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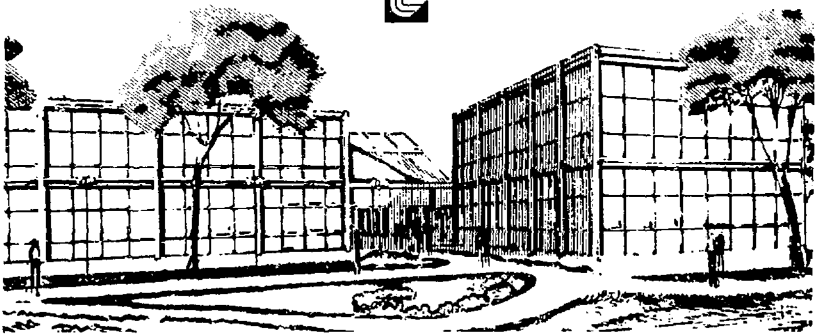

A HPGe COMPTON-SUPPRESSION AND PAIR SPECTROMETER*

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Summary

A HPGe detector incorporated into a Compton-suppression and pair spectrometer yields a continuum suppression factor of over 30. Cryostat housing requirements to obtain such suppression are discussed, sample spectra are presented, and several experiments making use of the HPGe dual system are discussed.

Introduction

Early Ge(Li) detectors were small. Consequently, the signal-to-noise or peak-to-Compton-continuum values were poor, and ways to improve peak identifiability were sought. Pulse-shape discrimination, Compton scattering-summing spectrometers, Compton-suppression spectrometers, and three-crystal pair spectrometers were all tried. The first two methods proved unsatisfactory, but the latter two have been more successful. These methods are more fully discussed and referenced in an earlier review.[1]

Compton-suppression and pair spectrometers are useful in measuring gamma-ray spectra. They improve upon the peak-to-continuum ratio of a Ge detector alone. Also, they simplify the spectrum, remove interferences, and lead to improved accuracies in determining transition intensities. Compton continuum suppression factors have varied from 4 to 12 depending on the geometry employed. Pair spectrometers can lead to dramatically simplified spectra, but generally they require longer data accumulation times.

Over the past five years, the efficiency of Ge(Li) detectors has increased from 10% to almost 50% relative to a 7.6 cm × 7.6 cm NaI(Tl) at 1.33 MeV. Excellent energy resolution (~ 2.0 keV @ 1.33 meV) has been maintained. Thus, the necessity or desire for continuum reduction appears to have lessened. This is unfortunate because suppression and pair spectrometers can always improve the signal-to-noise ratio regardless of the Ge(Li) detector size. The use of Ge(Li) detectors of 15% to 45% relative efficiency in combination with appropriate anticoincidence geometries can result in Co-60 peak-to-minimum ratios of from 100/1 to perhaps 500/1. Unfortunately, these larger Ge(Li) detectors no longer function effectively as three-crystal pair spectrometers because of the reduced amount of annihilation radiation that escapes. However, if careful attention is paid to the experimental arrangement, it is possible to achieve excellent continuum suppression and use the spectrometer simultaneously as a three-crystal pair spectrometer. This paper describes the use of a high-purity-germanium (HPGe) detector and large anticoincidence NaI(Tl) detectors in combinations which lead to simultaneous use of the system as a Compton-suppression and pair spectrometer.

Principles of Operation

The two most common anticoincidence geometries used for Compton-suppression spectrometers are illustrated in Fig. 1. Another geometry is discussed by Konijn, et al.[2] Generally, a Ge(Li) detector within its own vacuum housing is placed within a scintillation detector (usually NaI(Tl) or plastic scintillators with a split-annulus or split-halves enclosing geometry). Gamma rays from a source positioned outside are collimated to strike the central Ge(Li) detector. Those gamma rays scattering between θ-min and θ-max have a finite probability of interacting with the surrounding scintillator. If these scattered gamma rays can be detected above the scintillator noise level, they can be used as anticoincidence gates for the corresponding central Ge(Li) detector events. In principle, then, only full-energy events should remain in the Ge(Li) detector spectrum.

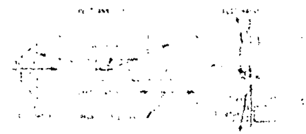

Fig. 1. The two most common geometries used in Compton-suppression spectrometers.

In practice, however, the Compton continuum is not eliminated, but only partially suppressed. Those gamma rays having scattering angles less than θ-min will not be suppressed, while those having backscattering angles greater than θ-max escape detection. The latter contribute high-energy photoelectrons to the Ge(Li) spectrum concentrated near the Compton edge. Contributions to the Compton continuum also come from gamma rays that scatter from inactive Ge, the cryostat housing, or the collimator walls and then interact completely with the Ge(Li) detector and from gamma rays that scatter out of the Ge(Li) detector and are totally absorbed in inactive Ge, cryostat walls, or the scintillator housing. Therefore, the extent of continuum suppression will depend on the completeness of enclosure by the anticoincidence detectors, the active to total volume of the Ge detector, and the materials enclosing and surrounding the central detector.

In three-crystal pair spectrometers, source gamma rays are collimated to strike only the central Ge detector. Those interacting with Ge via the pair production process produce electron-positron pairs, most of which lose their kinetic energy within the central detector. If the two oppositely directed 511-keV annihilation quanta escape the Ge detector and deposit their full energy in the surrounding scintillators, a triple coincidence will allow recording of only the double escape or pair peaks. As the central detector volume increases, the probability of both 511-keV quanta escaping decreases rapidly. Thus, large-volume Ge detectors make poor central detectors for pair spectrometers, but excellent detectors for Compton- suppression spectrometers. A more detailed discussion can be found in Ref. 1.

The HPGe Central Detector

The availability of HPGe offers the possibility that both the n- and p-junctions required to make a detector can be made vanishingly thin (0.1-100 μm); thus the active to total volume ratio can approach 1.0. With inactive Ge reduced to a minimum, the next requirement is to reduce the amount of total mass surrounding the detector. Figure 2 is a schematic drawing of the detector-holding arrangement. The detector is 31 mm

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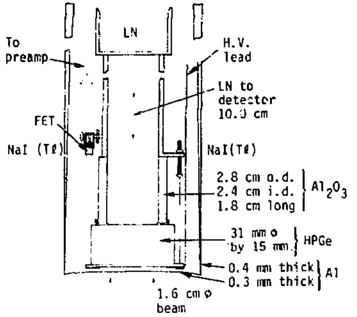

Fig. 2. A schematic drawing of the HPGe cryostat and detector mounting. (See text for details.)

in diameter and has a 14.5-mm-deep intrinsic region. Palladium is used for the p-contact (<0.1 mm) and diffused lithium for the n-contact (<0.01 mm). The detector operates at 2200 V, but is fully depleted at 300 V (~3 × 10^9 impurity atoms/cm^3). The detector is oriented so that collimated gamma rays enter through the p-contact: hence, backscattered photons will pass through the thinner junction.

The detector is mounted against tubular sapphire (Al_2O_3), which serves both as an excellent thermal conductor and as an electrical insulator. The sapphire is positioned against a tubular aluminum cold finger. Indium is used to improve thermal conductivity at each interface. The sapphire and detector are held to the tubular aluminum cold finger by three 0.25-mm-diameter stainless steel wires. Only one is shown in Fig. 2, as they are positioned at 120° intervals around the detector. These wires couple into a 0.75-mm-thick piece of lexan* that extends across the entire face of the detector. The lexan is 1.5 mm thick around the edge of the detector. This low-Z material is used to minimize mass, but it also serves to hold in place a small wire carrying the high voltage to the detector. The signal lead to the input FET is a Cu wire encircling the sapphire and twisted tightly into the indium and sapphire.

The enclosing walls of the aluminum vacuum housing are 0.40 mm thick in the vicinity of the detector, and get gradually thicker (for mechanical strength) away from the detector. The prestressed aluminum end window is 0.30 mm thick and was electron-beam-welded to the housing walls. Thus, mass surrounding the detector has been minimized. Note that no heat shield is employed and that the cold finger and insulator are tubular. It was necessary to adopt this "beam dump" geometry; otherwise the back-scattered gamma-ray distribution (centered about 225 keV) becomes enormous with the excellent Compton continuum suppression that this spectrometer yields.

The split-halves anticoincidence-detector geometry is used. The NaI(Tℓ) detectors, 34 cm in diameter and 17.5 cm thick are optically isolated and integrally mounted in a single housing. Nine 7.6-cm-diameter phototubes view each end. The detector vacuum housing entrance well is 5.0 cm in diameter and 25 cm long, while the gamma-ray-beam entrance well is 1.90 cm in diameter and 9.0 cm long. The much smaller beam entrance reduces the gamma-ray back-scattering solid angle (θ-max) and allows better suppression in the vicinity of the Compton edges. The NaI(Tℓ) well enclosure walls, designed to reduce mass absorption between the central HPGe detector and the anticoincidence detectors are 0.75-mm-thick aluminum.

Electronics

Figure 3 shows a block diagram of the electronics. The NaI preamplifiers should have excellent overload

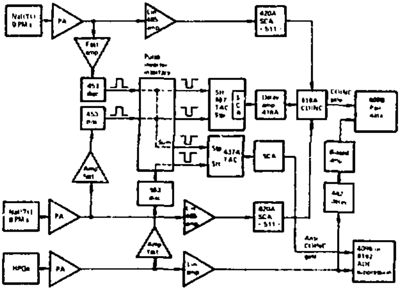

Fig. 3. Electronic circuit used to operate suppression and pair modes simultaneously.

characteristics and very fast recovery times for cosmic ray events. Constant fraction discriminators are used for both NaI and Ge signals. The threshold of the scintillation detector's discriminator should be set as close to noise level as possible, but not in it. The best suppression factor is obtained when the smallest energy interaction in the scintillator is detected. When the system is used as a suppression spectrometer, a signal from either scintillator half in coincidence with a Ge event anticoincidences or rejects that Ge event and stops the TAC. In operation as a pair spectrometer, both scintillator halves must register a 511-keV annihilation quanta. Hence, a "fast-slow" coincidence arrangement is used. A 467TAC fast-coincidence output gates the slow 418A triple-coincidence unit, whose output, in turn, allows acceptance of any Ge event by the analyzer. Note that a biased amplifier is introduced prior to the analyzer to select only that portion of the Ge spectrum above 1.0 MeV. Thus, Compton-suppression and pair data can be recorded simultaneously.

Performance

Figure 4 shows two spectra of Zn-65. The top spectrum is singles data, while the lower data is Compton suppressed. Both spectra were recorded simultaneously. The maximum suppression factor achieved was 25 in the vicinity of 700 keV. This leads to a peak-to-minimum Compton value of 1100 to 1. Zn-65 is a positron emitter; thus the 511-keV peak is normal. Note that the two spectra join at very low energy (~25 keV), corresponding to no suppression or gamma-ray scattering angles less than θ-min, about 2°30'.

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*Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Energy Research and Development Administration to the exclusion of others that may be suitable.

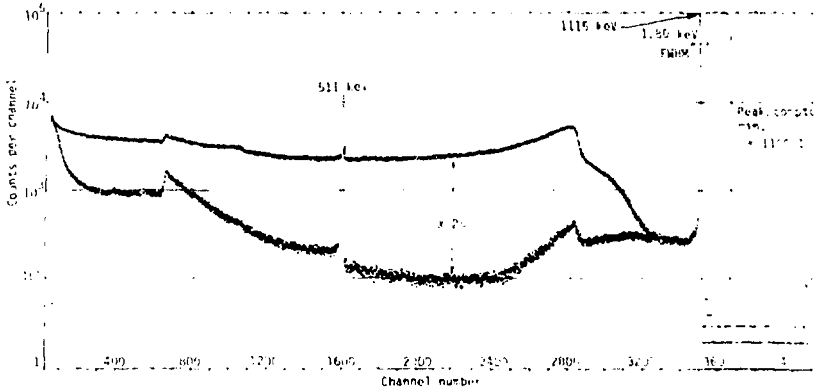

Fig. 5. Compton-suppressed (top) and singles (bottom) spectra of Zn-65.

Figure 5 shows a singles and Compton-suppressed spectrum of Co-60. Here, the two spectra join at about 30 keV for a [illegible]-min corresponding to about 2°20'. Note that the double escape peaks at 151 and 310 keV are suppressed beyond detection. For higher-energy gamma rays, they are not completely eliminated, e.g. the Na-24 2,754-MeV transition. This is easily understood if one considers two annihilation quanta that escape at 0° and 180° respectively, where there is no anticoincidence scintillator. Much less likely, but not zero, is the probability of *both 511-keV quanta not interacting* at all with either scintillator.

Note the presence of a small 511-keV peak in the [illegible] pressed spectrum. This is a result of [illegible] interacting via pair production with collimator [illegible] and any [illegible] in the vicinity of the detector. [illegible] quent to annihilation of the positron, one 511-keV quantum is totally absorbed by the HPGe detector. The [illegible] size of the backscattered gamma-ray peak centered at 22[illegible] keV is readily apparent. It would have had [illegible] greater area were it not for the "[illegible]" [illegible] used in mounting the detector (see Fig. 2). The [illegible] ray peaks show a FWHM of 190 keV, and the peaks are essentially Gaussian. Thus, without significant [illegible]

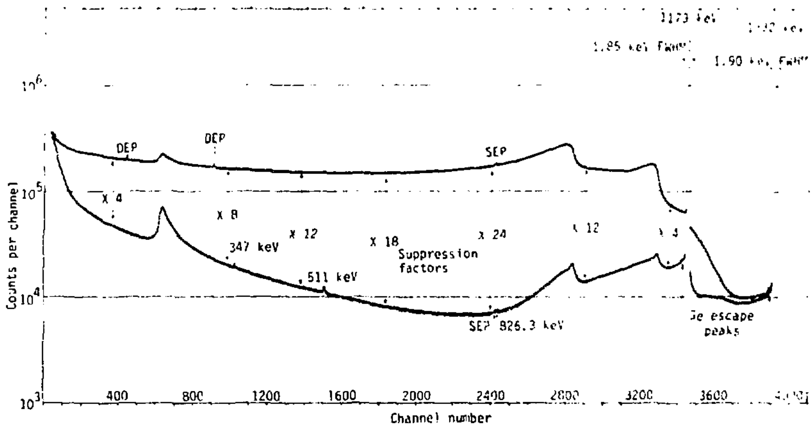

Fig. 5. Compton-suppressed (bottom) and singles (top) spectra of Co-60.

one observes the Ge fluorescent x-ray escape peaks. The excellent peak shape is in part due to collimation of the incoming gamma radiation toward the center of the HPGe detector (Fig. 2), and in part due to the excellent detector material quality, which allows the use of a large overvoltage.

The maximum suppression factor observed so far with this system is 31. It depends sensitively on the NaI(Tl) discriminator settings and the condition of the phototubes. With noisy or poorly working phototubes, small light signals will not be detected, and those events will not be rejected. A maximum suppression factor of 24 corresponds to 95.8% rejection, while a factor of 31 corresponds to 96.77%, a difference of less than one percent. In fact, some time after the Fig. 5 data were taken, six noisy and two non-working phototubes were discovered. Also the degree to which the Compton edge "peaks" are suppressed, and the low energy at which the spectra join depend on photomultiplier response and discriminator setting. In data taken earlier, the suppression factors were 25% better than for the data in Fig. 5. As a result, almost no increase was observed to occur in the spectrum towards the low-energy side of the suppressed 1.11-MeV Compton edge, contrary to the increase observed in Fig. 5.

Discussion

The excellent Compton continuum suppression and near-4π enclosure of the HPGe detector lead the spectroscopist to consider experiments not otherwise possible. For example, it is nearly impossible to measure quantitatively via beta-ray intensities the very weak forbidden beta branches whose endpoint energies lie well within strong allowed beta transitions. However, with significant Compton suppression, it is possible to observe very weak gamma transitions that depopulate levels fed by forbidden beta decay. Raman[3] has succeeded in measuring several such cases (although without suppression). The common radioactivities of Co-60, Zn-65, Cs-134 and Cs-137, and others, all contain possible forbidden beta branches observed via weak gamma-ray-transition-intensity measurements.

Similarly, one can measure weak gamma-ray branches that test various theoretical nuclear predictions. In the quadrupole vibrator model, small inter-particle couplings remove the degeneracy to lead to a triplet of levels (0+, 2+, and 4+) for the two-phonon vibration. Gamma-ray transitions between the 4+ and 2+ levels (the so-called "zero-phonon" transitions) are forbidden according to this model. These weak interband or model-forbidden gamma-ray transitions are generally hidden by the Compton continuum. The degree of forbiddeness could be measured by looking for such transitions. They have been observed[4-6] in a number of nuclei, and the [illegible]-keV transition seen in Fig. 5 is just such a "zero-phonon" transition in [illegible]. Other examples of weak interband (γ- to β-band) transitions have been observed in the deformed nuclei region.

In the search for states of very high angular momentum via in-beam spectroscopy, Compton suppression will allow the observation of weaker (ΔI = 2) E2 transitions. Thus, those groups who have in the past used Compton suppression spectrometers should make the small investment required to adapt their old anticoincidence scintillators to fit the modern high-efficiency Ge detectors.

The almost complete 4π enclosure (98.9%) [illegible] by this anticoincidence system combined with the small HPGe detector size makes the system an excellent pair spectrometer. One possible experiment would be the confirmation of the deviation from the experimental pair-production cross section observed[?] at low energies from the Bethe-Heitler prediction. Another experiment currently under investigation with this system is the search for double-pair production. Quantum electrodynamics predicts a nonvanishing probability for the formation of two electron-positron pairs at [illegible] MeV. Wilkinson and Alburger[7] were the first to attempt to measure the cross section, but they obtained only an upper limit. More recently, Robertson et al.[8] observed indirect evidence of this process. With the present spectrometer (both SCA's set to pass only 1.02 MeV) and with direct experimental observation [illegible] with both NaI and Ge detectors, the cross section of this process can be established, even exclusive of the dependent cascade first-order processes (see Ref. 7, appendix).

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