamma-ray spectrum showing photopeak and compton plateau

Other Effects

Any photons scattered into the crystal by shielding material, table tops, holders etc., will have less than the full energy of the original gamma-ray and this process will give rise to a general distribution of pulses a oscilloscopes the Compton plateau. However, the kinematics of the problem together with the angular probability of scatter tends to produce a bump on the low energy part of the spectrum and is called the backscatter peak. Even if the holders are removed and the detector is moved far from the table top, this peak, although smaller, still occurs from backscattering within the source itself and also from gamma-rays that pass right through the crystal and are scattered back into the crystal from the photomultiplier.

Table 1 - Calibration Gamma-Ray Energies

Radioactive Isotope	Decay Process	Daughter	Gamma-Ray Energy (MeV)
$^{133}_{56}\text{Ba}$	EC	$^{133}_{55}\text{Cs}$.031 (X) .080 .356
$^{60}_{27}\text{Co}$	β^-	$^{60}_{28}\text{Ni}$	1.333 1.173
$^{137}_{55}\text{Cs}$	β^-	$^{137}_{56}\text{Ba}$.032(X) .662
$^{22}_{11}\text{Na}$	β^+	$^{22}_{10}\text{Ne}$.511 (A) 1.275

Where EC = electron capture (a K-shell electron is captured by the nucleus producing a daughter with one less proton and one more neutron), β^- = emission of an electron or beta particle, β^+ = emission of a positron, A = annihilation (when a source emits positrons, the positrons usually annihilate with electrons in the source to produce two gamma-rays, each having the energy equivalent to the rest mass energy of the electron, namely 0.511 MeV), and X = X-Rays (in many decay schemes the daughter is highly ionized and as a result the characteristic X rays of the daughter are observed. In this experiment, only the X rays of heavier daughters are seen. in these elements the K shell electron is tightly bound and this produces high energy X rays).

PRELIMINARY EXERCISES IN NUCLEAR COUNTING

SCINTILLATION COUNTERS

A schematic diagram of a NaI(Tl) scintillation counter is given in Figure. 3 and its operation is described below.

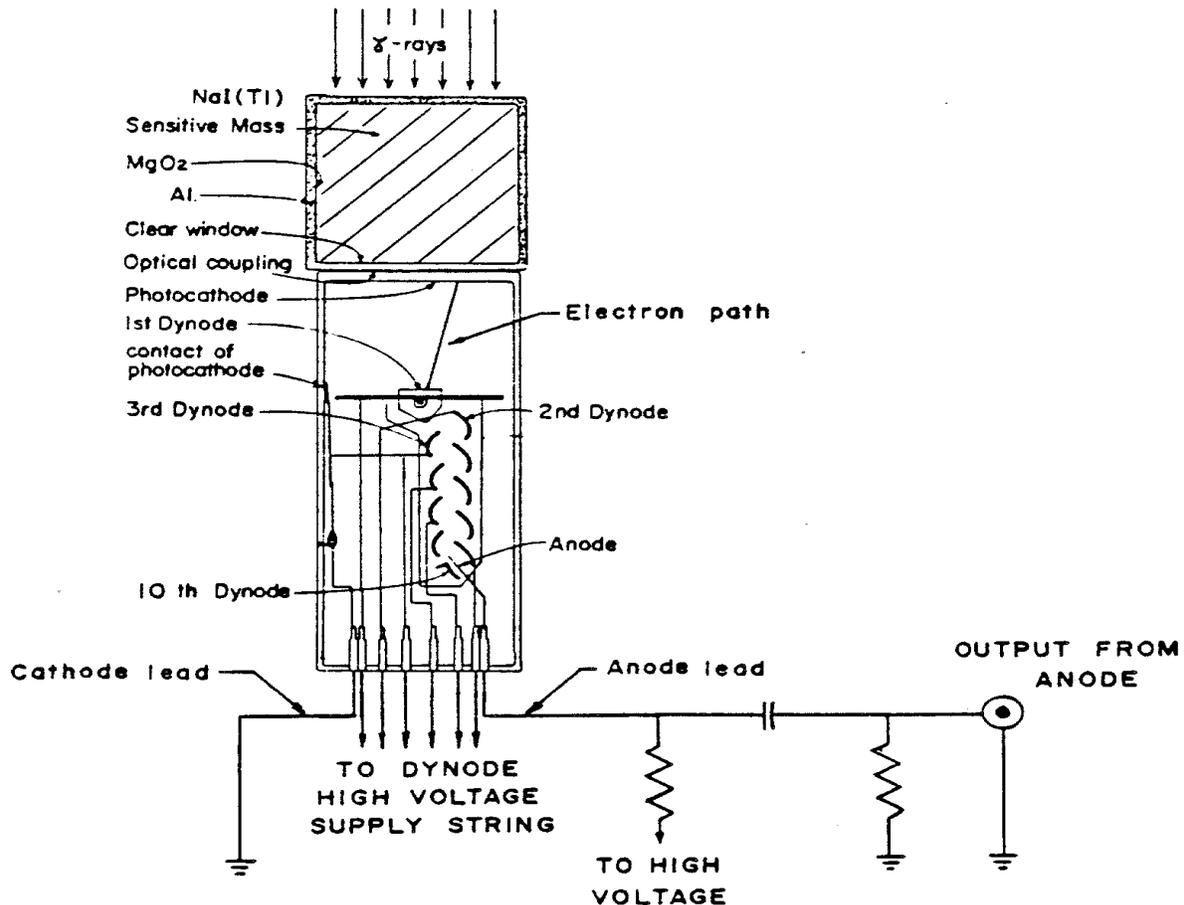


Figure 3. - Sodium Iodide Scintillation Detector

When a gamma ray (energy from 10 keV to 5 MeV) enters a single crystal of sodium iodide “activated” with a thallium impurity (about 0.1 to 1.0%) it may eject an electron from an atom giving rise by the photoelectric effect to a photoelectron which has all (except for the binding energy of the electron) of the energy of the gamma ray. This electron will lose all its energy by causing excitation in the crystal which upon de-excitation produces light. Rearrangement in the atom, such as the emission of X-rays which are absorbed in the crystal, adds to the light output so that all the energy of the gamma ray, except for an insignificant amount which goes into crystal vibration, results in light. This light, when it falls on the photocathode of a photomultiplier, ejects photoelectrons from the photocathode and these electrons are multiplied by secondary emission at the dynodes so that a measurable pulse of electrons is received at the anode.

The amplification of the ten dynodes (i.e. the ratio of the number of electrons reaching the anode to the number of photoelectrons entering the first dynode) is the multiplication of each dynode stage to the 10th power, and this depends on the accelerating voltage on each dynode stage. Thus, for every gamma ray that loses energy in the NaI (Tl) crystal, a charge pulse appears at the anode proportional to the energy lost by the gamma ray in the crystal, and to the photomultiplier amplification.

The stray capacitance (C_s of Figure 2) of the connections, cables, oscilloscope, etc., in the anode circuit gets charged by the charge pulse, so that a voltage pulse appears at the anode whose voltage is proportional to the gamma energy.

For details on the scintillation counter, see reference 1.

EXERCISE 1

Connect the high voltage input of the mounted scintillation detector to the high voltage supply (*H.V. Output terminal*) at the back of the multichannel analyzer. Turn on the High Voltage supply and the multichannel analyzer power switches.

NOTE: Do not attempt to adjust the high voltage supply. Excess voltage will damage the scintillation detector.

Using a ^{137}Cs gamma source (γ -ray energies 0.662 MeV and 0.032 MeV) observe the pulses from the scintillation detector on an oscilloscope. (If you have trouble triggering the oscilloscope, consult a demonstrator.) Note the effect, on the pulses, of moving the source closer to and farther from the detector. Note the randomness of time of arrival of the pulses. Note the rise and fall times of the pulses. Note the changes in the pulses if a longer cable is used to connect the detector to the oscilloscope. Note the changes in the pulses if a lower resistance termination is connected to the cable where it is connected to the oscilloscope -- try connecting a terminating resistor of 10 k Ω in parallel with the oscilloscope (this is considerably less than the input impedance of the oscilloscope). Use a **T** to connect the termination. Note the effects on the pulses of changing the high voltage. Be sure you understand what you are observing. If you don't, consult a demonstrator.

LINEAR AMPLIFIERS

A linear amplifier magnifies the size (voltage) of a pulse by a controllable amount, and may, at the same time, shape the pulse by changing its length, squareness, and polarity (positive or negative). Shaping sometimes includes the production of a bipolar pulse that goes positive and then negative. Each of the multi-channel pulse height analyzers (MCPHA) has a built-in linear amplifier, with both input and output connections (you may have to look carefully to find them!).

EXERCISE 2

Connect the scintillation detector output to the amplifier input. Connect the two oscilloscope Y inputs to the amplifier input and output (the location of the *amplifier input* terminal of the MCPHA, and the *amplifier output* connector depends on the instrument you are using). Compare the size, shape and arrival times of the pulse at the output and input. Observe what happens to the amplifier output pulse as the ^{137}Cs source is moved closer to and farther from the detector, as the amplifier gain is raised and lowered, as the high voltage is raised and lowered, and as a ^{60}Co source (gamma ray energies of 1.173 MeV and 1.333 MeV) is substituted for a ^{137}Cs source (gamma energies of 0.662 MeV and 0.032 MeV.)

NOTE: In this exercise, your oscilloscope trace is displaying a graph of pulse voltage *versus* time.

THE MULTICHANNEL PULSE HEIGHT ANALYZER (MCPHA)

A MCPHA is a device for analyzing the pulse height (voltage) distribution from a set of pulses such as is found from a scintillation detector. The particular instrument used here takes positive pulses from either the output of its own amplifier or from the output of an external amplifier, and sorts each of them according to height (voltage) into one of 256 channels, each channel having a width of approximately 0.030 volts. (Thus, for example, a pulse of 3.01 volts would fall in channel 101.) Each channel has its own memory position, and each time a pulse comes in of a particular height, one more count is added to the corresponding memory position. Thus, after data is accumulated for some time, the number of counts in each channel represents the total number of pulses of the corresponding height (voltage) that have come in that time. A display (obtainable on a cathode ray screen) then plots a histogram of number of counts *versus* pulse height. Thus, used in conjunction with a scintillation counter, the display represents (roughly) a spectrum of number of gamma rays *versus* gamma ray energy. This display can be read numerically using the channel select cursor and reading the number of counts shown in the *data* display and the channel number shown in the *channel* display. A description of the MCPHA is given in reference 5.

Note that only some of the instruments have built-in cathode ray displays. For those that don't, displays can be obtained on any oscilloscope screen using the *scope* x-y connectors at the back of the MCPHA. If there is no cathode ray display on your MCPHA consult your demonstrator. Note also that some of the MCPHA's have a plotter output at the back so that an x-y plotter can be connected to output the data.

EXERCISE 3

Use the MCPHA as a pulse height analyzer to analyze the pulses obtained using the ^{137}Cs source as in exercise 4. Note the effects of longer and shorter counting times, of changes in the scintillation detector high voltage, of changes in the amplifier course and fine gain controls. Try out all controls on the MCPHA and ask a demonstrator if you do not understand what some of these do. Also be sure you understand the relationship between the pulses you viewed on the oscilloscope in Exercise 2 and the pulse height spectra you obtain here.

THE EXPERIMENT

It must be noted that the spectrum you will be looking at is not really a gamma-ray spectrum but is the energy spectrum of the electrons that have received energy from the gamma-rays. In addition, the features of the spectrum are not as sharp as previously indicated because of the fact that the number of electrons emitted from the photomultiplier photocathode as a result of the flash of light produced by the incoming gamma-ray is of the order of a few hundred. This means that there is a significant statistical spread on the number of electrons emitted as a result of an individual interaction and this results in the smearing of the photopeak and Compton edge. The final spectrum for one gamma-ray should be similar to that shown in Figure 4. Of course if the radioactive source produces more than one gamma-ray then the end result will be a superposition of such pictures. A table of gamma-ray energies for various calibration sources is given in Table 1.

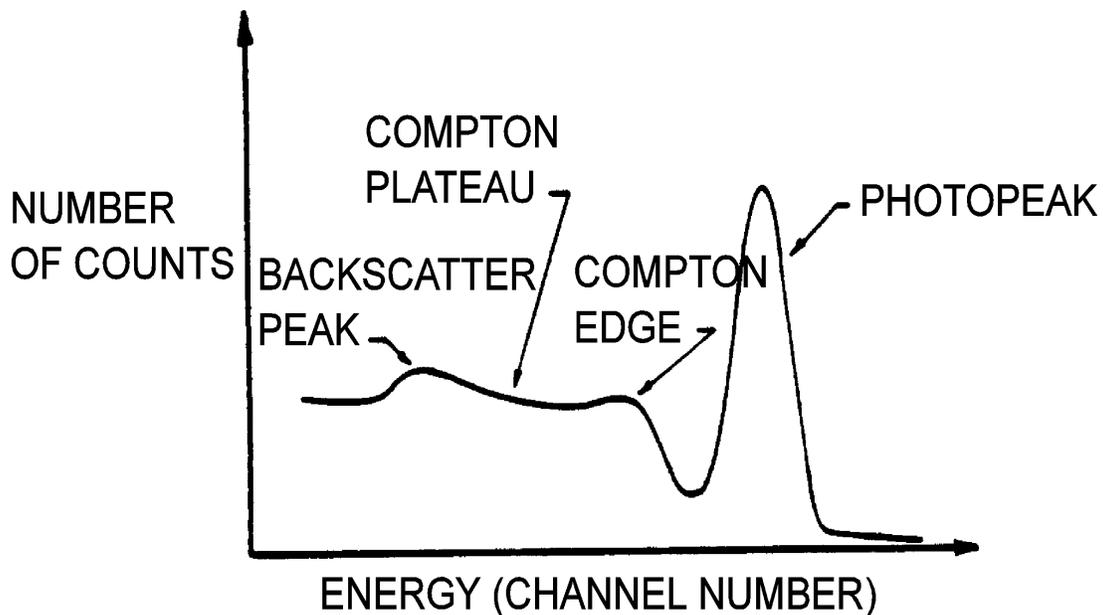


Figure 4. - A Typical Gamma-Ray Spectrum

SUPPLEMENTARY EXERCISES

1. - Spectrum shape

Connect the scintillation counter and oscilloscope to the multichannel analyzer. Use a ^{137}Cs source to observe the gamma-ray spectrum outlined in the introduction. Now, place the iron sample behind the source (not between the source and the detector) to enhance the backscatter peak and help you identify it. (Of course the iron sample is removed for the remainder of the experiment.)

2. - Setting the gain-energy calibration

Using Table 1, adjust the gain of the system until the largest energy photopeak (^{60}Co) is in a high numbered channel. After this do not adjust the gain or high voltage. Using the various sources, calibrate your system by making a plot of channel number versus gamma-ray energy. It should be a straight line. (It need not pass through zero.) Be careful about putting too much faith in channels much less than channel 20 because the threshold setting tends to eliminate small pulses and this will distort peaks in very low channels. Also, for high count rates you may get sum peaks (see parts 5 and 6) and this will tend to blur some spectra, *e.g.*, ^{133}Ba .

3. - Full-width-at-half-maximum or resolution

A measure of the quality of your scintillation detector is its ability to resolve gamma-spectral lines whose energies are close together. A measure of this is the full-width-at-half-maximum, this being the energy difference between the point half-way down a photopeak (on its high energy side) and the point half-way up the same photopeak (on its low energy side) divided by the energy at the centre of the photopeak. This is expressed as a percent. Using the 1.333 MeV line obtained from a ^{60}Co source, measure the full-width-at-half-maximum of your detector.

4. - Unknown source (Please Note! Unknown sources may not be available!)

Using the calibration curve from part 2 of the experiment, determine the energy and the uncertainty in the energy for the gamma-ray of the unknown source. Using Equation 1, calculate and then measure the position of the Compton edge. Identify the unknown, using the nucleonics data sheets as a guide, along with the reasoning that the source has to have a sufficiently long half-life that it will last at least a year in the lab. Note! Check with the Resource Centre before you start!

5. - Pileup and sumpeaks

If two gamma-rays enter the crystal at the same time then a sum peak appears which has an energy equal to the sum of the two individual rays. Sum peaks are usually very weak. Using ^{137}Cs , find the sum peak for two 0.662 MeV gamma-rays at the high end of the spectrum and measure its energy.

6. - Complex spectra and sum peaks

Lines in the spectrum of ^{133}Ba , in addition to the three strongest given in Table 1, are given in Table 2 in order of increasing intensity. Adjust the gain carefully until the 0.356 MeV line falls at about channel 220. This will mean that the 0.031 MeV line will be in about channel 20. Make a new calibration curve and try to find all the lines. If the count rate is low it will be easiest to determine the positions of the single peaks. To find the sum peaks put the source closer to the detector. Recall the caution against having the dead time too large.

7. - X-ray fluorescence - non-destructive analysis

The most common method of non destructive testing for trace materials in the forensic sciences is by the method of X-ray fluorescence. High energy photons are made incident on a target material and these cause K-shell electrons to be ejected from the target. Electrons cascade down to fill this inner shell hole and the target emits its characteristic X-rays. Thus the composition of the target can be determined. Use the ^{133}Ba source and increase the gain until the 0.111 MeV sum peak is in a high channel and make a new calibration curve. (It should contain five points). Replace the ^{133}Ba source with ^{137}Cs source. First place the lead target between the source and the detector. The lead will absorb the .032 MeV X-rays but a new X-ray peak characteristic of lead will appear. Measure its energy. Compare your results with the theoretical values for lead (0.072, 0.073 and 0.075 MeV). Of course the individual X-rays of a single target will not be resolvable with the scintillation counter.

Table 2.- Lines in Ba^{133} Spectrum

<i>Order of Intensity</i>	<i>Energy (Me V)</i>	<i>Comment</i>
1	.031	Cs^{133} X-ray
2	.080	
3	.356	
4	.302	
5	.161	
6	.054	
7	.276	
8	.111	.031 + .080
9	.062	.031 + .031
10	.436	.080 + .356
11	.383	
12	.383	.080 + .302
13	.387	.031 + .356

(jp - 1979, 1980, jv - 1990)