TABLE III. Minimum half-lives for the five transitions associated with the single matrix elements.

$2T$	$2A$	$3A$	$3P$	$3S$
$3.5\cdot10^5$ yr.	$3.5\cdot10^5$ yr.	$1.0\cdot10^{10}$ yr.	$4.1\cdot10^9$ yr.	$4.1\cdot10^9$ yr.

are associated with single matrix elements, the appropriate τ_0 being used in each case. It is seen from Table III that the minimum half-lives for $3A$, $3P$, and $3S$ are much too long to be reconciled with the observed half-life; these three transitions must therefore be discarded.[11] The minimum half-lives associated with $2T$ and $2A$ *are* consistent with the observed half-life. If we now examine the two remaining transitions, $3T$ and $3V$, which involve two distinct matrix elements apiece, we find that the first matrix element of $3T$ yields a minimum half-life identical with that listed for $3A$, whereas the first matrix element of $3V$ yields a minimum half-life identical with that listed for $3S$. The second matrix element of $3T$ yields a minimum half-life of $3.5\cdot10^6$ yr. (choosing the rather large value of 1/10 for α^2). The second matrix element of $3V$ leads to a minimum half-life three times shorter. Both of these latter half-lives are consistent with the observed half-life if we are willing to stretch the numbers somewhat (for W_0, ρ, etc.). It is clear that the cross-terms in both $3T$ and $3V$ yield minimum half-lives which are much too long.

We may therefore conclude that the observed half-life of Be^{10} requires the rejection of *all* matrix elements[11] except the four ($Q_3(\beta\sigma, r)$, $Q_3(\sigma, r)$, $Q_3(\beta\alpha, r)$, $Q_3(\alpha, r)$) which are associated with the energy spectrum given by D_2. Of these four, three ($2T$, $2A$, $3T$) are Gamow-Teller-type interactions, and one ($3V$) is a Fermi-type interaction. The D_2 spectrum is so different from the allowed spectrum that a careful measurement of the beta-spectrum from Be^{10} should be decisive for present-day theories of beta-decay. If the spectrum turns out to be allowed, as seems to be indicated by a preliminary measurement,[1] it will follow that present theories of beta-decay will have to undergo serious modification.

The author is indebted to Messrs. Albert Simon and Clayton Black for assistance with the numerical calculations.

[11] There is one loophole in this argument: *if* the half-life of the neutron is 30 minutes and *if* α^2 for the $Be^{10}\rightarrow B^{10}$ transition is as much as 1/10, the minimum half-life for the $3P$ transition would turn out to be $2.8\cdot10^6$ yr., consistent with the observed half-life. Other beta-ray evidence does not lend support to the pseudoscalar interaction (E. P. Wigner, private communication). However, even accepting this possibility, the predicted spectrum would be very different from the allowed spectrum (see curve D_4 in Fig. 1), and the measurement of the beta-spectrum from Be^{10} would still provide a crucial test of beta-theory. It is interesting to note that above $W=1.6$, D_4 and D_2 have roughly the same shape.

PHYSICAL REVIEW VOLUME 75, NUMBER 3 FEBRUARY 1, 1949

The Beta-Spectrum of Be^{10}

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(Received December 14, 1948)

RECENT investigations have thrown much light on the disintegration of Be^{10}, long an outstanding problem of nuclear structure and beta-theory. The accompanying paper of Marshak reviews the recent evidence and points out that, while the large spin change involved in the disintegration explains the long half-life, it also predicts a surprisingly unique spectrum shape. Because of the resulting importance of the experimental Be^{10} spectrum to beta-theory, it is desirable to report some results already obtained on the spectrum using an absorption method.

Measurements[1] made since the activity was first isolated by McMillan and Ruben[2] in 1940

[1] J. Levinger and E. Meiners, Phys. Rev. **71**, 586 (1947); D. J. Hughes, C. Eggler, and C. M. Huddleston, Phys. Rev. **71**, 269 (1947); A. K. Pierce and F. W. Brown, III, Phys. Rev. **70**, 779 (1946); E. M. McMillan, Phys. Rev. **72**, 591 (1947).

[2] E. M. McMillan and S. Ruben, Phys. Rev. **70**, 123 (1946).

have fixed the disintegration constants of Be^{10} quite well, even though it has been impossible to prepare sources of high specific activity. A consideration of all the experimental data leads to the following results:

$T_{\frac{1}{2}} = (2.7 \pm 0.4) \times 10^6$ years,
beta-energy $= 570 \pm 10$ kev,
no gamma.

The half-life is based on the values of McMillan and of Hughes, Eggler, and Huddleston which were obtained by independent methods and which agreed closely. The beta-end-point energy is the result of recent work of our own designed to eliminate errors in the absorption method as usually applied. If the maximum range is estimated by locating the intersection of the beta-portion of the absorption curve with the "tail" of the curve (caused by counter background, bremsstrahlung, or hard radiation), it is clear that, because the beta-curve approaches the tail asymptotically, the apparent end point will be less than the true maximum beta-range by an amount depending on the strength of the sample used. In fact, it is quite certain that this method will always result in a serious underestimate, for a simple analysis (similar to that given later—see Eq. (1)) shows that the beta-curve will approach zero as the fourth power of the residual range and hence will be impossible to measure near the maximum range. The Feather method, designed to circumvent the difficulty just described, is unsafe to apply to weak samples because the end point obtained will depend on the shape of the absorption curve which in turn will depend on the spectrum shape. In addition, the method gives end points relative to RaE, which was estimated visually and hence certainly underestimated. In order to obtain the Be^{10} end point with the weak samples available, the absorption curve was extrapolated to the end point by comparison with an accurately determined W^{185} absorption curve near the end point. The end-point energy of W^{185} has been carefully measured by Saxon, and it was possible to obtain samples of extremely high specific activity for its absorption curve. The shape of the W^{185} curve near its end point corresponds closely to the fourth power of the residual range, and a plot of the fourth root of the counting rate against absorber thickness proved to be a simple linear extrapolation to the end point. In order to elimi-

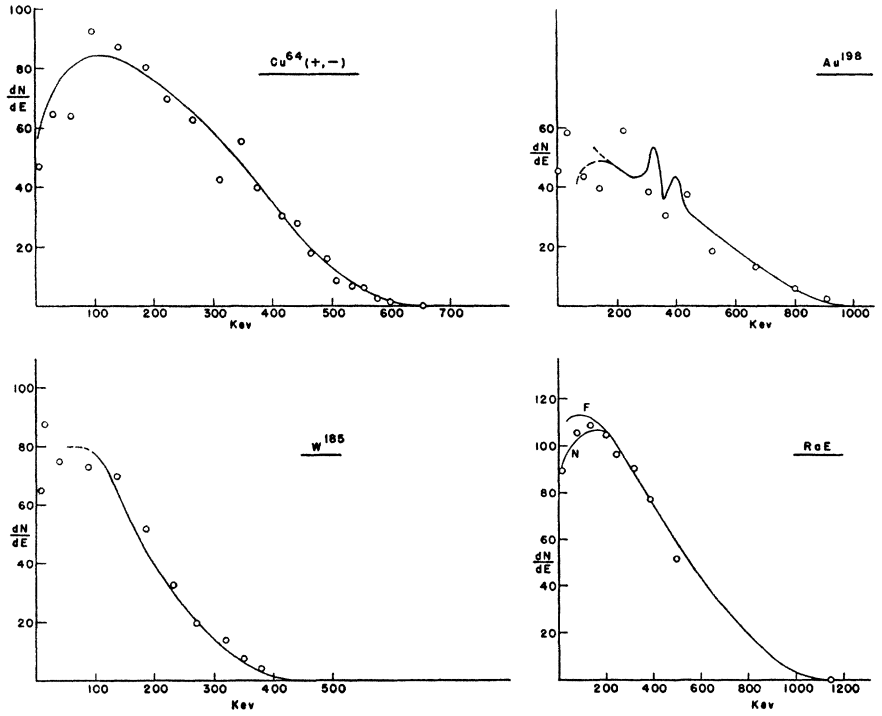

FIG. 1. Comparison of spectrum shapes given by the absorption method with spectrometer results.

nate any error in the usual beta-range-energy curves (which correspond to Feather ranges generally) a small part of the curve was established carefully using the range-energy results for W^{185} and similar data obtained for RaE. Although some of the early measurements had indicated the presence of a gamma in the disintegration of Be^{10}, more detailed work showed that the gamma was caused by impurities. In order to investigate the matter as carefully as possible, we have recently made measurements with various counter fillings, lead radiators, etc., to show the presence of gammas of different energies. The results show that there is much less than one gamma per disintegration for any gamma-energy above about 5 kev.

As it was clear that Be^{10} of high specific activity would not be available for some time, investigations were begun[3] to ascertain whether significant information on the spectrum shape could be obtained with weak samples. The method chosen was a comparison of the shape of the Be^{10} spectrum with the spectra of various "standards" possessing well-known spectrum shapes. The comparison was made both by means of the shape of the beta-absorption curve and of the beta-momentum distribution in a cloud chamber. In effect, the use of well-known comparison spectra serves to eliminate the many corrections that would be necessary if one were to attempt the absolute determination of the spectrum from the absorption curve or from the cloud-chamber momentum distribution. At the present time it is desired to consider only the possibility of the spectrum shapes calculated by Marshak, and for this purpose only the absorption method will be used.

If the law of absorption of initially monoenergetic electrons in a given counter geometry were known, then it would be a simple matter to calculate the beta-spectrum from an accurate absorption curve. As an example of monoenergetic electron absorption, the curve for In^{115} conversion electrons (300 kev) was first measured in the standard counter geometry (foil about $\frac{1}{2}''$ from a mica end-window counter) and was found to be approximately linear. If it is assumed that

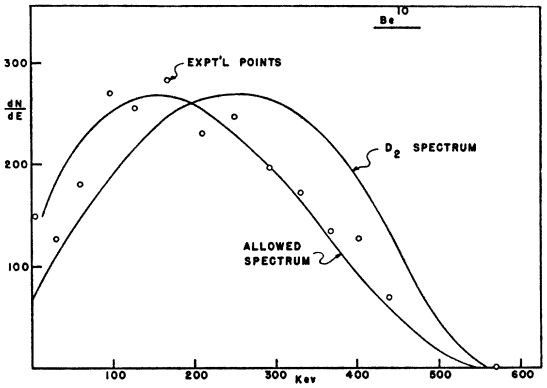

FIG. 2. The experimental Be^{10} spectrum and the calculated allowed and forbidden spectra.

monoenergetic electrons are absorbed in a strictly linear manner, then the beta-spectrum (dN/dE) follows from the absorption curve directly:

$$(dN/dE) = R(d^2I/dR^2)(dR/dE). \qquad (1)$$

Here I is the counting rate at absorber thickness R, and E is the electron energy corresponding to the range R. For values of R near the end point, it follows from Eq. (1) and from the beta-distribution that I will vary as the fourth power of the residual range. A spectrum obtained from an absorption curve by use of Eq. (1) would be expected to show some distortion because of the

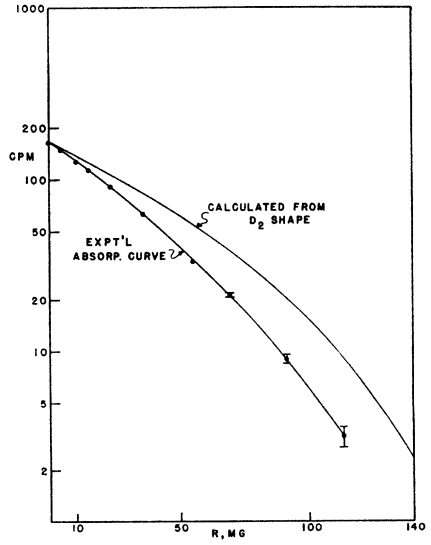

FIG. 3. Initial portions of the experimental absorption curve and the curve to be expected from the D_2 spectrum of Marshak.

[3] Some of the early results were reported at the 1948 Washington meeting of the Physical Society, Phys. Rev. 74, 1239 (1948).

known departure of actual electron absorption from linearity.

Careful absorption curves were run for a series of spectra, and the spectrum shapes were calculated from Eq. (1). The resulting shapes all differed from the known true shapes in the same manner, that is, in each case the most probable energy ("maximum" of the curve) was about 100 kev higher than for the true shape, although the end-point energy was correct. This shift was in the direction to be expected from the linear assumption, for the In^{115} curves had shown a slower than linear initial absorption which results in a depletion of the low energies when Eq. (1) is used. It was decided from these results that a simple method, and one of sufficient accuracy for obtaining an approximate beta-spectrum, would be to obtain a spectrum by use of Eq. (1) then shift the points by 100 kev (the value appropriate for an end point of 600 kev; the "shift" increases slowly with end-point energy). This method was tried for the standard spectra, using Eq. (1) and making the correction for nonlinearity by the simple shift, with the results shown in Fig. 1. The solid curves of Fig. 1 are the known[4] spectrum shapes, and the points are the results of the present analysis. The rather large scatter of the points is caused by the statistical error of the original data, but, within this error, the results of the method seem to compare quite well with the actual spectra.

As the absorption method in the simple form described gave consistent results, it was then applied to Be^{10}. Because of the weakness of the samples available it was difficult to obtain statistical accuracy, but an accurate absorption curve was finally obtained for which many of the points required several days counting apiece. Application of the standard method to the absorption curve then gave the spectrum shown in Fig. 2. On Fig. 2 there also appears the allowed spectrum for Be^{10} and the D_2 spectrum calculated by Marshak (see his paper for details). It seems quite definite that the experimental spectrum given by this method is in disagreement with the D_2 shape, and, in fact, in agreement with the allowed spectrum within experimental error. It is very difficult, of course, to fix the error of the present method quantitatively, and it is only because the D_2 shape is so unusual that a definite conclusion can be reached. As discussed by Marshak, there is a possibility that the D_4 shape could be consistent with the Be^{10} half-life. However, the D_4 does not differ from the allowed shape by a large enough amount so that it can be conclusively ruled out by the present measurements.

At the suggestion of Marshak the absorption curve to be expected from the D_2 shape was calculated by reversing the method. The calculated absorption curve for D_2 is given in Fig. 3 as well as the initial portion of the experimental Be^{10} absorption curve. The curves show again that the difference between D_2 and the allowed shape is much greater than the experimental errors of the absorption curve. We are continuing the cloud-chamber measurement of the spectrum which is in substantial agreement with the absorption work and at the same time are preparing material which will be of sufficient activity to be used in a spectrograph. We wish to express our thanks to D. Sherman and E. Hupke who have helped in some of the exceedingly tedious phases of this work.

[4] The curves are from the following sources: W^{185}, D. Saxon, private communication; Cu^{64}, C. S. Cook and L. M. Langer, Phys. Rev. **73**, 601 (1948); Au^{198}, D. Saxon, Phys. Rev. **73**, 811 (1948); RaE, Flammersfeld (F) and Neary (N) from data quoted by Konopinski, Rev. Mod. Phys. **15**, 229 (1943).