considered here. Proper velocity matching can always be achieved by projecting a third beam at frequency ω_3 with appropriately chosen $\vec{k}_3$ to yield a scattering beam at either $\omega_3 + \omega_p$, $\vec{k}_3 + \Delta\vec{k}$, or $\omega_3 - \omega_p$, $\vec{k}_3 - \Delta\vec{k}$.

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PULSE-SHAPE DISCRIMINATION ON THE GAMMA-RAY PULSES FROM $F^{19}(d, n\gamma)Ne^{20}$ OBSERVED WITH A LITHIUM-DRIFTED GERMANIUM GAMMA-RAY SPECTROMETER

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Lithium-drifted germanium gamma-ray spectrometers have been applied to the detection of high-energy gamma rays by Ewan and Tavendale.[1] They have found that the absorption of the gamma rays by pair production produces a very narrow peak ($\lesssim 0.2\%$ full width at half-maximum) at an energy $(E_\gamma - 2m_0c^2)$ that is superimposed on a background due to Compton scattering and electron escape. We are using one of these counters in a high-resolution study of the high-energy ($5\ \text{MeV} < E_\gamma < 12\ \text{MeV}$) gamma rays from the $F^{19}(d, n\gamma)Ne^{20}$ reaction[2] in order to obtain further information on the nuclear levels of Ne^{20} at high excitation energy.[3] In this Letter it is shown that the background under the $(E_\gamma - 2m_0c^2)$ peaks in a complex gamma-ray spectrum can be reduced considerably by pulse-shape discrimination against detector pulses containing a slow time-constant component. The resulting improvement in the quality of spectra will be advantageous in further studies of the $F^{19}(d, n\gamma)Ne^{20}$ reaction and is of general interest to experimenters using solid-state gamma-ray spectrometers.

The detector used for the measurements was a 5-mm deep by 19-mm diameter lithium-drifted germanium p-i-n diode fabricated by A. J. Tavendale. The compensated intrinsic region reached a thin aluminum layer on one face of the detector giving a thin window into the depleted region of the detector. The other face of the detector was over-compensated n-type germanium approximately 0.5 mm thick.

The pulse-shape discrimination tests were carried out with the circuit described by Alexander and Goulding[4] for pulse-shape discrimination of signals from an organic scintillator. The method is directly applicable to the solid-state detector, since the circuit is designed to accept pulses from the type of charge-sensitive preamplifier used with solid-state detectors. The geometry of the source and detector was such that the detector's edge was illuminated by a source of reaction gamma rays 4 mm in diameter and 9 cm away from the center of the detector. With this geometry, the $(E_\gamma - 2m_0c^2)$ peaks should be enhanced, since the high-energy electron-positron pairs recoil forward and have a greater chance of stopping completely in the depletion region.

Figure 1 compares the spectrum of high-energy gamma rays from the $F^{19}(d, n\gamma)Ne^{20}$ reaction with and without pulse-shape discrimination. The top curve (dots) is an ungated spectrum of pulses from the detector, whereas the lower curve (crosses) is the same spectrum, recorded simultaneously, but gated by pulse-shape selection. The background is reduced by a factor of approximately 2.5, whereas the prominent $(E_\gamma - 2m_0c^2)$ peaks are attenuated only by about 10%. The slight shift in the peak positions is not due to pulse-shape selection but arises because the spectra were analyzed simultaneously in two analog-to-digital converters which had slightly different gains. The energy calibration shown on the right-hand side of the diagram applies only to the gated spectrum. These preliminary data indicate that a considerable improvement of the spectrum can be realized using a pulse-shape discriminator that rejects pulses having a slow time-constant component.

The data shown in Fig. 1 are not suitable for illustrating the detector resolution since the gamma rays are Doppler broadened due to the kinematics of the $F^{19}(d, n)Ne^{20*}$ reaction and the short lifetimes of the Ne^{20} states relative to the slowing down time of the recoiling Ne^{20} ions. Although the intrinsic resolution of the detector at a gamma-ray energy of 5.3 MeV is $\lesssim 10$ keV (full width at half maximum), the widths of the peaks in Fig. 1 are typically 60 keV, showing that the gamma rays are not monoenergetic. The 6.13-MeV gamma ray in Fig. 1 follows the alpha decay of excited states of Ne^{20} and has less Doppler broadening (30 keV) because of the long

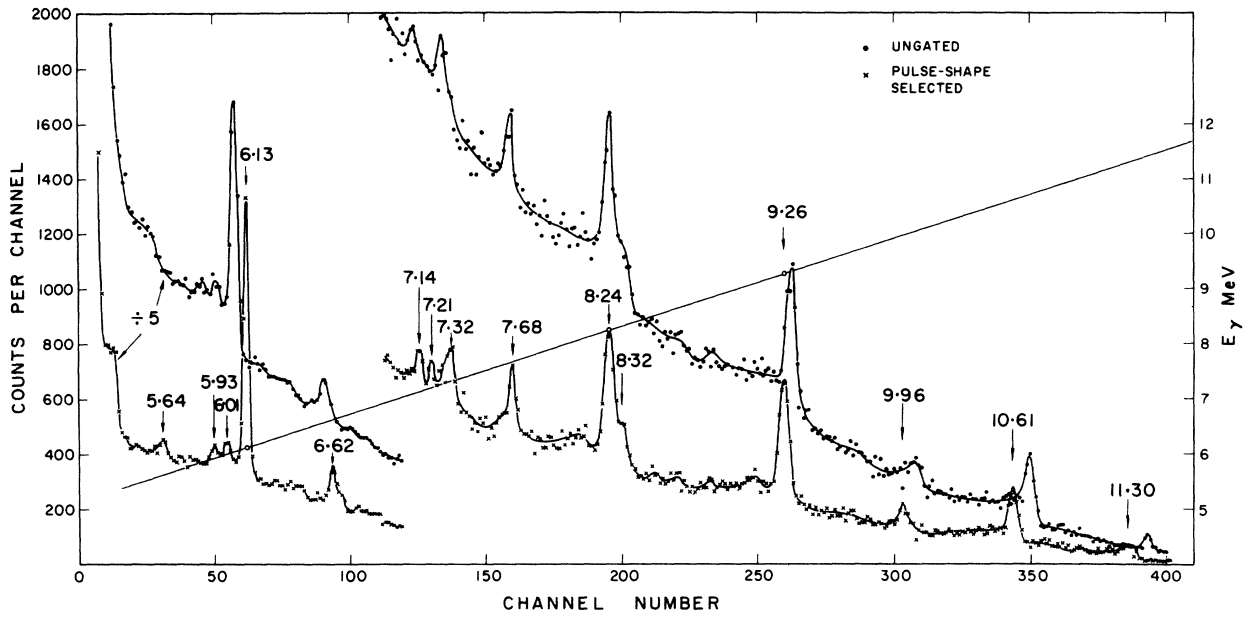

FIG. 1. The high-energy γ rays from the $F^{19}(d,n\gamma)Ne^{20}$ reaction at a bombarding energy of 3.0 MeV detected by a lithium-drifted germanium spectrometer. The top curve (dots) is an ungated spectrum. The lower curve (crosses) is the same spectrum gated by pulse-shape discrimination which rejects pulses containing components with a slow time constant. The spectra were analyzed simultaneously in encoders which have slightly different gains. The energy calibration shown applies only to the gated spectrum.

nuclear lifetime. At lower bombarding energies the peaks of the doublet at 8.24 and 8.32 MeV are completely separated because of the reduced Doppler broadening. Because of the Doppler broadening, any effect of pulse-shape discrimination on the resolution of the detector has not, as yet, been investigated.

Photographs of the pulse wave forms indicate that the ratio of the fast to slow components in the rejected pulses is not constant and that pile-up pulses are also being rejected. From the utilitarian point of view, the last point is important because of the presence of high rates of low-energy gamma-ray pulses in this type of experiment.

Since a great many of the rejected pulses are in the low-energy regions of the spectrum, pulse-shape discrimination would be desirable when studying low-energy gamma rays in the presence of high-energy radiation. In addition we have observed that the spectra from low-energy gamma rays themselves are improved by pulse-shape discrimination. Using our particular germanium counter for gamma rays of 0.9 and 1.84 MeV, up to 30% of the pulses in the region of the Compton distribution were removed by pulse-shape discrimination. The full-energy peaks were unaffected. Similar results for low-energy gamma rays were obtained with a thick-window germanium detector of smaller dimensions (3.5-mm depletion depth and 19-mm diameter).

The reason for some background events giving rise to pulses characterized by more than one time constant is not clear. Edge effects associated with low collecting field regions of the detector and trapping may be responsible.

The range of recoiling electrons from interactions with high-energy gamma rays is of the same order as the depth of the depletion region of the detector, so that there is an appreciable chance for ionizing events to occur partially in regions of the detector where the collecting field is small. For these events, some of the charge carriers may drift slowly to restore the equilibrium charge distribution of the detector. Therefore the decay of the current pulse from the detector will be characterized by more than one time constant.

For example, electrons that escape from the detector are degraded events and contribute to the background. In our detector, those escaping through the thick n-type face of the detector may give rise to pulses containing a long time constant

that can be rejected by pulse-shape discrimination.

Similarly, energetic electrons scattered into the detector due to gamma-ray interactions in the material supporting and enclosing the detector may be discriminated against since they pass through the surface of the detector where the collecting field may be small.

Fabri, Gatti, and Svelto[5] have observed the presence of a slow time constant in α-particle-induced pulses from silicon surface-barrier detectors cooled to low temperatures. They have attributed this effect to trapping since the effect is temperature dependent. In our measurements the integration time for charge collection was 1 μsec so that the pulses would have been degraded if a very long time constant was present in the current pulse due to trapping.

To summarize, it has been shown that the technique of pulse-shape discrimination can improve the high-energy gamma-ray spectra from lithium-drifted germanium detectors by reducing the background while still maintaining the intrinsic efficiency for the $(E_\gamma - 2m_0c^2)$ peaks. An investigation of the processes giving rise to pulse-shape differences in these detectors would be desirable.

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CROSS-SECTION FLUCTUATIONS IN THE $Mn^{55}(p,\alpha)Cr^{52}$ REACTION*

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Most measurements of statistical fluctuations in the cross sections of various nuclear reactions have been made with light target nuclei, $A < 40$.[1-7] In this Letter we wish to report similar measurements for the ground and first two excited states produced in the $Mn^{55}(p,\alpha)Cr^{52}$ reaction. Target nuclei of larger A are advantageous for fluctuation measurements because they more adequately meet the requirements necessary for the applicability of the theory of Ericson[8] and others.[9] However, due to the decrease in the width of the compound states, Γ, with increasing A, the possible distortion in the results introduced by the experimental energy resolution must be carefully investigated.[10]

Excitation functions of the ground state (0^+), 1.43-MeV first-excited state (2^+), and the 2.37-MeV second-excited state (4^+) in Cr^{52} were measured for $Mn^{55}(p,\alpha)Cr^{52}$ reaction. The differential cross sections were measured at 90°, 130°, 150°, and 170° in 5-keV steps with protons accelerated by the Argonne tandem Van de Graaff in the energy range 9.5 to 9.9 MeV. A manganese target of 50 $\mu g/cm^2$ thickness, prepared by vacuum evaporation onto a 100-$\mu g/cm^2$ carbon foil, was used in the experiment. The energy loss of the beam due to the target is less than 2 keV. The energy resolution of the proton beam from the Van de Graaff is not precisely known. However, from the narrowest peak observed in our excitation functions and magnetic spectrometer measurements of the linewidths resulting from proton scattering, we estimate the tandem energy resolution to be less than 5 keV. The reaction particles were identified with surface-barrier solid-state detectors which subtended an angle of 7° in the reaction plane. In order to discriminate against protons, the detectors were biased to just stop the ground-state α particles.