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A NEW METHOD FOR CALIBRATING THE PULSE HEIGHT DEFECT IN
SOLID STATE DETECTORS

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Abstract

The pulse height defect (PHD) of a Si surface barrier detector (1000 Ω -cm resistivity) has been measured with a cyclotron for elements from Kr to Au between energies of 15 to 160 MeV, and for elements from Ne to Fe between 5 and 50 MeV. A simple power-law formula for relating the PHD to the total energy is described. A procedure for calibrating a Si detector for the PHD from measurements for several elements has been developed and tested. This procedure reproduces the data to within the experimental error ($\pm 0.5\%$ of the total energy). Application of the measured and calculated PHD values to another detector of similar resistivity seems to be accurate to better than 10% of the PHD. Our PHD data are also compared to an existing PHD formalism.

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1. Introduction

As the capability of heavy ion accelerators expands to include heavier and heavier nuclei at ever greater energies, a greater need develops for accurate calibration of the energy and mass non-linearity of solid state detectors. These non-linearities are defined relative to the detector response to alpha particles. In general terms, the pulse height defect (PHD) is the difference between the detector response to a heavy ion and to an alpha particle of the same energy. (A more precise definition will be given later). The PHD for a given incident energy increases markedly with mass. For 100 MeV projectiles, the PHD is roughly 0.6% of the ion energy for Ne, 3% for Ar, 8% for Kr, 12% for Xe, and 20% for Au. The PHD also increases in magnitude with ion energy, being about 2 MeV for Kr at 10 MeV incident energy and 8 MeV for 100 MeV Kr.

Extensive work on the physical basis of the PHD has identified the major contributing factors¹⁻⁸). These factors can be grouped into four categories: 1) loss of free electrons by recombination of ion pairs; 2) loss of energy in low-energy non-ionizing collisions with lattice atoms, leading to phonon excitations; 3) loss of energy in the Au entrance window and underlying surface dead layer (when it exists); and 4) loss of free electrons at "trapping sites" such as lattice defects or impurities.

Identification of the factors contributing to the PHD has been accompanied by attempts to reproduce each factor with model calculations.^{7,9-11}) However, the most widely used techniques^{12,13}) for reproducing measured values and estimating corrections due to the PHD have been strictly

empirical formulae which lump all contributing factors into one or several parameters. Schmitt and co-workers¹³⁾ developed a widely used 4-parameter calibration equation relating the true energy to the observed pulse height. Like most other efforts of that time, the procedure was based on measuring the energy centroids of the low- and high-mass fission peaks of ^{252}Cf . (Thermal-neutron fission of ^{235}U has also been used⁸⁾). Subsequently, Kaufman et al.¹²⁾, utilizing beams from a Van de Graaff to recoil-scatter heavy target nuclei into a Si counter, developed an empirical 1-parameter formula which fit data measured between 4.5 and 80 MeV. More recently, Finch et al.¹⁴⁾ have used a mass separator with unit mass resolution to study the PHD of fission fragments having masses between 85-105 and 130-140 amu and energies up to 100 MeV. A major limitation of the above approaches is imposed by the limited range of ion energies, and masses available from fission (refs. 13-15) and the restricted energy range of Tandem Van de Graafs (refs. 6,7,12).

In the present work we present PHD measurements made at Lawrence Berkeley Laboratory's 88-Inch Cyclotron. These measurements cover a larger mass and energy range than previously reported work, and use a direct irradiation technique which avoids some errors inherent in recoil scatter measurements and which provides fragments with unit atomic number and mass resolution. The experimental technique is described in section 2. In section 3 we discuss a simple, accurate power-law formula for representing the measurements, and a reliable method of deducing calibrations for a large number of elements from the measurement of the PHD for just a few. Finally, in section 4 a comparison is made with the calibration technique of ref. 12.

2. Experimental Procedure

Recent use of the Berkeley 88-Inch cyclotron as a mass spectrometer for trace heavy-element detection¹⁶⁾, radio-isotope dating¹⁷⁾ and quark searches¹⁸⁾ led to the present use of direct cyclotron beams for PHD calibrations. Since it is a source of projectiles of any stable isotope, over a large energy range, the cyclotron is an extremely useful tool for PHD determinations. The energy range is limited at the upper end primarily by the maximum charge state which the ion source can produce, and at the lower end by the ability of the machine to accelerate particles on high harmonics of the lowest cyclotron frequencies. (The harmonic on which a particle is accelerated is defined as the ratio of the oscillation frequency of the cyclotron's electric field to the frequency of revolution of the particle in its orbital motion within the machine.) Charge states of Au from 6+ to 14+ were extracted from the ion source, and accelerated to energies ranging from about 25 to 140 MeV. Since the cyclotron beam energies are known quite accurately ($\pm 0.5\%$ is an upper limit of the absolute error) the degree of accuracy required for PHD measurements is routinely achieved. Extremely low intensities of essentially DC beam can be reliably obtained, permitting direct irradiation of the sample detectors without danger of detector damage. The corrections inherent in scattered-beam experiments (corrections due to uncertainties in the laboratory scattering angle, detector angular acceptance and target thickness) are completely avoided.

In this work, a Penning Ion Gauge (PIG) source was fed with a mixture of noble gases (Ne, Ar, Kr, Xe). In addition, either Au or a

combination of rare earths were mixed with Ta and used in the ion source as a mixed pellet at the edge of the ion discharge, opposite the anode opening. In this way many charge states of elements over a large mass range were produced by the ion source and injected into the cyclotron. Tuning of the cyclotron frequency, the dee voltage and electrostatic deflector voltages allowed quick selection of a particular isotope and charge state. Low intensity beams of 45 different ions were accelerated and extracted from the cyclotron during a typical 16 hour run. An old, expendable "search" detector was used to monitor the beam intensity before exposing the detector to be calibrated, to prevent damage to this detector by an excessive beam current. Sometimes slight frequency de-tuning was necessary to lower the beam intensity to acceptable levels. Typical beam currents ranged from ten's to thousand's of particles per second impinging on the detector. Ion energies from 5 to 160 MeV were achieved, without exhausting the potential of the machine.

Since the cyclotron can be tuned very precisely to select one value of the charge-to-mass ratio, it provides just one specific isotope at a time to the experimental area in nearly all cases. The extremely low backgrounds obtained for several Au beams are illustrated in fig. 1. The ability to readily provide monoisotopic and monoenergetic beams over a broad energy and mass range makes a cyclotron a superb tool for investigating the mass, charge and energy dependence of the PHD.

Because the cyclotron parameters are known for each ion, and because no intermediate scattering in a target occurs, the true energy incident at the detector is known very accurately. The particle energy is related to its charge Q , mass M , the magnetic field B and

and the cyclotron radius R by the uniform field cyclotron equation:
 $E = Q^2 B^2 R^2 / 2M$. Because the magnetic field varies azimuthally, the product $B \cdot R$ is determined empirically for a given setting of the main field and trim coil magnet currents. The same magnetic field was used in accelerating all the beams of one run. The absolute energy scale was determined from parameter systematics of the cyclotron¹⁹). The value of the ion charge and mass were determined unequivocally in nearly all cases from knowledge of the exact cyclotron frequency and the approximate ion energy as described more fully elsewhere¹⁶).

The pulse height response of the detector to alpha particles was measured using a thin ^{212}Pb source, which emits two alpha particles of substantially different energies in its decay chain. This calibration was extrapolated to higher energies using a mercury pulser. The alpha particle calibration defines an "alpha energy", E_α , for the centroid of each spectrum. The true total energy, E_T , minus the energy loss E_w of the heavy ion in the detector window, yields the "deposited energy", E_d . The PHD is then defined as the difference between the deposited energy and the alpha energy:

$$\text{PHD} = (E_T - E_w) - E_\alpha = E_d - E_\alpha \quad (1)$$

It should be noted that this definition of the PHD differs from that used by some other workers (e.g. ref.12) by excluding the energy loss in the detector surface dead layer from the PHD. Because the surface dead layer thickness can be measured without great difficulty, and since it varies from one detector type to another, it seems better to treat it separately in a general method for calibrating the PHD.

The experiments reported on in this work were performed with a single heavy ion Si surface barrier detector (ORTEC 15-016C) of 300 μm depletion depth and 1000 $\Omega\text{-cm}$ resistivity which was operated at its specified bias voltage of 150 volts. The variation of the PHD with detector type has been previously investigated extensively^{6,7,12}), and due to machine time constraints we have chosen to extensively study one detector rather than to perform a more limited study of many different detectors and detector types. The thickness of the Au window of the detector was checked by an X-ray fluorescence measurement, which agreed to within 10% with the thickness of 39.7 $\mu\text{g}/\text{cm}^2$ specified by the manufacturer. The effective surface dead layer of the detector was inferred from data obtained by irradiation with a 14.0 MeV $^{40}\text{Ar}^{2+}$ beam incident at three different angles to the surface: 90°, 45° and 30°. The shift in the energy centroid with angle was somewhat greater than expected from the Au window alone. Since in the X-ray fluorescence measurement no peaks were observed for elements other than Au and Si, we assumed an additional thin Si dead layer (16.3 $\mu\text{g}/\text{cm}^2$) beneath the Au window whose thickness was calculated using standard range-energy tables²⁰). Such an additional dead layer may be due to any of several factors: a thin undepleted surface region, an oxygen impurity at the surface which acts as an electron acceptor, charge diffusion against the electric field gradient, or prior use of the detector with heavy ions²¹). It should be noted, however, that the measured FWHM of 45 keV for 8.785 MeV alpha particles indicates good bulk collection properties.

The "search" and "data" detectors were mounted on a rotating platform and moved successively into the axis of each beam. Pulses from each were amplified first by a charge sensitive preamplifier, then by a double

delay line amplifier, and were digitized by a 4096 channel analogue-to-digital converter, and written on magnetic tape with the aid of a computer.

The accuracy of the PHD data is limited by the accuracy to which three different quantities can be measured or calculated: the total ion energy E_T , the "alpha energy" E_α , and the energy loss in the surface dead layer E_w . Experience with measuring the absolute energies of beams from the 88-Inch cyclotron using a magnetic analysis system²²⁾ has led to an upper limit on the error of E_T of $\pm 0.5\%$. The accuracy of E_α depends on the measurement of the energy centroids of the two alpha particle peaks and the extrapolation to higher energies with a linear pulser. The error in this extrapolation has been estimated to be $\pm 0.36\%$ of E_α . The error of E_w arises from the uncertainties in the dead layer thickness and in the range-energy relations²⁰⁾. The error of E_w has been estimated as $\pm 2.5\%$ of E_w based on the reproducibility of the dead layer measurements. The window correction is comparable to the PHD only for lighter masses, and in all cases makes only a negligible contribution to the PHD error. The net uncertainty in the PHD is less than the size of the data points shown in fig. 2.

3. Results and Discussion

PHDs have been measured for elements ranging from Ne to Au, for energies from about 5 to 160 MeV. The PHD data for one counter is shown in fig. 2 in MeV. units and log-log format. Two important features should be noticed: the PHD is linear with E_d for each element,

and different elements lie on different lines. The four solid lines represent linear least-square fits to the Au, Ta, Xe and Kr data. The good agreement with the data reveals the utility of a simple power-law fitting function:

$$\text{PHD} = 10^b E_d^a \quad (2)$$

where a is the slope and b is the y-intercept of a plot of $\log \text{PHD}$ versus $\log E_d$. The fitted slopes and y-intercepts for these four elements are given in Table 1. Both the slopes and the intercepts increase with atomic number (Z) and a typical value for the slope is 0.6.

Since the data for each element cluster on separate lines, it is desirable to have a procedure for mathematically generating calibration lines for all elements from lines measured for just a few. This has been done by fitting the slope and intercept parameters of Eq. (2) to simple functions of the atomic number (Z) and mass number (A). Figure 3 shows linear fits of the slope, a , to the square of Z and A for the Au, Ta, Xe and Kr data shown in fig. 2. The fitting functions are:

$$a(Z) = 0.02230 \left(\frac{Z^2}{10^3} \right) + 0.5682 \quad (3)$$

$$a(A) = 0.03486 \left(\frac{A^2}{10^4} \right) + 0.5728 \quad (4)$$

Using one of these correlations for the a parameter, a value of the intercept, b , can be calculated from the measured PHD and the deposited energy (E_d) according to the following equation:

$$b = \log \left(\frac{\text{PHD}}{E_d^a} \right) \quad (5)$$

Values for $-b$ based on Eqs. (3) and (5) and the data for Fig. 2 are shown in fig. 4 plotted versus $100/Z$ and $100/A$. Equivalent results can be obtained using Eq. (4) instead of Eq. (3). With the exception of the lightest elements (Ne and Mg), where the PHD is very small and the percent error is large, the calculated intercepts are accurately represented by a straight line. The fitting equations are

$$b(Z) = -0.1425 \left(\frac{100}{Z} \right) + 0.0825 \quad (6)$$

$$b(A) = -0.2840 \left(\frac{100}{A} \right) + 0.0381 \quad (7)$$

The slope and the intercept calculated from Eqs. (3) or (4) and (6) or (7) can be used in Eq. (2) to compute the PHD for any element.

As a test of the scheme, the PHD lines were calculated from Eq. (2) for the remaining elements in Fig. 2. The slope and intercept were calculated from Eqs. (3) and (6). The results, shown by the dashed lines in fig. 2, provide good agreement with the observed PHD. This calibration scheme is valid for elements from Ne to Au and energies from 5 to 160 MeV.

Computed PHDs from Eqs. (3) and (6) have been displayed in several ways to facilitate their use by other scientists. The range of applicability of these results will be discussed later. Figure 5 displays calculated PHD versus deposited energy calibration lines for a range of elements from Ne to U. These lines are useful for a quick assessment of the PHD to be expected in a particular experimental situation. It

is also useful to plot the PHD versus the alpha energy, since this is an observable quantity. Equations (1) and (2) can be combined to write the alpha energy in terms of the total energy as

$$E_{\alpha} = E_d(1 - 10^b E_d^{a-1}) \quad (8)$$

Equations (2) and (8) allow one to uniquely generate the curves in fig. 6, which relate the PHD to the alpha energy. With these curves one can find the PHD directly from the alpha energy. It is useful to notice that these curves are quite nearly linear over a large energy range, and could be parameterized easily.

The effect of atomic mass on the PHD of four Xe isotopes at 130 MeV has been measured; however the data is too limited to understand the systematics of the PHD with atomic mass. The standard deviation of the PHD for isotopes 128,130,131, and 132 is 0.25 MeV, which is within the estimated error of measurement. Thus the isotopic effect seems to be smaller than the effect arising from the same fractional change of Z.

Comparison of our PHD predictions with data from Wilkins, et al.⁶⁾ in fig. 7 indicates generally good agreement (6-10% of the PHD), even though the resistivity of their detector is 380 ohm-cm (our detector had a resistivity of 1000 ohm-cm). Their data overlap somewhat with the low-energy range of ours. In fig. 7, data (adapted from Tables 2, 3 and 4 of ref. 6) for three elements (Au, Ag and Cu) are compared with

our PHD calibration lines for the same elements. The Au line is a fit to our measured data, and the Ag and Cu lines are calculated with our calibration procedure. In this comparison the energy loss in the detector surface window has been subtracted from their tabulated PHD values, in accordance with our definition. This is evidence that the application of our calculated PHD lines to other detectors of similar type is probably reliable to better than 10% of the PHD.

4. Comparison with the Kaufman Calibration Procedure

The PHD of solid state detectors has been previously studied by Kaufman and his associates (refs. 6,7,12) over an energy range of 4.5 to 80 MeV. They included the energy loss in the detector window as part of the PHD, and fit the energy dependence of the PHD for all elements simultaneously with a 1-parameter formula. This formula relates the PHD, $\Delta\epsilon$, to the total energy, ϵ , as

$$\Delta\epsilon = \frac{6\epsilon}{8+\epsilon} \frac{A}{1 + 525\epsilon^{-1.407}} \quad (9)$$

Both the PHD and the total energy are in LSS units⁹). The A-parameter has been observed to vary¹²) by up to 7% from one detector to another (of comparable resistivity, bias voltage, age, etc.) and must be determined by calibration.

To test the PHD scheme of ref. 12, our data have been plotted in fig. 8 in LSS units and with the window losses included in the PHD (in accordance with the definition of PHD in refs. 6,7,12). In the low LSS range one sees the clustering of the measured elements, as

observed by Kaufman. In the intermediate and high energy range this clustering clearly breaks down. This failure of our data to cluster on a universal curve in LSS space confirms recent results by Finch et al.¹⁴⁾ who observed that the PHDs of the light fission fragments fell below the LSS curve on which all of the heavy fission fragment data fell. The same data for Kr, Xe and Au are shown in fig. 9 along with three curves calculated with eq. (9) for different values of the A parameter. The divergence of the data from the calculated curves is very apparent in this figure, especially at higher energies. One should note that because of the bending of the curve below the data, extrapolation to high energies with this formula will predict PHDs that are too small. On the other hand, the comparison between the predictions of our PHD calibration scheme and the lower energy data⁶⁾ indicate that our scheme is useful at lower energies as well.

5. Summary

Use of the cyclotron as a source of monoisotopic heavy ion beams of known energy for PHD determinations of solid state detectors has been described. The PHD of an ORTEC surface barrier detector has been measured for elements from Kr to Au, from 15 to 160 MeV and for elements from Ne to Fe between 5 and 50 MeV. The data have been fit with a simple power law formula. A new procedure for generating PHD calibration lines for any element from lines measured for a few elements has been described. The accuracy of this procedure is confirmed to $\pm 0.5\%$ of the total energy, between about 15 and 160 MeV. This accuracy is within the experimental error. Supporting data suggest that the range of reliability extends down to 4.5 MeV. Application of the specific calibration lines presented here, to other detectors with resistivities between several hundred and

one thousand Ω -cm is probably accurate to within 10% of the PHD and may be accurate to within a few percent. For energies above 50 MeV, the clustering of the measured PHD values for different elements produced by use of LSS units breaks down. The observed strong dependence of the PHD on atomic number and energy in LSS space limits the usefulness of formulae such as eq. (9) to estimate PHD data and indicates that the response of a silicon surface barrier detector to heavy ions cannot be accounted for by such a model.

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TABLE 1. Measured coefficients for PHD calibration lines.

Isotope	a	b
$^{197}_{79}\text{Au}$	0.7060	-0.1036
$^{181}_{73}\text{Ta}$	0.6902	-0.1057
$^{129}_{54}\text{Xe}$	0.6295	-0.1538
$^{84}_{36}\text{Kr}$	0.5990	-0.3227

Figure Captions

- Fig. 1 Pulse height spectrum of counts vs. energy for Au^{7+} , Au^{9+} , Au^{11+} , and Au^{13+} beams. Note the near absence of background events.
- Fig. 2 PHD of a silicon surface barrier detector vs. deposited energy. The PHD is defined to exclude the energy loss in the surface window (see text). Long lines are linear least-square fits to the data with equal weights; short lines are extrapolations using method described in the text. Errors are less than the size of the data points, (See discussion in text).
- Fig. 3 Measured values of the parameter a (of eq. (2)) for Au, Ta, Xe and Kr, plotted versus Z^2 and A^2 . Lines are linear least-square fits to the data with equal weights.
- Fig. 4 Calculated values of the parameter $-b$ (of eq. (2)) for all the data of fig. 2, plotted versus $1/Z$ and $1/A$. Lines are linear least-squares fits to the data with equal weights.
- Fig. 5 Computed PHD vs. the deposited energy. Lines generated by the procedure described in text. Range of reliability discussed in the text.
- Fig. 6 Computed PHD vs. the alpha energy. See Fig. 5 and text.
- Fig. 7 PHD vs. the deposited energy. Data from Wilkins et al.⁶⁾. Lines generated from data presented in this paper.
- Fig. 8 Measured PHD vs. the total energy in LSS units for several elements. Our PHD data, have been plotted with the energy loss in the surface window included, in accordance with Kaufman's usage¹²⁾.
- Fig. 9 Measured PHD vs. total energy in LSS units for three elements. See fig. 8. Curves calculated with eq. (9).

XBL 7710-2090

Fig. 1

XBL 783-7655

Fig. 2

XBL 783-7427

Fig. 3

XBL 783-7428

Fig. 4

XBL 783-7654

Fig. 5

XBL 783-7653

Fig. 6

XBL 783-7656

Fig. 7

XBL 778-1671

Fig. 8

XBL 7710-10309

Fig. 9

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