# Detection of neutron-excess isotopes of low-Z elements produced in high-energy nuclear reactions\*

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A search was made for new isotopes of the elements lithium through nitrogen produced in the high-energy (4.8-GeV) proton irradiation of a uranium target. The fragments were identified by  $\Delta E - E$  and time-of-flight techniques. An electronic pulse-width discriminator greatly reduced the background allowing high sensitivity. A new method for analyzing time-offlight data and a new algorithm for particle identification were introduced. Two new isotopes, <sup>14</sup>Be and <sup>17</sup>B, were observed to be particle stable and the existence of <sup>19</sup>C was confirmed. It was shown that <sup>12</sup>Li and <sup>16</sup>B are particle unbound. Approximate production cross sections were determined for <sup>14</sup>Be, <sup>17</sup>B, <sup>18</sup>C, and <sup>19</sup>C, and upper limits estimated for <sup>13</sup>Li, <sup>19</sup>B, <sup>20</sup>C, and <sup>22</sup>N.

 NUCLEAR REACTIONS U(p, x), E = 4.8 GeV; <sup>14</sup>Be, <sup>17</sup>B, <sup>18</sup>C, <sup>19</sup>C measured σ; <sup>13</sup>Li, <sup>19</sup>B, <sup>20</sup>C, <sup>22</sup>N σ upper limits.
 NUCLEAR STRUCTURE <sup>14</sup>Be, <sup>17</sup>B, <sup>19</sup>C observed particle bound; <sup>12</sup>Li, <sup>16</sup>B particle unbound.

#### I. INTRODUCTION

The sudden interest in the field of neutron-excess isotopes of low-Z elements began in 1965 with the discovery<sup>1</sup> of <sup>8</sup>He in fission and the measurement of its half-life<sup>2</sup> when produced in a high-energy nuclear reaction. With the discovery<sup>3,4</sup> of <sup>11</sup>Li, <sup>12</sup>Be, <sup>14</sup>B, and <sup>15</sup>B the advantages of high-energy nuclear reactions for the production of exotic nuclei became evident. These advantages include the high cross sections for the neutron-excess isotopes and the nonspecificity of the reactions. Since then high-energy nuclear reactions and counter-telescope techniques have been used to discover <sup>17</sup>C, <sup>5</sup> <sup>19</sup>N, and <sup>21</sup>O, <sup>6</sup> and tentatively <sup>19</sup>C.<sup>7</sup> This method has also shown  ${}^{10}Li^{4}$  and  ${}^{13}Be^{5}$  to be particle unbound. High-energy nuclear reactions combined with an on-line mass spectrometer have been used<sup>8-11</sup> to discover <sup>27-33</sup>Na and <sup>48-51</sup>K. Another fruitful method for the production of exotic nuclei has been heavy-ion-transfer reactions, which were used to discover<sup>12-15</sup> 28 isotopes of the elements carbon through chlorine. These workers<sup>16</sup> also presented evidence for the particle instability of <sup>14</sup>Be, but this is contradicted by the present work<sup>17</sup> using high-energy nuclear reactions. The present experiment presents the discovery of <sup>14</sup>Be and <sup>17</sup>B, confirms the existence of <sup>19</sup>C, and shows <sup>12</sup>Li and <sup>16</sup>B to be particle unbound.

The above described experiments are concerned with the particle stability of nuclei. It is generally agreed that determining masses of nuclei far

from  $\beta$  stability is of fundamental importance to nuclear physics with applications to many other fields. If the nuclei are at the limits of particle stability then their mere existence or nonexistence, as determined in counter experiments such as this one, sets meaningful limits on their masses and tests the predictions of mass formulas. The method most often used for predicting the particle stability of nuclei in this region has been the mass relations of Garvey and co-workers<sup>18, 19</sup> which have been fairly successful. However, the discovery of <sup>11</sup>Li in 1966 was a significant exception because it had been clearly predicted to be unbound at that time. Progress was made so that a few years ago it was believed that all particlestable isotopes of the elements up through boron had been discovered.<sup>20-22</sup> The situation changed a year ago when Thibault and Klapisch<sup>23</sup> recalculated the masses and predicted <sup>17</sup>B to be bound by 0.6 MeV and <sup>19</sup>B to be bound by 0.2 MeV. The present experiment was stimulated by this recalculation which predicted <sup>17</sup>B to be the lightest undiscovered bound isotope. Thus, while the discovery of <sup>17</sup>B was not unexpected, our discovery of <sup>14</sup>Be was doubly surprising: first because it had been predicted to be unbound by 1.5 MeV, and second because it had been concluded from the above-mentioned heavy-ion-transfer

experiment<sup>16</sup> that in all probability it was unbound. The present study was designed to search for neutron-excess particle-stable nuclei at the limits of stability by  $\Delta E$ -E and time-of-flight (TOF) techniques. The cross sections expected from sys-

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tematics<sup>24</sup> for new nuclei were only about 10 to 20  $\mu$ b. The difficulty of the experiment can be understood by considering the total number of fragments entering the telescope. From previous work<sup>24</sup> on the high-energy proton irradiation of uranium it is known that the production cross sections are 0.85 b for all fragments from lithium to sodium, 4.4 b for helium isotopes, and probably 10 b for evaporation-like hydrogen isotopes. Also several barns of fission and spallation products are produced. Thus, it is necessary to identify uniquely one in  $10^6$  of the fragments entering the telescope. This sets severe requirements on resolution, tailing, and background rejection, and necessitates the collection and careful processing of an enormous amount of data. A previous experiment<sup>25</sup> demonstrated the feasibility of the  $\Delta E$ -E TOF technique but background problems limited its sensitivity. The pertinent differences in equipment for the present experiment are given in Sec. II. A new pileup rejection system based on pulse-width discrimination is described in Sec. IID and Appendix A. It was incorporated to decrease the background and thereby increase the sensitivity of the experiment. As part of the data analysis described in Sec. III B, corrections to the time-of-flight data were made for the dead layer and the variation in collection time with depth of fragment penetration in the E detector. A refinement to the algorithm for particle identification is described in Sec. III C. The results, given in Sec. IV, reflect these improvements by extending the limits of known particle stability and by setting small upper limits on the production cross sections for nuclides now at the limits of detection.

#### **II. APPARATUS**

## A. General

The 4.8-GeV external proton beam of the Bevatron bombarded a 28-mg/cm<sup>2</sup> uranium metal target inside a 0.91-m-diam evacuated scattering chamber. The average beam intensity was  $6 \times 10^{11}$  protons/ pulse, with a 1-sec-long beam pulse occurring every 6 sec. Fragments were identified in a  $\Delta E - E$ telescope in which the two detectors were separated by 25 cm. The time of flight between the two detectors and the E signal were used to identify the mass number of the fragment, and the  $\Delta E$ -E information was used to distinguish the elements. Many of the details of the experimental equipment have been previously published<sup>24,25</sup> and only significant differences will be explained here. The general technique of  $\Delta E - E$  TOF identification has also been used recently by other workers.<sup>26,27</sup>

#### **B.** Detectors

Since the resolution of the apparatus depends primarily on the characteristics of the  $\Delta E$  and Edetectors, special care was taken in their fabrication. The atomic-number resolution depends critically on the thickness uniformity of the  $\Delta E$ detector, and therefore, in order not to degrade the inherent resolution of the  $\Delta E$  detector, silicon wafers which were to be made into detectors were preselected as described in Appendix B.

The mass resolution depends primarily on the time resolution of the  $\Delta E$  and E detectors. At the beginning of the experiment measurements were made on the rise time of each detector-preamplifier-shaping-amplifier combination for  $\alpha$  particles and for electronic pulses injected onto the detector by a fast rise time (1-nsec) pulser. A <sup>148</sup>Gd 3.18-MeV  $\alpha$  source was used for the  $\Delta E$  detector measurements and a <sup>212</sup>Pb 8.78-MeV  $\alpha$  source was used for the  $\Delta$ t source was used for the E detector measurements. The charge injected from the pulser was matched to the  $\alpha$  particles in each case. The results obtained from these measurements are summarized in Table I.

The pulser rise time is somewhat slower than the  $\alpha$ -particle rise time because of the finite rise time of the pulser itself. For these measurements and throughout the experiment, we applied bias voltages substantially over that necessary to deplete the detectors completely in order to decrease the charge-collection times. The values of the minimum field listed in Table I were calculated from the net bias voltage minus the voltage needed to deplete the detector, divided by the thickness. The detectors were cooled with thermoelectric coolers in order to reduce leakage current, electronic noise, and charge-collection time. An energy calibration for each detector was obtained by using the above mentioned  $\alpha$ sources in conjunction with a precision pulse generator.

During the experiment the detector telescope was placed at  $90^{\circ}$  to the beam. This did not cause much loss in yield because the angular distributions are only slightly forward peaked.<sup>24</sup> The

TABLE I. Detector characteristics.

	$\Delta E$	Ε
Thickness (µm)	24	67
10-90% rise time for $\alpha$ particles (nsec)	1.9	2.7
10-90% rise time for pulser (nsec)	2.2	3.0
Bias (V)	100	190
Minimum field (V/ $\mu$ m)	3.8	2.6
Temperature (°C)	-21	-25

plane of the target was at  $45^{\circ}$ . The  $\Delta E$  detector was located 17 cm from the target in order to avoid the halo of the beam, and the flight path to the *E* detector was 25 cm. A larger area rejection detector was positioned just behind the *E* detector. The  $\Delta E$  and *E* detectors had sensitive areas of  $5 \times 7$  mm and were collimated to  $4 \times 6$  mm by copper collimators 0.5 mm thick.

#### C. Electronics

A schematic diagram of the electronic apparatus is shown in Fig. 1. Much of the equipment was the same as that used in an earlier experiment.<sup>25</sup> but there were several significant changes, the most important of which was the addition of a pulse-width-discriminator system to complement the existing 50-nsec pileup rejector. This will be described in Sec. IID. The details of the fast preamplifiers, amplifiers, and crossover discriminators have been described,<sup>25</sup> except that now the fast amplifiers clipped the pulses to a width of 70 nsec. The cables between the preamplifiers and amplifiers were 40 m long. The cables transmitting the fast signals were 2.2-cmdiam Heliax coaxial cable. The time-to-amplitude converter was started by the E discriminator signal and stopped by the delayed signal from the  $\Delta E$ discriminator. The time of flight of a fragment (TOF) was relative to time zero  $(T_0)$  which was determined approximately at the beginning of the experiment with the pulser. This was sufficient for the on-line monitoring of the data, but for the final data analysis, done off line,  $T_0$  was determined precisely from the real particle data. During the experiment two pulsers were used.



FIG. 1. Schematic diagram of the electronics. The following abbreviations have been used: PWD is pulsewidth discriminator; C/O is crossover discriminator; TAC is time-to-amplitude converter; PI is particle identifier; SCA is single-channel analyzer; and PUR is pileup rejector.

Each was split and one side was appropriately attenuated and delayed so that one pulser simulated a high-energy zero-flight-time fragment and the other a <sup>14</sup>C which deposited 10 MeV in the *E* detector. The dual pulsers were controlled by a relay system that switched from one pulser to the other between each beam burst. The pulser events ( $\approx 2/\text{sec}$ ) were tagged as they were written on magnetic tape to allow off-line editing and stabilization of the data. The system was set up to measure flight times from 10 to 30 nsec—adequate for fragments from Li through N in the energy range 10 to 60 MeV over the 25-cm flight path.

The  $\Delta E$  and E energy signals, the analog particle-identifier (PI) signal, the time-of-flight (TOF) signal, the  $\Delta E$  and E pulse-width-discriminator (PWD) signals, together with a clock signal relative to the start of each beam burst, were all digitized, sent to a small on-line computer, and then stored on magnetic tape. The time of day was also stored with each buffer on tape. Three different kinds of on-line oscilloscope displays were generated by the computer. The first was a histogram display of the analog particle-identifier signal in which adjacent elements could be resolved. Six sets of digital windows could be set on the particle spectrum, and for each of these one could display either the TOF spectrum, the calculated  $T_0$  spectrum (described in Sec. III B), or the calculated mass spectrum. The third type of display was histograms of the  $\Delta E$  and E PWD signals and the energy spectrum in the E detector. Digital windows were set on the  $\Delta E$ , E.  $\Delta E$ PWD, EPWD, and TOF signals, and only events which satisfied these five requirements were displayed.

The gains of the  $\Delta E$  and E systems were matched via pulsers once every 12 hours during the  $3\frac{1}{2}$ week data-collection period. In addition, the fasttiming characteristics were carefully monitored by not only observing the on-line mass resolution but also periodically determining the peak position and the full width at half maximum (FWHM) of the  $T_0$  spectrum for both the pulser and for <sup>11</sup>B fragments.

#### D. Pulse-width discriminator

The function of the pulse-width discriminator (PWD) is to perform pileup rejection on the signals from each of the detectors on a time scale which is a fraction of their rise time. Conventional pileup rejectors operate on times longer than the width of the clipped amplifier output and have a time resolution which is several times larger than the detector-preamplifier rise time. A pulsewidth discriminator has a pulse-pair resolution which is of the order of the square root of the rise time times the square root of the time resolution for single events. The PWD which we used measured the time difference from leading edge to crossover of shaped detector pulses.28 Overlapping pulses appear wider and were discarded in the later data analysis. However, the width above a fixed discriminator level of a single pulse increases with its amplitude, and therefore to utilize fully the pulse-pair resolution, one must first correct the PWD output for walk with amplitude. Details of the theory of its operation are discussed in Appendix A. An expression for its pulse-pair resolution is derived and numerical estimates are carried out. Also the related problem of walk with energy is discussed.

#### **III. DATA ANALYSIS**

The data consisted of  $1.25 \times 10^7$  events written on 40 magnetic tapes. The five essential guantities recorded for each event were  $\Delta E$ , E,  $\Delta E$ PWD, EPWD, and TOF. Tagged pulser events from two pulsers were recorded simultaneously with the data for real particles. Using the pulser events all the data were edited for drifts and stabilized. The philosophy of data analysis was to use contour plots to examine two parameters at a time. Then, using appropriately constructed algorithms, the data were transformed to form a new contour plot. The algorithms were adjusted so that the data formed ridges parallel to one axis, and then could be projected onto the other axis to form a histogram. Thus, the five-dimensional parameter space was reduced to a two parameter (charge vs mass number) contour graph. Finally the background was studied in order to determine which region of the original five-parameter space to accept.

#### A. Editing and stabilization

First the data were inspected for drifts. This was done by plotting the centroids of each of the two pulsers for each of the parameters vs time. These plots exhibited occasional discontinuities as well as other spurious but unexplained behavior. About 2% of the data were rejected on this basis. Then events were regrouped by stabilization periods, each of which contained 140 events from each of the two pulsers and several thousand data events, corresponding to about 10 min of data taking (which was short compared to the time constants of the remaining drifts). The next step was to use the pulser-simulated events to eliminate these small drifts. The pulser amplitudes had been adjusted so that one of the pulser peaks fell at each end of the  $\Delta E$ , E, and TOF spectra. This allowed two-point stabilization of these three quantities. Both pulser peaks occurred near the lower end of the PWD spectra of each detector and one of them was arbitrarily selected for stabilization. First the centroids of both pulser peaks in all five parameters were calculated. Then, in order to eliminate wild events, the centroids were recalculated using only those events which fell within  $\pm 4\%$  of full scale of the raw centroids. New tapes were written for which the real data within each of the stabilization groups was shifted by linear transformations to fix the edited pulser peaks for each parameter at their nominal positions. This procedure reduced the effect of the small instabilities in the electronics, but was essential to combining the data collected over a long period of time.

The data analysis was now approached as three partially independent and parallel tasks: the determination of the mass number for each event, the determination of the nuclear charge for each event, and the editing of each event according to the  $\Delta E$  and E PWD signals. The  $\Delta E$  and E signals were expressed in MeV by a linear calibration, and the TOF signal was converted to T in nsec by a calibration curve with a small second-order term measured with a precision delay box.

#### B. Determination of mass number

The determination of the mass number is based on the nonrelativistic equation,<sup>29</sup>  $E = \frac{1}{2}Am_0v^2$ . Since the distance between the two detectors is known and the time of flight of each event is measured as well as its energy in the *E* detector, its mass number can be calculated as

$$A = \frac{2E}{m_0 D^2} (T - T_0)^2, \qquad (1)$$

where  $T_0$  is an unknown zero of time. It was necessary to determine  $T_0$  directly from the real particle data. Our approach to this problem was to assume a value of the mass number  $A_0$  and to solve Eq. (1) for  $T_0$ . The events of a particular element were selected according to the PI signals as discussed in Sec. III C, and the value of  $A_0$  was selected as that of the principal isotope of the element. This calculated estimate  $T_z$  of  $T_0$  is:

$$T_{z} = T - D \left(\frac{A_{0}m_{0}}{2E}\right)^{1/2} .$$
 (2)

The second term on the right side of Eq. (2) is the calculated time of flight  $T_c$  for a particle of mass number  $A_0$  and energy E. For events where the real mass is equal to the assumed mass, a scatter plot of  $T_e$  vs  $T_c$  should exhibit a grouping of

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the data forming a horizontal straight line at a value of  $T_z$  which gives  $T_0$ . If the real mass is not equal to the assumed mass, data points will cluster in families of straight lines which extrapolate to  $T_0$  as  $T_c \rightarrow 0$ , because  $T_z - T_0 = [1 - (A/A_0)^{1/2}]T_c$ .

A contour plot representing such a scatter plot for boron isotopes is shown in Fig. 2(a). As suggested in the above arguments the different isotopes fall into distinct families. Although the family of curves are similar in shape they are by no means straight lines. We therefore investigated this problem and found that if three effects were taken into consideration the families became straight-line extrapolations to the same intercept, and furthermore, the values of  $T_0$  determined for all isotopes of the elements Li through N were the same. The effects were: (1) the dead layer on the front of the E detector, (2) the different chargecollection times for particles which penetrate the E detector to different depths, and (3) the walk of the  $\Delta E$  discriminator with amplitude. These ef-



FIG. 2. Contour plots of calculated  $T_{zero}$  vs calculated time of flight for boron isotopes with an assumed mass of 11. The lowest contour is at the 5-count level and there are two logarithmically spaced contour levels per decade. The data in Figs. 2-10 are representative of  $4.5 \times 10^5$  events of Li through N, or 3.6% of the total amount of data recorded for this experiment. Dead layer and walk with range corrections have been applied in (b) but not in (a). Note in (b) the extrapolation of all the isotopes to a common  $T_{zero}$  at zero flight time.



FIG. 3. Histogram of calculated  $T_{zero}$  for boron isotopes with an assumed mass of 11. This figure shows only those events that deposited from 18 to 22 MeV in the *E* detector.

fects were included by modifying Eq. (2) to read

$$T'_{z} = T - D \left( \frac{A_0 m_0}{2(E + \delta E)} \right)^{1/2} + \phi \overline{R} + \epsilon \Delta E , \qquad (3)$$

and the expression for the calculated time of flight becomes

$$T_{c}' = D\left(\frac{A_{0}m_{0}}{2(E+\delta E)}\right)^{1/2}.$$
 (4)

Instead of using range-energy tables to calculate corrections (1) and (2), the  $\Delta E$  and E data themselves, together with the power-law approximation to range-energy relations, was used. The expression which results for the energy loss in the E detector dead layer is

$$\delta E = \frac{\delta x}{x} \frac{(E + \Delta E)^b - E^b}{b E^{b-1}} , \qquad (5)$$

where  $\delta x$  is the *E* dead layer thickness, *x* is the  $\Delta E$  detector thickness, and *b* is a dimensionless number. The expression for the average charge-deposition depth in the *E* detector is

$$\overline{R} = x \frac{b}{b+1} \frac{E^b}{(E+\Delta E)^b - E^b} .$$
(6)

TABLE II. Parameters for the time-of-flight analysis.

	Symbol	Value
Dead layer on front of the $E$ detector $(mg/cm^2)$	δχ	0.14
Power in the range-energy equation	b	1.6
Coefficient of walk with range $(psec/mg cm^2)$	φ	8.5
Coefficient of walk with $\Delta E$ (psec/MeV)	e	7.5
Time resolution for <sup>11</sup> B (psec)	FWHM	290
Time resolution for pulser (psec)	FWHM	100

It was found that with suitable values of  $\delta x$ ,  $\phi$ ,  $\epsilon$ , and b, satisfactory  $T'_{z}$  vs  $T'_{c}$  contour plots could be obtained as shown in Fig. 2(b). The ridge for <sup>11</sup>B is straight and horizontal and the other isotope ridges are straight and extrapolate to a common value of  $T_{0}$ . Furthermore, the fitted values of the parameters which are given in Table II are reasonable in terms of the physical effects which they account for. The mass number for each event was then calculated as follows:

$$A = \frac{2(E + \delta E)}{m_0 D^2} (T + \phi \overline{R} + \epsilon \Delta E - T_0)^2.$$
 (7)

By taking a cut from Fig. 2(b) corresponding to energies between 18 and 22 MeV, the time resolution of our apparatus is obtained for <sup>11</sup>B particles which deposit 20 MeV in the *E* detector and 14 MeV in the  $\Delta E$  detector. The histogram resulting from such a cut is shown in Fig. 3, which indicates that the FWHM time resolution is 290 psec. The pulser energy resolution in the *E* detector was only 120 keV and therefore the mass resolution found at mass 11 of 4.4% comes mainly from the time resolution.

The pulser time resolution was only 100 psec and may be compared with an estimate based on the characteristics of our preamplifiers. For the case which simulates the above mentioned <sup>11</sup>B fragment, the contribution of the *E* detector timing may be neglected because of its lower capacitance and the higher energy. Taking the capacitance of the  $\Delta E$  detector as 160 pF, the 10-90% rise time as 2.5 nsec, the mutual transconductance ( $g_m$ ) of the field-effect transistor as 25 mA/V, and double delay-line shaping, one



FIG. 4. Contour plot of  $\Delta E$  vs *E*. The banana-shaped ridges correspond to the elements Li through N. The rectangular shape of the plot is caused by the  $\Delta E$  and *E* single-channel analyzers. The lower right corner is cut off because these particles penetrate the *E* detector and are rejected by the veto detector. The lowest contour is at the 1-count level and there are two logarithmically spaced contour levels per decade.

calculates a time resolution (FWHM) equal to 35 psec. On bench-top tests 60 psec was achieved. The value of 100 psec at the accelerator during the experiment is not unreasonable. Also the pulse-width discriminators had excellent time resolution for real particles as described in Sec. III D. It was concluded that the 290-psec time-offlight resolution for real particles was due to the gold contact layer on the detectors which had a sheet resistance of several ohms. It is thought that this resistance together with the detector capacitance caused an RC integration short compared to the rise time of the pulse, and the net effect was a variable delay depending upon the point at which the particle struck the face of the detector. It should be noted that an earlier experiment with a 17- $\mu$ m  $\Delta E$  detector had a resolution of only 170 psec.

#### C. Determination of nuclear charge

The Z determination proceeded in two steps. First the value of a particle-identification (PI) algorithm was calculated from the  $\Delta E$  and E signals of each event. Then the mass dependence of the calculated PI was removed using the mass number calculated in Sec. III B. The PI algorithm is constructed so as to obtain a function of  $\Delta E$ and E which depends only on particle type and not on  $\Delta E$  or E separately. It should map families of curves in  $\Delta E$ -E space into families of straight lines parallel to the E axis in PI-E space. A contour plot of  $\Delta E$  vs E is given in Fig. 4. The algorithm, which is a modification of that used by Butler, Poskanzer, and Landis<sup>25</sup> is

$$\mathbf{PI} = \left[ \left( \frac{E + \Delta E}{K} \right)^{p} - \left( \frac{E}{K} \right)^{p} \right]^{1/2}, \tag{8a}$$

where

$$p = b - \frac{c}{x} \frac{\Delta E}{E} . \tag{8b}$$



FIG. 5. Contour plot of E vs particle identification signal (PI). The lowest contour is at the 5-count level.

We found that the curvature in plots of PI vs Ecould be removed over a wider range of elements and energies using a power p which decreased linearly with  $\Delta E/E$  rather than just with  $\Delta E$  as in Ref. 25. The values of the parameters used were b=1.7, c=0.1 mg/cm<sup>2</sup>, and K=300. Again, x is the  $\Delta E$  detector thickness in mg/cm<sup>2</sup>. A contour plot of our new PI algorithm vs E is given in Fig. 5.

Figure 6(a) shows a histogram obtained by projection of Fig. 5 on the horizontal axis. The elements are separated from each other but the value of PI depends upon the mass as well as the nuclear charge. For example, an inspection of Fig. 5 shows that the Be group is divided into two peaks, one corresponding to <sup>7</sup>Be and the main peak to <sup>9</sup>Be and heavier isotopes, <sup>8</sup>Be being unstable. The heaviest isotopes of element Z are buried under the light isotopes of element Z + 1, which are produced in higher yield. This is the reason why an independent determination of the mass number by time-of-flight measurements is necessary. In order to determine the nuclear charge of each event it is necessary to remove this mass dependence of the PI signal, which is shown in Appendix C to be:

$$Z \propto \mathrm{PI}/A^{0.3} \,. \tag{9}$$

A histogram of Z is given in Fig. 6(b). The widths



FIG. 6. Histograms of (a) particle-identification signal (PI) and (b) calculated nuclear charge (Z).

of the peaks have been reduced with <sup>7</sup>Be moved underneath the other isotopes of Be. The FWHM resolution in Z is 0.14 Z units. The peaks are not symmetric but exhibit a tailing towards low Z which will be of importance in the display of the results in Sec. III F below.

## D. Pulse-width discrimination

The pulse-width-discriminator signals were used to edit out events affected by pileup in either detector. The time walk with amplitude of the PWD signal over the range of energies which was accepted, was large compared to the intrinsic resolution of the instruments and was removed before the application of acceptance windows. It was found that the *EPWD* signal depended slightly on the type of particle and this dependence was also removed at this stage.

Figure 7(a) shows the walk with amplitude of the EPWD. It is shown in Appendix A that the amplitude dependence of the PWD signals is expected to be of the form

$$PWD \propto \mathcal{E}^{-1/q} \,. \tag{10}$$

where  $\mathscr{E}$  is the value of  $\Delta E$  or E, and q is an integer. We determined the trend of the PWD signals by performing fits to scatter plots of PWD vs  $\mathscr{E}^{-1/q}$  and found q=3. From plots of PWD vs  $\mathscr{E}^{-1/3}$ , slopes and intercepts ( $\alpha$  and  $\beta$ ) were de-



FIG. 7. Contour plots of (a) E pulse-width-discriminator (E PWD) signal vs E and (b) normalized E pulsewidth-discriminator (NE PWD) signal vs E for Li through N fragments. The acceptance region for the final data analysis is shown in (b). The lowest contour is at the 5-count level in both plots. In (b) the vertical scale has been expanded by a factor of 5.

TABLE III. Parameters of the pulse-width-discrimiator analysis.

	Value		
	Symbol	$\Delta E$	E
Power of walk with energy	-1/q	-1/3	-1/3
Coefficient of walk with energy (nsec MeV <sup>1/3</sup> )	β	3.8	3.6
Coefficient of walk with range(psec/mg cm <sup>2</sup> )	γ	•••	11
Time resolution for <sup>11</sup> B (psec)	FWHM	140 (14 MeV)	70 (20 MeV
Time resolution for pulser (psec)	FWHM	115	60
Acceptance window (psec)	FWQM	200	90

termined and used to define a normalized PWD signal (NPWD) as

$$NPWD = PWD - (\alpha + \beta \mathcal{E}^{-1/3}) . \tag{11}$$

This form proved satisfactory for the  $\Delta E$  signal but it was found that the *E* pulse-width discriminator also had a shift with particle type which amounted to 50 psec between Li and N. This shift results from the different charge-collection times for particles which penetrate the *E* detector to different depths. It was removed by subtracting a term proportional to the average depth  $\overline{R}$ , at which particles deposit their charge in the *E* detector as calculated in Sec. III B. The normalized *E* pulsewidth-discriminator signal was then calculated as

$$NEPWD = EPWD - (\alpha + \beta E^{-1/3}) - \gamma \overline{R}$$
(12)

and a graph of NEPWD vs E is shown in Fig. 7(b). Typical values of the parameters are given in Table III.

A histogram of yield vs NEPWD is given in Fig. 8. After the determination of the parameters  $\alpha$  and  $\beta$  for each tape, such a histogram was formed and the values of NPWD for which the yield was  $\frac{1}{4}$  of its maximum value were determined. If the



FIG. 8. Histogram of normalized E pulse-width-discriminator (NEPWD) signal showing the acceptance window that was used in the final data analysis.



FIG. 9. Contour plots of nuclear charge (Z) vs mass number (A) for a small part of the data (a) without and (b) with the pulse-width-discriminator windows applied. The lowest contour is at the 1-count level.

central peak has a Gaussian shape with no background then 90% of the single events will fall in the acceptance region defined by these values. For the real data only 79% of the events fell within the windows of each PWD. Typical values for the FWHM and the full width at quarter maximum (FWQM) are given in Table III.

# E. Background study

Before combining the  $1.25 \times 10^7$  events into a two-parameter histogram of yield vs nuclear charge and mass number, a study was carried out to determine what region of the five-dimensional



FIG. 10. Contour plot of normalized E pulse-widthdiscriminator (NE PWD) signal vs E for events falling in the high-mass background region of Fig. 9(a). Compare with Fig. 7(b). The lowest contour is at the 1count level.

parameter space ( $\Delta E$ , E,  $N \Delta E$  PWD, NEPWD, and T) to accept in order to obtain the best rejection of background events. A single data tape containing  $4.5 \times 10^5$  events was processed to construct the contour plot of Z vs A shown in Fig. 9(a) with all values of the parameters included. The density of background events in the high-mass region on the right side of Fig. 9(a) is appreciable and is comparable to the data of Butler, Poskanzer, and Landis.<sup>25</sup> Figure 9(b) shows the factor of 80 improvement achieved by applying the PWD windows.

Scatter plots were made of  $N \triangle E PWD$  vs  $\triangle E$  and NEPWD vs E for events falling into the high-mass background rectangle indicated in Fig. 9(a). All events falling into this high-mass background region are unphysical and result from random coincidences in one of the detectors. The E graph for these events is shown in Fig. 10. We have grouped the events into two categories indicated by A and B. Category A corresponds to coincidence events where two particles penetrate the  $\Delta E$  detector and overlap in the *E* detector. When the E signal is small and comparable to the perturbing signal the EPWD signal is thrown far out. Category B, which extends up to 10 MeV, corresponds to events where a fragment and an  $\alpha$ particle penetrate the  $\Delta E$  detector but only the  $\alpha$  particle hits the *E* detector. The yield of  $\alpha$ particles is much larger than any other fragment and the maximum energy which they can deposit in the 67- $\mu$ m *E* detector is 10 MeV. The contour plot of  $N \triangle E PWD$  vs  $\triangle E$  shows less structure. The points scatter about a horizontal straight line displaced about 1 standard deviation below the region corresponding to single events, and this small displacement is probably due to chance coincidences with  $\alpha$  particles.

In view of the above considerations only events which deposited more than 10 MeV in the E detector were accepted, but the upper energy limit of 60 MeV corresponding to the E single-channel analyzer [ESCA] was kept. Time-of-flight limits of 10.6 < T < 27 nsec were imposed. From Fig. 4 it can be shown that this time-of-flight requirement is redundant with the E requirement for the heaviest isotopes of Be through N. These E and T windows selected out 60% of the events.

# F. Final data displays

A rescaling of the mass and charge values was carried out for each tape before summing all data tapes. The experimental values of the masses of <sup>9</sup>Be and <sup>13</sup>C and the experimental values of the nuclear charges of isotopes of Be and C were determined for the first 10% of the events on each tape. A slight transformation of the charge and mass scales was then determined which caused these values to fall at predetermined values. This rescaling amounted to a small fraction of the intrinsic charge and mass resolution. At this time a tape containing 3% of the data was discarded because of poor resolution. Finally all data were summed into a two-parameter histogram of yield vs nuclear charge and mass number (see Fig. 11). Plotted in this figure are the 4.1 million events which survived all the selection criteria. Although this representation is complete, the iso-



FIG. 11. Contour plot of nuclear charge (Z) vs mass number (A) constructed from all of the data. The solid points indicate the positions of the peaks. For the weak peaks the positions of the points are based on extrapolations from the clearly resolved peaks. The lowest contour is at the 3-count level and there are two logarithmically spaced contour levels per decade.

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topes will be more easily discernible when mass histograms are constructed for each element.

There are two kinds of tailing in Fig. 11. One is a tailing to low mass, evident for Be and B. This is due to a dead time in the  $E_{rej}$  circuitry which failed to eliminate all particules which passed through the active area of the E detector. Thus, some long-range particles were recorded which deposited only part of their energy in the Edetector. Since mass is calculated as  $Et^2$ , these events always tail to low mass and can be seen again in Figs. 13(b) and 13(c). The second kind of tailing, a tailing to low-Z values, is a less obvious but more serious effect. It is noticeable in Fig. 11 but more clearly seen in Figs. 6(b) and 12, and is the cause of a small but discernible background trailing from one element ridge to the one lower. The origin of this tailing must come from a tailing in the  $\Delta E$  signal because an error in the determination of E would influence the mass as well as the charge. The possibility of slow charge collection was eliminated because of a lack of correlation of this effect with the  $\triangle E$ PWD signal. Thin spots in the detector or channeling are other possible explanations. Since this low-Z tailing was observed with several different detectors, the



FIG. 12. Graph showing the determination of the extent of tailing to Z-1 in the nuclear charge spectrum. The abscissa has been normalized to Be (Z=4) and the <sup>13</sup>B data have been normalized to the <sup>10</sup>Be data in intensity. The average of the smooth curves drawn through the <sup>10</sup>Be and <sup>13</sup>B data points was used to calculate the predicted shape of the <sup>16</sup>C curve, and it was normalized to the <sup>16</sup>C data for comparison.

explanation based on channeling is most likely.<sup>30</sup>

In order to construct mass histograms for each element from which relative yields could be estimated it was necessary to subtract this low-Ztailing. Its shape was determined for those Avalues where a nuclide is known to be particleunstable. Figure 12 shows the charge distributions for mass cuts at masses 10, 13, and 16. The charge coordinate has been normalized to Be by scaling according to the FWHM of the peaks. In addition, the mass cut for A = 13 was normalized to A = 10 in intensity to compare directly the shapes for two different cases. Since both <sup>10</sup>Li and <sup>13</sup>Be are known to be particle-unstable, these plots give directly the shape of the low-Z tailing. The agreement between the two cases is sufficiently good that the average was used for the subtraction by normalizing at  $+\frac{1}{2}Z$ . It amounted to a tailing at one Z lower of 0.3% for Be. 0.6%for B, 1.2% for C, and 1.4% for N. Applying these corrections which were accurate to about 10%, mass histograms for Li through N were constructed and are illustrated in Figs. 13(a)-13(e). For the C and N data the mass resolution was marginal and therefore tighter windows of only 12 to 34 MeV for E and 11.1 to 23.2 nsec for Twere used.

## **IV. RESULTS**

The mass-yield histograms [Figs. 13(a)-13(e)] show the existence of all previously known particlestable nuclei in this region except for <sup>9</sup>C. In addition, two new nuclei, <sup>14</sup>Be and <sup>17</sup>B, are clearly observed and the stability of <sup>19</sup>C can be confirmed. Several criteria were considered to verify the existence of <sup>14</sup>Be and <sup>17</sup>B. In the numerical output, from which Fig. 11 was constructed, there is a two-dimensional island at the proper place for each nuclide before any tailing subtraction was performed. The net number of events in Figs. 13(b) and 13(c) included in the <sup>14</sup>Be and <sup>17</sup>B peaks are 150 and 50, respectively, clearly above statistical uncertainties where the tailing corrections for these nuclei were 60 and 35 counts. respectively. Both the positions and widths of the peaks are correct for the assignments to <sup>14</sup>Be and <sup>17</sup>B. Furthermore, although the many windows ap-

TABLE IV. Yield ratios A/(A-2) and production cross sections.

$^{A}Z$	Yield ratio	σ(μb)
<sup>14</sup> Be	1/225	≈10
<sup>17</sup> B	1/100	≈5
<sup>18</sup> C	1/20	≈100
<sup>19</sup> C	1/60	≈5

plied to the data imply stringent conditions, it must be verified that the parameters are reasonably distributed within these windows. Thus, all five of the individual experimental parameters were examined for the new isotopes, as shown in Fig. 14. Those for <sup>14</sup>Be are distributed in a manner similar to those for <sup>12</sup>Be and those for <sup>17</sup>B are similar to <sup>15</sup>B. An examination of the tagged pulser events showed that there was no pileup on the pulser down to a level of  $10^{-4}$  and thus pileup onto a simulated <sup>14</sup>C event does not give rise to any spurious peaks.

The products of the breakup of a metastable nucleus can give rise to spurious peaks of a lower-Z isotope in a particle identifier. For example, <sup>8</sup>Be  $\rightarrow 2\alpha$  identifies as <sup>7</sup>Li.<sup>31</sup> Our apparatus, which combines particle identification, time of flight, and pulse-width discrimination, is hardly sensitive to this effect. In order for two fragments to be improperly identified as one, both of the fragments from the breakup must enter the small solid angle of the telescope and, in addition, pass through each of the detectors simultaneously. Thus, the center-of-mass motion of the two fragments must be small, both perpendicular and parallel to the detector-telescope axis. It can be shown that these requirements set an upper limit of about 10 keV on the Q value for the breakup reaction. The existence of such metastable states is improbable.

Although, in general, relative yields cannot be taken as relative cross sections because of the



FIG. 13. Mass yield spectrum for lithium, beryllium, boron, carbon, and nitrogen isotopes. Both zero- and 1-count levels are shown for clarity, and the arrows for the new and missing isotopes point to the expected positions of the peaks based on the positions of the main isotopes.

various experimental discriminations, it was found that for isotopes differing by only two mass numbers, our relative yields at 90° agreed with ratios of the published total production cross sections.<sup>24</sup> For four nuclei for which new cross sections may be estimated, Table IV lists our yield ratios and the corresponding cross sections based on the published values. Other two-mass-number yield ratios (leading to <sup>11</sup>Li, <sup>12</sup>Be, <sup>14</sup>B, and <sup>15</sup>B) are in the range of 1/20 to 1/40. Thus, it appears from the <sup>14</sup>Be, <sup>17</sup>B, and <sup>19</sup>C yields that the massyield curve in this light-element region is getting steeper the further one goes from stability. This is in contrast to the results in the Na and K region.<sup>10</sup> However, the sharp decrease in the <sup>14</sup>Be yield. which crosses the N=8 neutron shell, is consistent with the decrease in yield observed at the N = 20 and 28 shells for the very neutron-rich isotopes of Na and K.<sup>10</sup>

The particle instability of <sup>12</sup>Li and <sup>16</sup>B can be established by their absence in Figs. 13(a) and 13(c). In addition, the mass resolution of neighboring nuclides is consistent with the absence of <sup>12</sup>Li and <sup>16</sup>B. Furthermore, when a mass cut at A = 16 is taken, as shown in Fig. 12, the predicted low-Z tailing from <sup>16</sup>C can explain all events recorded in the <sup>16</sup>B mass region.

The instability of <sup>13</sup>Li is less certain. There are no counts recorded in the peak region of <sup>13</sup>Li, but there is a general background of approximately one event per nuclide in that area of the Z vs A matrix (see Fig. 15). This gives a limit on the <sup>13</sup>Li/<sup>11</sup>Li ratio of about 1/1400. Although this ratio is smaller than the <sup>14</sup>Be/<sup>12</sup>Be ratio by a factor of 6, the <sup>13</sup>Li/<sup>11</sup>Li ratio is expected to be lower because <sup>13</sup>Li is further from  $\beta$  stability. Therefore, from these data it cannot be concluded that <sup>13</sup>Li is particle unstable although the upper limit on the cross section is about 0.2  $\mu$ b.





FIG. 14. Distribution of raw data parameters for (a)  $^{14}$ Be and (b)  $^{17}$ B. The smooth curves for  $^{12}$ Be and  $^{15}$ B have been approximately scaled to match the histograms.

A matrix for the predicted particle-stable nuclei  $^{19}$ B,  $^{20}$ C, and  $^{22}$ N was also undertaken. The actual numbers of counts, before corrections for tailing, are shown in detail in Fig. 15. Four main criteria were applied to the data to determine whether there was sufficient evidence for particle stability. These were:

(1) A two-dimensional island should exist in the Z vs A matrix at the appropriate positions before corrections for tailing.

(2) All experimental data parameters should have the same distributions as known neighboring isotopes.

(3) The net number of events should be 3 times the statistical error.

(4) The yield should be reasonable based on systematics.

Unfortunately, all three candidates failed at least one of the above criteria. It was therefore concluded that there is insufficient evidence in these data to prove the particle stability of <sup>19</sup>B, <sup>20</sup>C, or <sup>22</sup>N. However, the cross section limits for these nuclei can be set at approximately 1  $\mu$ b.

# V. CONCLUSIONS

This experiment has proven the particle stability of <sup>14</sup>Be and <sup>17</sup>B, has shown the instability



FIG. 15. Enlarged sections of several high-mass regions of the two-parameter nuclear charge (Z) vs mass number (A) plot. The numbers represent counts and the areas are shaded for more than 9 counts. The inner enclosed areas show the predicted locations of the indicated high-mass nuclides.



FIG. 16. Low-Z region of the chart of the nuclides. Enclosed in boxes are those nuclei predicted to be particle stable (Ref. 33). Nuclei known to exist are shaded. Nuclei which have been shown experimentally to be unbound with respect to nucleon emission are indicated by an  $\times$ . This figure was constructed in collaboration with J. Cerny.

of <sup>12</sup>Li and <sup>16</sup>B, and has confirmed the existence of <sup>19</sup>C. In addition, production cross sections have been estimated for four nuclides and approximate upper limits have been set for four others. It was found that in this region of elements the production cross sections fell off more steeply than expected as one went to the limits of particle stability. This present extension of our knowledge of the limits of particle stability was made possible by improvements in apparatus and techniques.

The previous negative result<sup>16</sup> for <sup>14</sup>Be was based on a heavy-ion-transfer experiment in which the yield was more than a factor of 10 lower than that expected from systematics. In that work the log of the cross section was plotted vs the Qof the reaction calculated for both products in their ground states, and a linear extrapolation was made from the region of measured cross sections. One must conclude that either the linear systematics or the long extrapolation must be questioned.

At the time of our discovery of <sup>14</sup>Be it was not realized that the new mass<sup>32</sup> of <sup>14</sup>B implied the particle stability<sup>17</sup> of <sup>14</sup>Be using the transverse mass relations of Garvey and Kelson. In retrospect, the surprising fact is the mass of <sup>14</sup>B which was 1 MeV lower than that predicted by these mass relations. A recalculation of the mass table taking into account the recent experimental masses of both <sup>11</sup>Li <sup>11</sup> and <sup>14</sup>B<sup>32</sup> has been prepared.<sup>33</sup> <sup>14</sup>Be is predicted to be bound by 0.4 MeV and <sup>17</sup>B by 0.5 MeV. <sup>12</sup>Li, <sup>13</sup>Li, and <sup>16</sup>B are predicted to be unbound by 3.9, 4.5, and 1.1 MeV, respectively. In fact, <sup>19</sup>C is now predicted to be marginally bound and the only known particle-stable nucleus still predicted unbound is <sup>32</sup>Na. A recent summary of the situation has been given by Thibault.<sup>34</sup>

In order to graphically display the present situation and the future prospects, Fig. 16 has been constructed using the most recent mass predictions.<sup>33</sup> The lightest undiscovered isotope on the neutron-excess side of stability is predicted to be <sup>19</sup>B and on the neutron-deficient side it is <sup>20</sup>Mg. Of the heavier elements on the neutron-excess side, only oxygen and sodium may be at the limits of particle stability. However, these predictions are based on the Garvey-Kelson relations, and naturally, must be verified experimentally.

#### ACKNOWLEDGMENTS

We wish particularly to thank Richard Epply for writing the data acquisition program, Don Landis for designing the fast electronics, Fred Goulding for contributing many valuable suggestions, and Jack Walton for fabricating the detectors. Catherine Thibault and Robert Klapisch are to be thanked for discussions which stimulated the experiment, and Nick Jelley for carefully reading the manuscript. The encouragement of Earl K. Hyde and the cooperation of the Bevatron staff are also greatly appreciated.

# APPENDIX A. PULSE-WIDTH DISCRIMINATION THEORY

The principle of our pulse-width discriminator is to measure the width of each shaped detector pulse from leading edge to crossover. A block diagram of the apparatus with illustrative wave forms is given in Fig. 17. Wave forms 1, 2, and 3 represent an unperturbed event and events perturbed by a small pulse coming early and late. respectively. The time delay between the main and perturbing pulses is large compared to the intrinsic resolution of the instrument. The wave forms illustrate an asymmetry in the operation of the PWD in this time region: a small perturbing pulse coming early alters greatly the time of the leading-edge discriminator while the crossover time signal is affected to the same extent for both early and late perturbing pulses. Thus, it appears that this apparatus is more effective in detecting the presence of small perturbing pulses coming early than coming late. However, in order to determine the pulse-pair resolution it is necessary to describe the response to two pulses which come at nearly the same time and not widely separated, and easily rejected in any case, as illustrated in Fig. 17. It will be shown that this pulse-pair resolution is proportional to the spread in the charge-deposition profile relative to that of a single event and is not sensitive to the time order of the two events. Thus, although a leadingedge-to-crossover discriminator is equally effective for small pulses coming early or late, a leading-edge-to-trailing-edge discriminator would be more effective, but not as dramatically as one would believe based on the long time scale arguments.



FIG. 17. Pulse-width-discriminator block diagram. Wave forms labeled "Good" are from a single event. Wave forms labeled "Bad" illustrate two ions passing through the detector separated by about one rise time.

Suppose that two ions impinge on the detector at times  $t_1$  and  $t_2$ . For what values of  $t_2 - t_1$  will the PWD output differ significantly from the output produced by a single event? For a single event which impinges on the detector at time  $t_0$  we assume that the unipolar output rises like a power of time, at least until the discriminator level is reached:

$$V = Ht^{q}, \tag{A1}$$

where V is the output voltage; H is a factor proportional to the amplitude, E or  $\Delta E$ , of the pulse; t is the time; and q is a dimensionless number characteristic of the electronics. We assume that timing variations due to the crossover trigger may be neglected since the velocity of the crossover is large compared to the velocity at the leading edge.

If two ions strike the detector at times  $t_1$  and  $t_2$  having relative amplitudes  $H_1$  and  $H_2$ , the unipolar output voltage will then be

$$V = H_1(t - t_1)^q + H_2(t - t_2)^q.$$
 (A2)

Since we are interested in events of a unique amplitude we set

$$H_1 + H_2 = H \tag{A3}$$

and, for convenience, we define the zero of time by

$$H_1 t_1 + H_2 t_2 = 0. (A4)$$

Thus, the crossover discriminator will trigger as if the pulse resulted from a single event. Let wbe the level of the leading-edge discriminator and y and y' be the times at which it will fire for single and double events:

$$w = Hy^{a} \tag{A5}$$

and

$$w = H_1(y' - t_1)^a + H_2(y' - t_2)^a .$$
 (A6)

Equation (A6) which defines y' may be expanded in a Taylor series assuming  $t_1$ ,  $t_2 \ll y'$ . When the resulting equation is truncated and combined with (A5) the solution is

$$y - y' = \frac{q - 1}{2y} \left( \frac{H_1}{H} t_1^2 + \frac{H_2}{H} t_2^2 \right).$$
 (A7)

The quantity in brackets is the mean square time spread of the charge deposition. We determined the width of the acceptance window  $\Delta t$  by the points on the single event peak at one quarter of its maximum amplitude. To obtain the pulse-pair resolution of the PWD defined by 50% rejection of two nearly overlapping signals we set

$$y - y' = \Delta t/2 \tag{A8}$$

and solve the resulting equation for  $t_2 - t_1$ :

$$t_2 - t_1 = \left(\frac{H}{H_1} \frac{H}{H_2} \frac{y \Delta t}{q - 1}\right)^{1/2}$$
 (A9)

From the structure of this equation we see that the pulse-pair resolution depends on the amplitude ratio of the two pulses which are piled up. The apparatus has the best resolution when the two pulses have equal amplitude, but if one pulse is 10 times smaller than the other the resolution is worse only by the factor 1.7. Of course, if the amplitude ratio is very large, the assumption that the small pulse is rising as  $t^{q}$  will no longer hold. We now discuss the determination of q and y, and the related problem of the walk of the PWD output with amplitude.

Since the crossover timing is independent of amplitude, the amplitude dependence of the PWD output is given by relation (A5), which may be solved to yield

$$y = \left(\frac{w}{H}\right)^{1/q}.$$
 (A10)

As described in Sec. IIID scatter plots of y vs  $\mathcal{E}^{-1/q}$  were made from the data for various values of q. It was found that a linear relationship was obtained for q=3. An integral value of q for the initial rise of the pulse would be predicted if the detector-preamplifier-amplifier circuit is describable in terms of multiple *RC* integrators. The value of y was read off the straight line and the pulse-pair resolution was then calculated for equal amplitude pulses. Table V summarizes these results.

# APPENDIX B. DETERMINATION OF $\Delta E$ DETECTOR THICKNESS UNIFORMITY

A 1-mm<sup>2</sup> <sup>241</sup>Am  $\alpha$  source (5.48 MeV) was placed 2.5 cm from a  $4-\times 6$ -mm Si(P) detector. The wafers to be tested were placed as absorbers between the  $\alpha$  source and the detector. Two  $\alpha$ energy spectra were recorded for each wafer, one with the wafer near the source and the other with the wafer near the detector. The former geometry illuminates only a small central spot of the wafer and the latter illuminates a  $4 - \times 6$ -mm area. If we assume that the thickness inhomogeneity of the small spot is negligible, then a comparison of the linewidths in the two geometries gives the inhomogeneity of the wafer. Range-energy relations were used to deduce the wafer thickness from the energy of the transmitted  $\alpha$  particles and to relate the change in linewidth to the thickness inhomogeneity. The FWHM variation in detector thickness is given by

$$\Delta x = (W_2^2 - W_1^2)^{1/2} / (dE/dx) ,$$

TABLE V. Pulse-pair resolution of the pulse-width discriminators.

		Value		
	Symbol	$\Delta E$	Ε	
Acceptance window (psec)	$\Delta t$	200	90	
Discriminator level (MeV)	w	0.3	0.4	
Power of time	q	3	3	
Trigger time	У	1.5	1.4	
(nsec)		(14 MeV)	(20 MeV)	
Pulse-pair resolving time (psec)	$t_2 - t_1$	770	500	

where dE/dx is the specific energy loss at the degraded  $\alpha$  energy and  $W_2$  and  $W_1$  are the  $\alpha$  linewidths (FWHM) in the two geometries. The detector used in this experiment, which had a thickness of 24  $\mu$ m, had a  $\Delta x$  of 1.0  $\mu$ m.

# APPENDIX C. MASS DEPENDENCE OF PI

When c = 0 our PI algorithm [Eq. (8) of Sec. III C] reduces to the square root of the algorithm first introduced by Goulding and Landis, and has the value

$$PI \propto [x/a(Z,A)]^{1/2}$$
. (C1)

The quantity x is the  $\Delta E$  detector thickness and a(Z, A) is the constant entering in the approximate range-energy relation

$$R = a(Z, A)E^b.$$
 (C2)

Since the specific energy loss depends only on the nuclear charge Z and the velocity of the ion v we can write

$$\frac{dE}{dx} = f(Z, v) . \tag{C3}$$

Expression (C2) may be differentiated to obtain

$$\frac{dE}{dx} = \frac{1}{abE^{b-1}} , \qquad (C4)$$

which when combined with (C3) yields

$$a \propto A^{-(b-1)}.$$
 (C5)

By substituting this into (C1) we expect the expression

$$PI/A^{(b-1)/2}$$
 (C6)

to be approximately independent of mass and to be a function of nuclear charge only. From the Bethe-Bloch expression for dE/dx one expects that (C6) will be linearly proportional to nuclear charge. Inspection of Fig. 6(b) shows this to be approximately true.

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