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A Calorimeter for 300 GeV Neutrons and Protons[†]

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A total absorption calorimeter for determining the energies of hadrons has been built and tested in beams at the National Accelerator Laboratory. The calorimeter is being used in an experiment to measure neutron total cross sections. The design of the calorimeter is described and its performance is reported. The resolution of the calorimeter for 300 GeV protons is found to be 12.8% FWHM.

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The ionization calorimeter, or total absorption spectrometer, has proven to be a valuable device for measuring hadron energies since its first introduction in cosmic ray experiments by Grigorov, Murzin, and Rapaport.[1] The principle of operation is based on the total absorption of the energy of an incident, high-energy hadron by a large volume of dense material, such as iron, throughout which detectors are interspersed to sample the ionization energy loss. Within this volume the incident particle interacts and generates a complex cascade of electromagnetic showers and hadrons (pions, nucleons, and nuclear fragments). This cascade process has been studied by various groups[2,3,4,5], and experiments on calorimeter properties have been carried out using proton beams from accelerators below 30 GeV.[6,7,8] Homogeneous detectors, in particular large volumes of sodium iodide scintillator, have also been explored.[9] While many terms and names have been used for these devices, the general term calorimeter will be used in this report.[10]

The calorimeter of the present study was designed as a neutron detector in an experiment to measure total cross sections of neutrons on hydrogen and other elements between 50 and 300 GeV at the National Accelerator Laboratory.[11] As the neutron beam has a continuous energy spectrum, the energy resolution of the calorimeter is required to measure any energy dependence of the cross sections. This calorimeter is made of alternating plates of iron and plastic scintillator, as illustrated in Figure 1. The iron is in the form of thirty plates, each 3.81 x 61 x 61 cm , bolted on 5.08 cm centers to a base plate of cast aluminum. Thirty sheets of Pilot "F" plastic scintillator each 0.635 x 61 x 61 cm were sandwiched between the iron plates. Thus the calorimeter is 900 g cm^{-2} thick in iron plus 20 g cm^{-2} of plastic scintillator. Light is brought from the scintillators through simple light pipes of 0.635 cm thick lucite, tapered from 61 to 15.25 cm , and bent through 87° . The 15.25 cm wide light pipes from the 15 scintillators on either side are brought together in a bundle to the rear of the calorimeter where matching lucite cones reduce the area to match the cathode areas of four RCA 8575 photomultipliers. These phototubes were found to be the best of various RCA and Philips photomultipliers studied, with respect to dynamic range and gain stability. Some tubes, in particular (such as the 56 DVP), displayed a gain which varied with count rate.

In order to equalize the pulse heights from the 30 scintillators, a Ru^{106} beta source was placed at the center of each scintillator in turn, and the corresponding light pipe was then masked so that the phototube current due to the beta source was the same to within ±5% for each of the 30 scintillators.

Ahead of the calorimeter proper is located a set of seven disc-shaped scintillation counters of from 1.91 to 11.42 cm diameter centered on the beam axis. These are preceded by an iron converter plate normally 2.54 cm (20 g cm^{-2}) thick. Neutrons which interacted in the iron plate produced charged particles into a forward cone which were detected in the disc counters. The pulses from these counters were then used to determine the radius from the beam axis of the interacting neutron. A 20 cm diameter anti-coincidence counter several meters upstream of the converter insured that only incident neutral particles were detected.

The calorimeter phototubes are run with 300V between the cathode and first dynode, with four "afterburner" power supplies to stabilize the voltage to the last four dynodes, and with high voltages of 1700-1800V overall. The anode pulses are summed in a LeCroy model 127L active fan-in and the output distributed in a model 128L active fan-out to several discriminators and to a Northern "Econ I" pulse-height analyzer. Pulses from the phototube anodes are clipped to about 18 ns and clipping lines are terminated with resistors to minimize pulse overshoot. A pedestal is added to the pulse into the pulse height analyzer in order to minimize non-linearities near threshold.

High-energy muons could be studied by inserting a 2.4 m long iron block into the beam 100 m upstream of the calorimeter. Trigger counters upstream and downstream from the calorimeter were then used to insure that the muons passed through the calorimeter. The resulting muon pulse height distribution in the calorimeter counters is given in Figure 2.

The neutron spectrum obtained with 300 GeV protons incident on a beryllium target is given in Figure 3. The peak in the spectrum corresponds to about 240 GeV. At very low energies (below 30 GeV) there is a large number of low energy gamma rays. The height of this gamma peak is a strong function of the cleanliness of the proton targeting, the neutron collimator, and the placement of lead filters in the beam. Normally, the beam contains 5 cm of lead ahead of the first sweeping magnet. From calculations and from flux measurements in charged-particle beams at larger production angles, it is probable that there is a neutral kaon component in the beam which constitutes as much as 30% of the beam near 30 GeV but falls rapidly to a few percent near 100 GeV and a negligible fraction above 200 GeV.

The most interesting data relevant to the calorimeter performance is data taken with a monochromatic proton beam. This beam was made by shifting two collimators in the neutron beam and appropriately energizing bending magnets normally used as sweeping magnets in the neutron beam. The protons were primary beam protons diffraction scattered through about one milliradian by the Be target and the energy spread is believed to be <1%.

In order to simulate the neutron case, protons were required to interact in the iron neutron converter ahead of the calorimeter by requiring about three times the single-particle threshold in the triggering disc counters. (Anticoincidence counters are of course removed from the logic in this case.) Pulse height spectra from 200 and 300 GeV protons are presented in Figure 4. The 300 GeV spectrum, taken with a 10 g cm^{-2} iron converter plate, has a full width at half maximum of 12.8%. (This broadened to 13.5%

FWHM with a 20 g cm^{-2} iron converter.) The 200 GeV peak in Figure 4 was taken with a 20 g cm^{-2} converter and has a 14.4% FWHM. The center of the 200 GeV peak is quite accurately 2/3 of the center of the 300 GeV peak, confirming that the calorimeter energy response is linear over this range of energies to within experimental uncertainties of less than ±2%. These experimental uncertainties arise from the relative normalization of the two pulse-height spectra.

It is of interest to make an absolute calibration of the calorimeter; that is, to be able to convert a pulse height measured relative to some lower energy standard (such as the pulse height from muons or electrons) to an absolute hadron energy. This was done by comparing the average pulse height from muons traversing the calorimeter with the average 300 GeV proton pulse height. The proton-muon pulse height ratio was 120:1, with an uncertainty of ±5%. The energy loss of a muon traversing the calorimeter is well known from range-energy tables if the muon energy is known. Here the muon energy was <u>assumed</u> to be 10 GeV, although average energies as low as 5 GeV and as high as 20 GeV are possible. The energy loss in 3.81 cm, or 30 g cm^{-2}, of iron by 10 GeV muons is 58.9 MeV, and the energy loss in 0.635 cm of plastic scintillator is 1.81 MeV, so that the muon energy loss in each module is 60.7 MeV or about 1.82 GeV in the entire calorimeter.[12] This figure is uncertain by ±5% if the average muon energy is between 5 and 20 GeV. From the proton-muon pulse height ratio, protons produce pulses corresponding to 218 GeV in "visible" energy in the calorimeter, or 72±5% of 300 GeV. The error results from combining the uncertainty in proton-muon pulse height ratio and the uncertainty in muon energy loss in quadrature. There are several reasons for this 28% inefficiency: (1) A fraction of the energy in collisions with iron nuclei goes into nuclear binding energy and is lost to escaping fast neutrons. (2) Nuclear fragments and slow protons are detected less efficiently in plastic scintillator than relativistic particles. (3) There is a "transition" effect on the detection of the electromagnetic shower component due to the difference in critical energy between iron and plastic. This results in a pulse height lower by a few percent in the scintillator for a given electromagnetic shower energy than would be the case with a homogeneous detector.[13] (4) In addition, there are undoubtedly other small effects due to the different ratios between radiation length, interaction mean free path, and dE/dx for iron and plastic.

An absolute normalization was calculated for a calorimeter used in recent cosmic ray experiments at Echo Lake, Colorado.[14] It is interesting in retrospect to compare with these figures. There the transition effect was calculated to contribute an average 8% loss in "visible" energy, and the nuclear effects and scintillator nonlinearity 15% at 300 GeV. Consequently, the present measured figure of 72±5% may be compared with 77% for that detector.[15]

In summary, we have been able to achieve an energy resolution of 12.8% FWHM for 300 GeV protons with a relatively simple calorimeter. It is probable that this resolution could be further improved somewhat by using longer gate widths, elimination of the clipping of the phototube pulses, and better scintillator matching.

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15. Because the transition effect is relatively small in this calorimeter, the discrepancy between these results and the Echo Lake calorimeter may be greater than these figures would indicate. Based on the present calibration, it is probable that an underestimate of hadron energies by about 10% was made in the Echo Lake data.

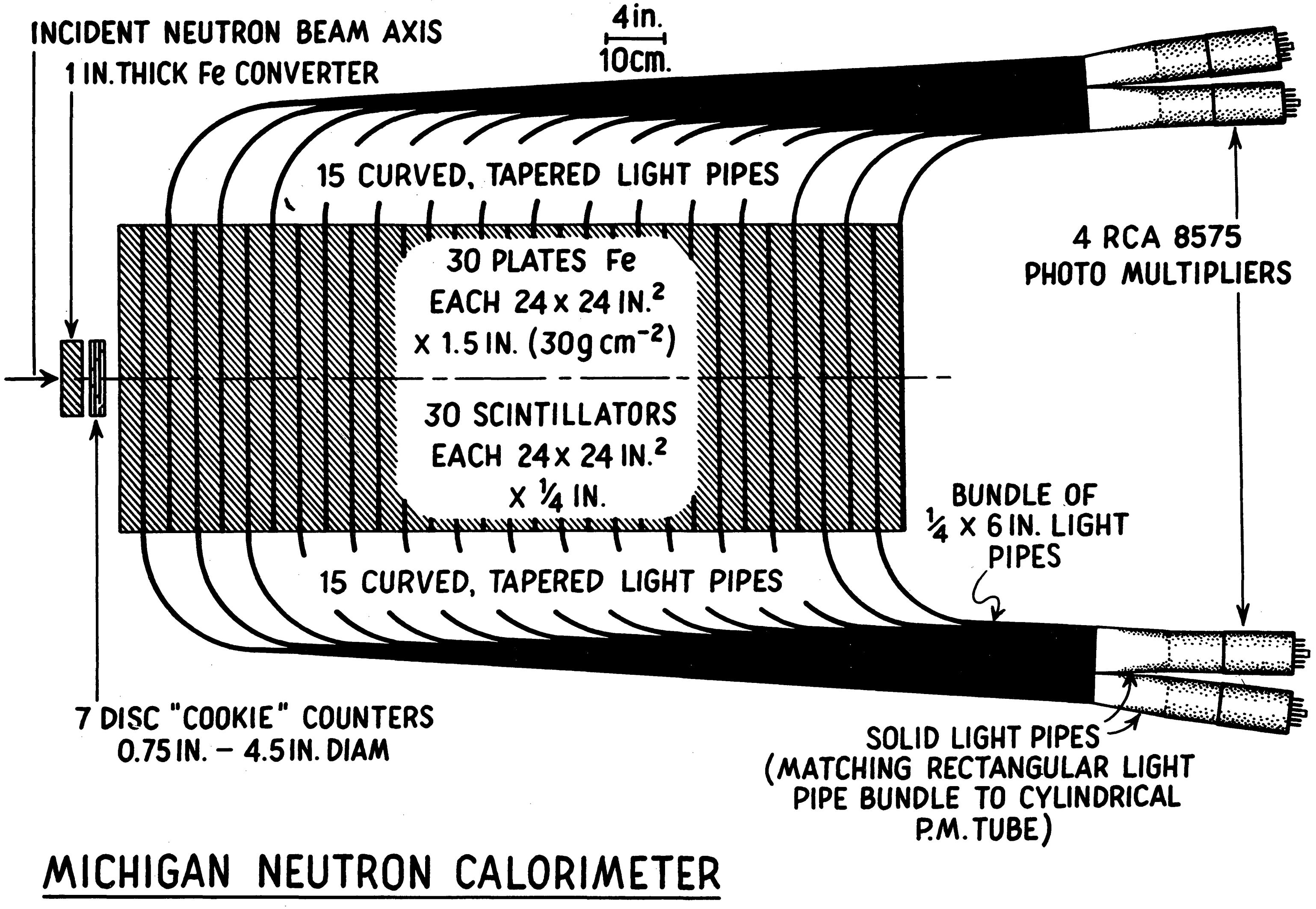

Figure 1. Plan view of the calorimeter.

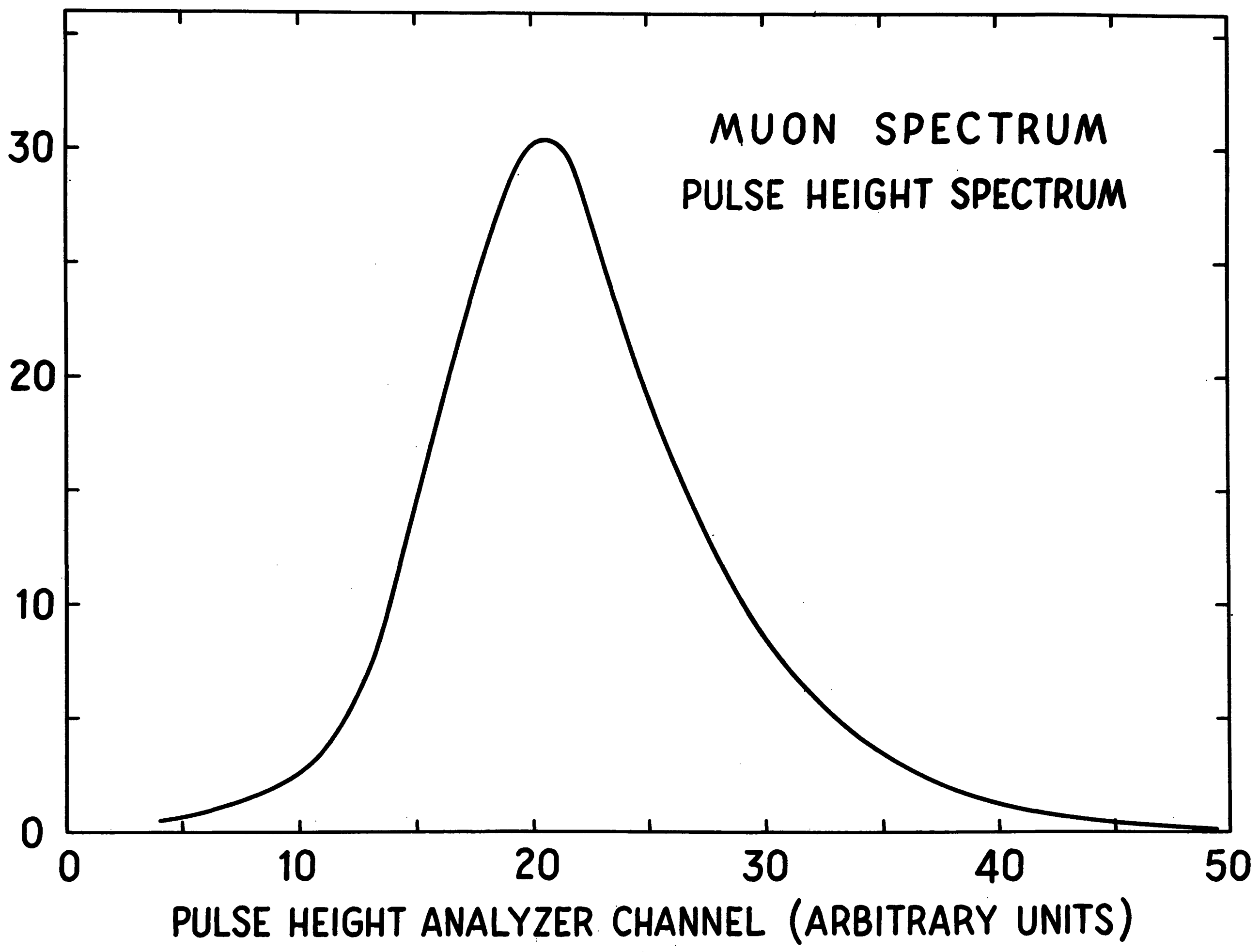

Figure 2. A muon pulse height spectrum taken with the calorimeter. The numbers on the abscissa scale differ by a factor of 25.3 from those of Figs. 3 and 4.

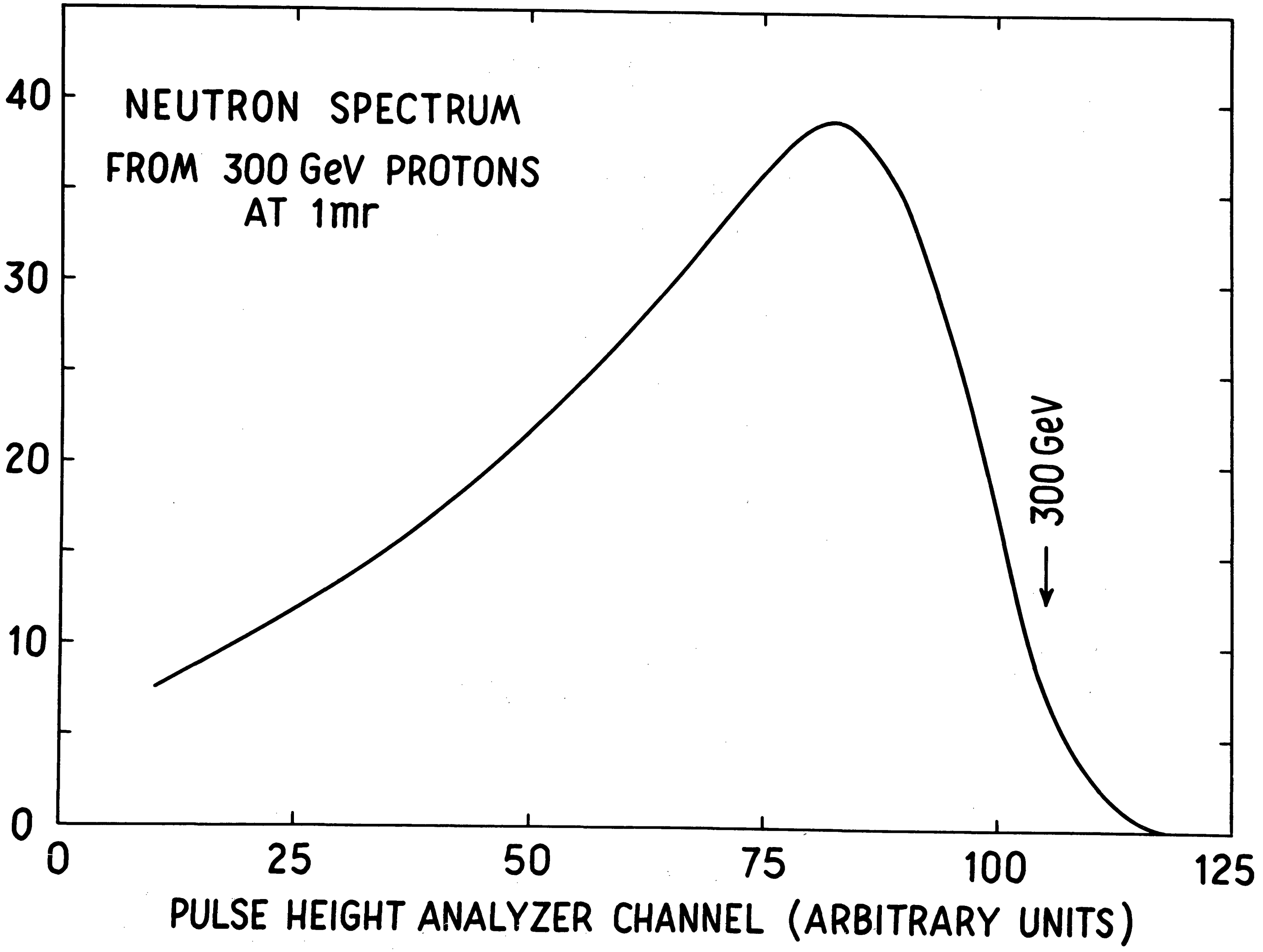

Figure 3. A typical pulse height spectrum of neutrons produced by 300 GeV protons on a 12-inch beryllium target at 1 mr.

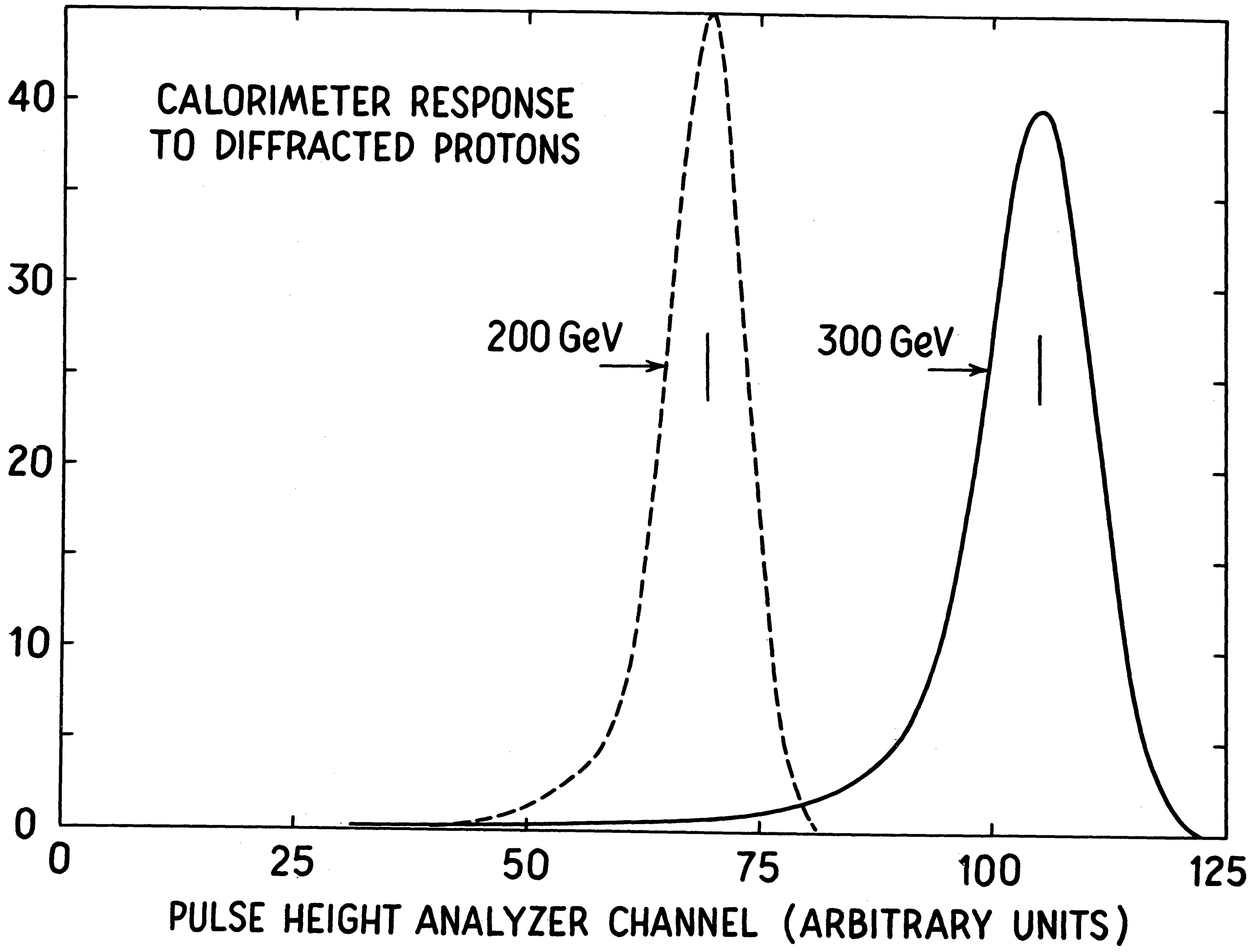

Figure 4. The pulse height spectra from 200 and 300 GeV protons incident on the calorimeter.