0− to 0+ Beta Transition $Pr^{144} \rightarrow Nd^{144}$*

FRED T. PORTER AND PAUL P. DAY
Argonne National Laboratory, Lemont, Illinois
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The Argonne double lens beta spectrometer and associated coincidence circuit have been used to observe the beta transitions of Pr^{144}. The validity of the spin and parity assignment, 0− to Pr^{144} is supported by a measurement of the shape of the $(1.2\pm0.1)\%$ abundant 2.3-Mev beta transition, observed in coincidence with the 697-kev gamma ray. Its shape is that of the unique ($\Delta I=2$, yes) first forbidden transition expected if the transition goes from 0− Pr^{144} to the 2+ first excited state of even-even Nd^{144}. The shape of the $(1.0\pm0.1)\%$ abundant 807 ± 5-kev beta transition to the 2.19-Mev level in Nd^{144} was observed in coincidence with the 1.49 and 2.19-Mev gamma rays. Its allowed shape is consistent with a 0− assignment for Pr^{144}. With this assignment the transition between the ground states is a 0− to 0+ case. The shape of this 2996 ± 3 kev 97.8% abundant transition was obtained from the total spectrum by small subtractions of the inner groups. Its nearly allowed shape is easily explained with a pure axial vector shape factor; in contrast, the tensor-pseudoscalar formalism fails to reproduce the shape. The ratio of axial vector matrix elements $\lambda=(i\int\gamma_5/\int\boldsymbol{\sigma}\cdot\mathbf{r})$ can be determined from the shape; our data give $\lambda=5\pm2$. This is the same absolute magnitude as some theoretical estimates but has the opposite sign. Our experimental results are in good agreement with those of Graham, Geiger, and Eastwood who have already pointed out that this 0− to 0+ transition does not offer a sensitive measure of the relative size of pseudoscalar to axial vector coupling constants although the net relative contribution of the direct pseudoscalar part to the whole AP shape factor must be $\lesssim 1\%$ (with Rose-Osborne formalism).

An incidental result of the present work is that the $H\rho$ of the K conversion line of the 133.5-kev transition following the β decay of Ce^{144} has been measured as 1064.8 ± 0.6 gauss-cm.

I. INTRODUCTION

THE main features of the decay of 17 min Pr^{144} have been known for some time[1–3] (see Fig. 1). The evidence appeared consistent with an assignment of 0− to the Pr^{144} ground state. The intense 3 Mev β transition to the ground state of even-even Nd^{144} is then a 0− to 0+ transition, one in which only the Gamow-Teller and pseudoscalar matrix elements can contribute. The pure tensor[4] interaction predicts a violently nonallowed shape for 0− to 0+ and, in the days when the He^6 β-recoil correlation experiment[5] spoke strongly for tensor as the G.T. part of the beta interaction, this meant that the pseudoscalar interaction certainly had to be included in order to try to explain the nearly allowed shape. This was discussed recently by Zirianova[6] and by Laubitz.[7] It is worth emphasizing that this conclusion does not depend at all on any subtleties of the ground state shape measurements, since the T shape factor increases by 100% from 0.3 to 3 Mev.

Our interest in the problem was stimulated by the obvious lack of agreement between the earlier work[1–3] and the experimental results of Laubitz[7] on the ground-state transition shape and by the observation that axial vector interaction alone could quite easily explain the nearly allowed shape of the ground-state transition in contrast to the forced, if not impossible, TP fitting.[6,7] During the course of our work we learned that a group at Chalk River[8] had been working along the same lines as we, and that their results are in good agreement with ours. Further, the results of the He^6 recoil energy spectrum measurement[9] as well as reappraisals of the β-recoil correlation work have since indicated strongly that the G.T. part of the β-decay interaction is axial vector. The purpose here, then, is first to establish the 0− assignment for Pr^{144} by examining carefully the shape of the 2.3-Mev β spectrum in coincidence with the 697-kev gamma ray (see Fig. 1). Its shape should be the first forbidden unique one ($\Delta I=2$, yes) if the 0− assignment is correct for the Pr^{144}; we find it very close to the unique shape. The 807-kev group, measured

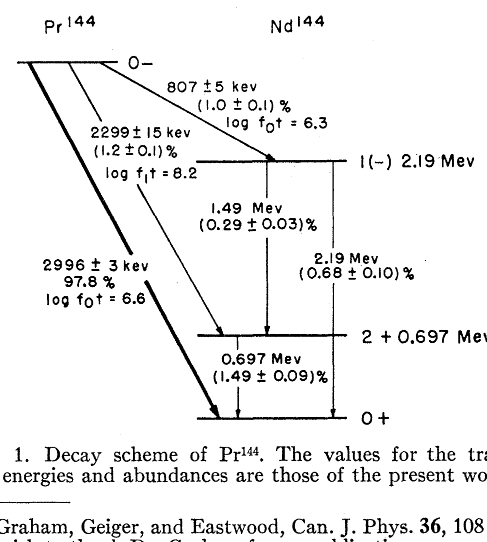

FIG. 1. Decay scheme of Pr^{144}. The values for the transition energies and abundances are those of the present work.

* Based on work performed under the auspices of the U. S. Atomic Energy Commission.

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7 M. J. Laubitz, Proc. Phys. Soc. (London) **A69**, 789 (1956).
8 Graham, Geiger, and Eastwood, Can. J. Phys. **36**, 108 (1958). We wish to thank Dr. Graham for prepublication communication about their results.
9 Herrmannsfeldt, Burman, Stahelin, Allen, and Braid, Phys. Rev. Letters **1**, 61 (1958).

in coincidence with the 1.49- and 2.19-Mev gammas, has the allowed shape also consistent with 0− assignment. Secondly, we examine the transition between the ground states in the light of the 0− assignment.

For a 0− to 0+ transition with axial vector as the G. T. part of the interaction, only two matrix elements $\int\gamma_5$ and $\int\boldsymbol{\sigma}\cdot\mathbf{r}$ can give significant contributions.[4] The abundant ground-state transition derived from the total spectrum by small and insensitive subtractions of the inner groups has been fitted to the theory (assuming no systematic experimental errors); we find the ratio of the matrix elements ($\lambda = i\int\gamma_5/\int\boldsymbol{\sigma}\cdot\mathbf{r}$) $\lambda=5$ with a standard deviation of 2 (on a least squares basis). This one parameter problem gives relatively sharp values in contrast to the usual first forbidden nonunique cases where the flexibility of 2 or 3 parameter fits yields only broad ranges for the parameters.

II. 2.3-MEV GROUP IN COINCIDENCE

A. Circuitry

The operation of the Argonne double lens spectrometer with its coincidence circuitry has been described in some detail before.[10] Also its scattering properties and performance with somewhat lower energy spectra than those in Pr^{144} can be seen as given by Porter *et al.*[11] We have extended considerably the investigations of the scattering in the spectrometer and some of these details will be discussed in the section on the ground-state transition. As far as the coincidence circuitry is concerned, only one change should be noted, namely, that the "fast" coincidence circuit in the fast-slow arrangement now is similar to that of Bell, Graham, and Petch[12] with 404 A limiter stages whose outputs are delay-line shaped and detected with a biased G7A diode. With 40 mμsec shaping time we obtain a measured 2τ value of ~70 mμsec. This conservative value keeps the measured over-all coincidence effciency high.

The method for the measurement of the coincidence efficiency deserves one comment in addition to the description given in reference 10. This method assumes that for a fixed gamma input the efficiency depends solely on the beta pulse height. This is not exactly true because the transit time of the beta particle in the spectrometer varies with energy. Thus 10-volt pulses (in the slow analyzer) produced by 30-kev electrons and 10-volt pulses produced by backscattered 1-Mev electrons do not have the same delay curve. The shift in this example is some 3 mμsec (for a one meter path length), a value small compared to the full width of the curve in the present experiments.

B. Gamma Detector

The gamma detector consisted of a $2\frac{1}{2}$-inch diameter by $2\frac{1}{8}$ inch high cylindrical NaI(Tl) crystal, a Lucite light pipe (28-inch $\times 2\frac{1}{2}$-inch diameter), and a Du Mont 6363 phototube, all enclosed in a brass tube $3\frac{1}{4}$-inch o.d. with $\frac{1}{8}$-inch wall thickness. Pulse-height measurements with and without the light pipe showed that it transmitted 0.4 of the crystal output. Wrapping with shiny Al foil was better than no wrapping. The whole assembly is introduced into the spectrometer with sliding O-ring seals so that the position of the crystal relative to the source can be adjusted. The vacuum seal is 0.030-inch Cu sheet soldered on the crystal end of the brass tube. This formed part of the absorber "sandwich" which is necessary for this experiment. Since Pr^{144} is conveniently studied with equilibrium sources of its parent 284 day Ce^{144} the lower energy γ radiation (principally the 134-kev gamma) of Ce^{144} was attenuated to prevent overburdening the gamma channels with low amplitude pulses. The absorber, consisting of 3.25-inch diameter disks clipped to the end of the counter tube, had on the source side 1.1 g/cm^2 of Be to stop most of the beta's and then a Pb-Cd-Cu "sandwich" in that order. The net effect of the whole absorber is to reduce the 134 kev γ by a factor 0.007 and the 700 kev γ by 0.74.

To maximize the solid angle, the gamma detector should be as close to the source as possible without introducing any scattering distortions. Since the source is mounted independently of the gamma detector the scattering effect of the gamma detector can be measured easily by focusing a particular energy (most sensitively the lowest energy of interest in the spectrum) and moving the detector in steps toward the source from a fully retracted position. At 800 kev, the lowest energy of interest for the 2.3-Mev group, the distance between the beryllium disk and the source was reduced to $\frac{1}{8}$ inch where about 0.25% increase in the rate was noticed. One quarter inch showed no effect and that was the spacing for the experiment.[13]

C. Source Preparation

Old fission product Ce^{144} (Oak Ridge batch 50) was cleaned from inert solids by hexone extraction.[14] Careful surveys of the gamma spectrum and conversion electron spectrum failed to show any impurities. In particular Ce^{141} was present <5 in 10^{-3}. The possibility of Sr^{90}-Y^{90} contaminant was checked radiochemically to be less than 1 in 10^4 of the decays.

An aliquot of the source material was dried on a Pt disk, weighed, and counted, giving ~80 μg/millicurie.

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[10] Porter, Freedman, Novey, and Wagner, Phys. Rev. **103**, 921 (1956); see also Argonne National Laboratory Report ANL-5525 (unpublished).

[11] Porter, Wagner, and Freedman, Phys. Rev. **107**, 135 (1957).

[12] Bell, Graham, and Petch, Can. J. Phys. **30**, 35 (1952).

[13] Using Be is definitely worthwhile. Even such a low Z material as Lucite shows distortions sooner than Be. For example at the more sensitive energy of 300 kev on a 3-Mev spectrum Be at $\frac{1}{2}$ inch shows 0.8% increase while Lucite shows about 1.8%.

[14] Glendenin, Flynn, Buchanan, and Steinberg, Anal. Chem. **27**, 59 (1955).

This was done in order to have a firmer idea of the specific activity. All samples used in the present work were prepared by volatilization (sublimation) from hot Pt or W filaments[15] in vacuum onto 200 $\mu g/cm^2$ Al foil. Appropriate masks defined the size of the source. For the coincidence work a $\frac{1}{4}$-in. diameter source of 7×10^7 disintegrations/min (Ce+Pr) was used. This was visible as a haze on the Al backing and was probably, on the basis of the specific activity of the source material, $\leq 50\ \mu g/cm^2$. Small source holder rings ($\frac{3}{4}$-in diameter) and their supports have been shown to be a source of scattering (3% effects on a 3-Mev spectrum) in the large transmission mode of operation of the spectrometer. Therefore the $\frac{3}{4}$-inch diameter 200 $\mu g/cm^2$ Al foil was in turn glued onto a 4-inch diameter Mylar foil (900 $\mu g/cm^2$, aluminized on both sides) in which a $\frac{5}{8}$-inch hole had been punched. The large foil is supported on a thin Al ring of 4-inch diameter. Electrical resistance from outside ring to Al foil was <10 000 ohms.

D. Experimental Procedure and Treatment of Data

We give here a recitation of some of the pertinent details of the experiment. One of the important points in a measurement of this type is that the gamma channel accept the same part of the gamma spectrum at all times, in this case the 697-kev photopeak. Besides fluctuations in the electronic gain, two other effects are important. First of these is the gain change in the photomultiplier due to the changing magnetic field during the survey of the spectrum. Mu-metal shielding reduced this to 1.3% gain decrease in going from 0.8 to 2.3 Mev. A much more important effect is the increase in the gamma count due to the increase in bremsstrahlung as more betas are pulled toward the gamma counter on the axis of the spectrometer with increasing field (about 3% increase in the G channel count as the β energy focused is varied from 0.8 to 2.3 Mev). It should be pointed out that even without the complication of the "variable bremsstrahlung" effect just mentioned, there is some danger in using the usual method of normalizing with the gamma count because the real coincidences/gamma count is not a very flat function of gamma channel setting (the 697-kev photopeak is sitting on the Compton distributions of the 1.49 and 2.19 gammas, which are not in coincidence with the 2.3-Mev β group). A study of the real coincident rate as a function of gamma channel setting showed that analyzed gamma gain must be constant to ~5% to keep the real rate constant to 1%. Now, with the channel width extending from 575 to 825 kev (spanning the base width of the 697-kev photopeak) the analyzed gamma counting rate was a monotonic function of the gain such that 1% gain change results in 3% change in counting rate. Thus the procedure was to check that each analyzed gamma count met within limits a prescribed value which took into account the "variable bremsstrahlung" effect and small half-life corrections. No analyzed gamma count strayed from the prescribed value by more than ±1.5% so that the variable gain effect on the real rate was less than ~0.2%.

Each point on the spectrum was surveyed eight times during the run, taking every other point with increasing spectrometer current and the alternate points with decreasing current. The total elapsed time of the run was about 50 hours. The resolving time of the fast circuit $2\tau_f$ was monitored every 10 hours by the insertion of 100 mμsec delay in the β side. Before and after the run $2\tau_f$ was measured with independent sources. These values agreed with the delayed values, within statistics, giving $(1.09\pm0.02)\times10^{-9}$ min. Auxiliary experiments showed $2\tau_f$ to be independent of beta energy from 100 kev to 3 Mev. About every 3 hours checks were made on analyzed beta and gamma gains via pulse-height distributions, gamma window width via precision pulser, and the working current of the potentiometer in the spectrometer current control.

The differential coincidence efficiency[10] was determined before and after the run using Zr^{95}-Nb^{95} as a source of coincidences with gammas of approximately the same energy as the 697-kev Pr^{144} gamma. The over-all coincidence efficiency was 99.2% at 800 kev increasing to 99.7% at 2.3 Mev. Uncertainties in over-all efficiencies are ~0.1%. The beta integral discrimination level was 47 kev. No cooling was used on the beta photomultiplier (Du Mont 6292) which viewed the 1-mm thick ×10-mm diameter anthracene crystal through a 1-inch diameter ×30-inch long Lucite light pipe. The beta background was 45 c/m.

The treatment of the data follows the pattern of reference 10 with the exception discussed above, that we did not normalize to unit analyzed gamma count. Slow-chance and dead-time corrections[16] were the order of 0.1%. The beta rate at the peak of the spectrum was 1.1×10^5 counts/min, the analyzed gamma rate 2×10^4 counts/min. The (fast) chance rate at the peak of the spectrum was ~6% of the triple rate, while at 2.14 Mev, the highest energy point, it was 28% of the triple rate. A total of 1400–1700 coincidences were collected on every point.

[15] Filaments were raised to high temperature in vacuum before loading to remove any volatile foreign material and, in the case of W, volatile oxides.

[16] The analysis of dead time effects depends on the particular circuitry of the fast-slow arrangement, gain setting, etc. We would like to point out that fast channel dead time may not be negligible in many experiments although they were here. They arise in the distributed amplifiers or in the limited stages. For these experiments the fast channel effective dead times were 2 μsec. An additional factor $(1+\delta_\gamma g)(1+\delta_\beta b)$ should appear in the dead time correction factor,[10] where δ's are the beta and gamma effective fast channel dead times and g and b are the rates below the respective analyzer windows. The latter restriction is imposed if the slow channel dead times are longer than the fast ones. Finally one should note that in computing slow chance[10] rate the expression should have just τ_s, not $2\tau_s$, if the fast channel dead times are longer than the triple coincidence circuit pulses.

The spectrometer resolution correction was made using the first and second moments of the transmission curve of the spectrometer, derived from the line shape of the 134-kev K conversion line, together with the first and second derivatives of the experimental momentum spectrum, which were obtained graphically. With the transmission at 5% the width at half-height of the line is 6.7%. The corrections are less than 1% for all the points except the four of highest energy, the highest reaching 13% correction.

There are two additional corrections which deserve special mention and they are treated in the following two sections.

E. I.B.—Beta Coincidence Correction

Because the beta groups measured in coincidence are very low intensity transitions, the coincidences between inner-bremsstrahlung (I.B.) photons and betas of the intense 3-Mev transition are not negligible. The ideal way to observe the magnitude of the effect would be to put in place of the Pr^{144} a pure 3-Mev beta emitter. This not being available, the 2.3 Mev pure beta emitter Y^{90} was used. While it is a unique transition, the intensity and angular distribution of I.B. from the forbidden transitions are not markedly different.[17–19] The gamma counter position and absorbers were the same as for Pr^{144} run but the gamma window was lowered from 700 kev to 560 kev so that the I.B. photons in the window per β would be the same (calculated) as for the Pr^{144} case. With a source of $\sim 1.7 \times 10^8$ (Sr+Y) a maximum rate of 1 c/m with chance rate of 2 c/m was observed. The end point of this spectrum in coincidence with I.B. between 455 and 655 kev had an end point of ~ 1.8 Mev as expected (2.3 minus 0.45 Mev). This momentum distribution was expanded in momentum by a factor to take into account the higher end point for the Pr^{144} case and adjusted in magnitude by a factor to take into account the difference in the source strengths of the Pr^{144} and Y^{90}. This adjusted real rate was subtracted point by point from the Pr^{144} data. The correction was $<2\%$ for any point. Another approach would be to calculate the correction. It is judged by us that this relatively crude empirical procedure is more accurate in view of the strong β-I.B. directional anisotropy, and the problem of folding in crystal response curves.

F. β-γ Direction Correlation Correction

A large β-γ directional anisotropy exists between the 2.3-Mev beta group and the 697-kev gamma ray; the fact that it is β energy dependent means large corrections to the spectrum observed in coincidence. Graham *et al.*[8] find about 15% less than a full unique anisotropy, one of the largest β-γ anisotropies ever measured. They do not rule out the possibility that the correlation is full "unique." Therefore in the correction of the coincidence spectrum we assumed first that the maximum anisotropy was "full unique," namely

$$A(E_0) = [W(\pi,E_0) - W(\pi/2,E_0)]/W(\pi/2,E_0) = 1. \quad (1)$$

(E_0 is the end point beta energy) and that the energy dependence is the same as that given by the theory for a spin sequence $(0,-) \rightarrow (2,+) \rightarrow (0,+)$. The problem then is to integrate the correlation function

$$W(\theta,E) = 1 + a_2(E)P_2(\cos\theta), \quad (2)$$

over the solid angle of the detectors with coordinate-dependent weighting factors to take into account the variation in the efficiency over the detector aperture. Here θ is the angle between β and γ directions, E the beta energy, $a_2(E)$ was obtained from Hauser's treatment,[20] and $P_2(\cos\theta)$ is a Legendre polynomial. The beta efficiency was taken as constant over the spectrometer aperture. The gamma detector response was measured with a collimated beam of gamma rays. Since the Pr^{144} 697-kev gamma is of low intensity, Zr^{95}-Nb^{95} (mostly 767 kev, some 722 and 754 kev) and Cs^{137} (660 kev) sources were used. The collimator consisted of three one-inch thick lead plates spaced an inch apart. The holes were 0.055-inch diameter and the source was confined to a small cylinder 0.055 diameter and $\sim\frac{1}{4}$ inch long one inch back of the last Pb plate. The collimator and gamma detector were assembled outside the spectrometer. The collimator is on a carriage which rotates about an axis. The collimated beam passes directly over the axis; this intersection defines the source position, and the gamma detector and its absorber sandwich is placed relative to this point exactly as it was relative to the source in the spectrometer. X-ray film exposed at the face of the detector showed a sharp spot $\sim\frac{1}{16}$-inch diameter. The calculated angular divergence of the beam was <1 degree. The response was surveyed across various diameters of the detector with the electronic window including only the photopeak as during the coincidence runs. Background was taken with a 1-inch Pb plug blocking the beam and constituted $\sim\frac{1}{3}$ of the rate. Only small differences were observed between different diameters of the crystal. The 760 kev and 660 kev normalized response curves showed no significant differences.

The numerical integration was done assuming a point source and using this experimentally obtained response function. The result was that

$$N'(E)/N(E) = 1 + 0.527\ 2A(E)/[3 + A(E)], \quad (3)$$

where $N'(E)$ is the observed coincidence distribution, $N(E)$ the true distribution of betas, and $A(E)$ is the anisotropy.

[17] Bolgiano, Madansky, and Rasetti, Phys. Rev. **89**, 679 (1953).
[18] T. B. Novey, Phys. Rev. **89**, 672 (1953).
[19] C. S. Wu in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 649.
[20] I. Hauser, Nuovo cimento Suppl. **5**, 182 (1957).

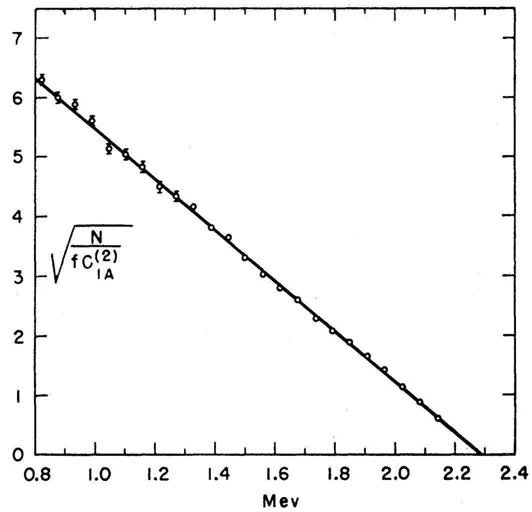

FIG. 2. Kurie plot of the 1.2% abundant 2.3-Mev beta group of Pr^{144}. The data were obtained with the magnetic spectrometer in coincidence with NaI detector viewing the 0.697-Mev gamma ray. The unique ($\Delta I=2$, yes) correction factor $C_{1A}^{(2)}$ has been applied.

The particular geometry of this case indicated finite size source effects might be significant. The expansions of Feingold and Frankel[21] do not converge rapidly enough for our case so the more complicated integration[22] over both detectors and the source was done with one simplifying assumption, namely, that the gamma detector and its actual response curve was replaced by an ideal gamma counter with uniform response but of a diameter chosen so that the result of the integration for a point source agrees exactly with the result of the integration for a point source and the actual detector. The net effect of the finite source consideration was that 0.527 in Eq. (3) was replaced by 0.513, which was used in correcting the spectrum. The correction factor (Eq. 3) ranged from 1.26 near the end point to 1.09 at 800 kev or about a 16% correction to the spectrum shape over the energy range observed. If one takes $A(E_0)=0.85$ and the same sort of energy dependence as the "unique" case the correction factor would range between 1.23 to 1.08 or about 14% correction to the shapes. Thus the order of 2% uncertainty in the experimental shape is introduced by the uncertainty in the magnitude of the β-γ directional anisotropy.

G. Results

A Kurie plot of the 2.3-Mev β group is shown in Fig. 2 with the $C_{1A}^{(2)}$ correction factor applied.

$$C_{1A}^{(2)} \propto K^2L_0+9L_1. \tag{4}$$

The notation is that of Konopinski and Uhlenbeck.[4] The superscript on the C indicates $\Delta I=2$, K is the neutrino energy, L_0 and L_1 are combinations of electron radial wave functions tabulated by Rose *et al.*[23] The Fermi function is screening corrected.[24]

A weighted least squares fit to a straight line gives a standard deviation of ± 3 kev for E_0. This estimate for the standard deviation of course reflects only the internal consistency of the data and not the uncertainties in calibration of the instrument. But it is just the uncertainty from the internal consistency of the data that should be included in the shape factor errors. The experimental shape factor is given in Fig. 3. The error flags include the contribution from counting statistics, uncertainty in the fast coincidence resolving time of $\pm 5\%$, and the uncertainty in E_0 just noted. These are the major contributors to the error. The next largest contributor ($\sim 2\%$) is the uncertainty in β-γ anisotropy correction; this is not included in the flags.

The solid curve is $C_{1A}^{(2)}$, and it is seen that the experimental uncertainties very definitely include the unique shape factor and indicate then the assignment of 0− to Pr^{144}.

Can the assignment 1− be excluded? The answer is not simple. With a spin change $(1-)\rightarrow(2+)$ four matrix elements contribute, $\int \mathbf{r}$ and $\int \boldsymbol{\alpha}$ from the vector part of the beta interaction, and $\int \boldsymbol{\sigma}\times\mathbf{r}$ and $\Sigma_{ij}|B_{ij}|^2$ from the axial vector part. This is a three parameter

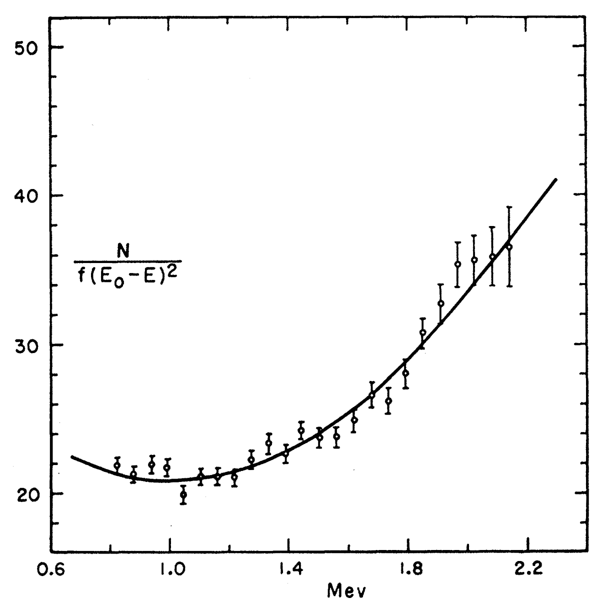

FIG. 3. Experimental shape factor for the 2.3-Mev beta group in Pr^{144}. Data taken in coincidence with the 0.697 gamma ray. The error flags (standard deviations) include contributions from the number of counts, uncertainty in the resolving time of the coincidence circuit *and* uncertainty in the E_0 value.

[21] A. M. Feingold and S. Frankel, Phys. Rev. **97**, 1025 (1955).

[22] We are much indebted to Dr. James P. Monahan for helping us set up the problem and for coding the numerical part for the IBM-704 computer.

[23] Rose, Perry, and Dismuke, Oak Ridge National Laboratory Report ORNL-1459, 1953 (unpublished).

[24] National Bureau of Standards Applied Mathematics Series No. 13 (U. S. Government Printing Office, Washington, D. C., 1952).

fit problem and it is certain that small admixtures of the other matrix elements with $\Sigma_{ij}|B_{ij}|^2$ (only contributor to $(0-) \rightarrow (2+)$ transition) are within the experimental errors. As an example we have considered the case in which the other contribution comes mainly from $\int \boldsymbol{\sigma} \times \mathbf{r}$. The energy dependent factor for this matrix element increases almost linearly with β energy and with a slope comparable to the higher energy part of the unique factor. The parameters a and b (and their standard deviations) in the following expression,[4]

$$C_{1A}{}^{(1)} \propto b[a(\tfrac{1}{6}K^2L_0+M_0+\tfrac{1}{2}L_1+\tfrac{2}{3}KN_0) + (\tfrac{1}{12}K^2L_0+\tfrac{3}{4}L_1)], \quad (5)$$

were found using a weighted least squares procedure.[25] The electron radial wave function combinations L_0, M_0, N_0, L_1, have been corrected for finite charge distribution after Rose and Holmes.[26] Here

$$a = \left|\int \boldsymbol{\sigma}\times\mathbf{r}\right|^2 \Big/ \Sigma_{ij}|B_{ij}|^2, \quad (6)$$

and b normalizes the expression to the experimental values. The result shows that at the 68% confidence level the largest positive value for a from these data is $a = 3.5 \times 10^{-4}$. If one defines the $\int \boldsymbol{\sigma}\times\mathbf{r}$ contribution as

$$\frac{\left|\int \boldsymbol{\sigma}\times\mathbf{r}\right|^2 (\tfrac{1}{6}K^2L_0+M_0+\tfrac{1}{2}L_1+\tfrac{2}{3}KN_0)}{\int\left|\boldsymbol{\sigma}\times\mathbf{r}\right|^2 (\tfrac{1}{6}K^2L_0+M_0+\tfrac{1}{2}L_1+\tfrac{2}{3}KN_0)+\Sigma_{ij}|B_{ij}|^2(\tfrac{1}{12}K^2L_0+\tfrac{3}{4}L_1)}, \quad (7)$$

at a particular energy, then the $\int \boldsymbol{\sigma}\times\mathbf{r}$ contribution is less than 2.8% in the energy range 0.8 to 2.3 Mev despite the large ratio (~100) of the energy dependent factors.

Graham *et al.*[8] have also measured the shape of this group in coincidence, but their data could not rule out as much as 25% $\int \boldsymbol{\sigma}\times\mathbf{r}$ contribution. Their β-γ directional anisotropy analyzed on a $(1-)\beta(2+)\gamma(0+)$ basis admitted either an 8% or 60% $\int \boldsymbol{\sigma}\times\mathbf{r}$ contribution. Thus they could not on the basis of this argument alone completely rule out the 1– assignment. But at the 68% confidence level the present shape measurements and the β-γ anisotropy of Graham *et al.* rule out (1–) for the Pr^{144} assignment. This is stated with the reservation that no complete analysis of the shape or β-γ anisotropy has been made with the complete *V-A* mixture, a three parameter problem. Strictly speaking the value of the β-γ anisotropy is not consistent with a 0– assignment, but the expected systematic difficulties[8] in the measurement usually result in a reduction of the true anisotropy. It is important to point out, as the Chalk River group has, that any increase in the experimental value[27] for the anisotropy makes the argument *against* (1–) stronger.

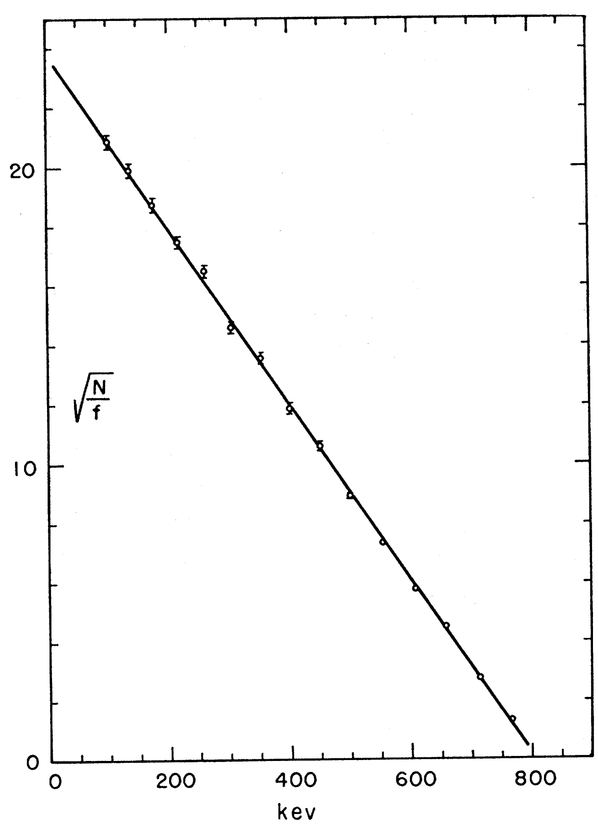

FIG. 4. Kurie plot of the 1.0% abundant 807-kev beta group in Pr^{144}. Data taken in coincidence with 1.49- and 2.19-Mev gamma rays.

III. THE 807-KEV GROUP IN COINCIDENCE

The shape of the 807-kev group is not definitive in establishing the spin assignment of Pr^{144}. The most probable assignment for the 2.19-Mev level state in Pr^{144} is 1– on the basis of 0.697γ-1.49γ directional correlation.[1,8,28] The allowed shape of the 807 group as shown in Fig. 4 is consistent with the scheme as shown and it was necessary to demonstrate this consistency.

[25] W. E. Deming, *Statistical Adjustment of Data* (John Wiley & Sons Inc., New York, 1958), Chap. IX.

[26] M. E. Rose and D. K. Holmes, Oak Ridge National Laboratory Report ORNL-1022 (unpublished).

[27] T. Davidson and T. B. Novey (private communication) have found in preliminary experiments values for this β-γ an isotropy consistent with the "full unique" value after large corrections for the β-IB contribution to the results.

[28] R. M. Steffen, Phys. Rev. **95**, 614 (1954). Also refers to unpublished polarization direction correlation work by Brazos and Roberts supporting parity change in the cascade.

The same kind of procedures and precautions which have been described above were followed in obtaining the 807-kev beta spectrum. Because there is no β-γ directional anisotropy[8] from the 2.19 Mev γ and little (none if the 807-kev β transition is allowed as in scheme of Fig. 1) expected from the 1.49 Mev γ, the gamma detector was set to accept all pulses >975 kev.[29] The distance from the source to the Be disk covering the end of the gamma detector was $\frac{7}{8}$ of an inch, a distance giving $<0.3\%$ increase in the count at 300 kev on a 3-Mev spectrum due to backscattering. The beta channel integral level was 40 kev. The over-all coincidence loss at 100 kev was 6.8% dropping to 0.1% by 260 kev. I.B.-β coincidences were checked by a procedure described above using an Y^{90} stand-in. This correction was $\sim$1% up to 459 kev, then increased to 7% at 713 kev, and was 22% at 767 kev. Chance rates ($2\tau_f=75$ mμsec) varied over the spectrum from 10% of the total coincidence rate at 100 kev to 1% at the peak of the spectrum, to a maximum value of 35% at the highest energy point. Between 1400 and 2000 coincidences were recorded for each point during the 73 hr running time. The data, corrected for chance coincidences, dead time, I.B.-β coincidences, coincidence efficiency, and spectrometer resolution are shown in Fig. 4. The error flags indicate standard deviations calculated from number of counts and uncertainty in the chance rate only.

IV. H_ρ OF THE Ce^{144} 134 KEV K LINE AND THE β TRANSITION ENERGIES

If the 134-kev K line momentum is known accurately one has a "built in" calibration line in the Ce^{144}-Pr^{144} sources. In addition there was some interest in more accurate values of this line for calibration purpose in our low-energy permanent magnet spectrograph. We have compared the 134-kev K line with the Cs^{137} 660-kev K line by way of the combination source technique. Cs^{137} and Ce^{144} are successively volatilized (sublimated) from a hot filament onto 200 μg/cm^2 Al with a $\frac{1}{8}$-inch diameter mask, the mask remaining always fixed with respect to the source foil and nearly touching it. The source spot was invisible. Normalized plots of the line shapes are compared by superposition. No differences in the line shapes were ascertainable. The readings of the Rubicon Type B potentiometer in the current control are checked against a Leeds and Northrup type K potentiometer across a water cooled manganin shunt ($<3°$C temperature variation) passing the spectrometer current. The potentiometers were compared directly and against a third potentiometer (L & N White). All of this showed up some nonlinearities in the potentiometer and the current control which can be summarized in a correction of 2 parts in 10^4. The line positions could be determined to 2 parts in 10^4 at 1% resolution. Since only the components of the earth's field transverse to the spectrometer axis are compensated in this instrument, a correction must be made for the uncompensated earth's field along the spectrometer axis. This is investigated by running low-energy lines with the current reversed in the coils of the spectrometer and noting the shift in position of the line. This effect results in a correction of 5 in 10^4 for the 134 kev K line and less than 2 in 10^4 for the 660 kev K line. Regarding the uncertainty of the axial field correction as the same order of magnitude as the correction, we give the results:

$$\frac{Ce^{144}(134 \text{ kev } K \text{ line } H_\rho)}{Cs^{137}(660 \text{ kev } K \text{ line } H_\rho)}=0.3149\pm0.0002.$$

Taking the Cs^{137} (660 kev K line H_ρ)$=3381.28\pm0.5$ gauss-cm,[30] the H_ρ of the Ce^{144} 134 kev K line is 1064.8 ± 0.6 gauss-cm or 91.52 ± 0.06 kev. Using the Pr K-binding energy[31] of 41.99 ± 0.10, the energy of the transition is (133.51 ± 0.12) kev.

On the basis of 8 runs, in various modes of operation of the spectrometer, of the total spectrum, E_0 for the ground state transition is 2996 ± 3 kev, where the standard deviation is computed including both internal consistency and calibration error.

V. GAMMA-RAY INTENSITIES

The gamma-ray intensities lead directly to the intensities of the weak inner beta groups and hence to the small subtractions from the total spectrum which will yield the ground-state beta spectrum shape. There have been other determinations of these intensities which are summarized in Table I.

Our method makes use of 4π beta counting to get absolute disintegration rates coupled with calibrated NaI crystal[32] measurement of the gamma intensity.

TABLE I. Photon abundance (% of Pr^{144} decays).[a]

γ energy (Mev)	Present work[b]	Graham *et al.*[c]	Kreger & Cook[d]
0.697	1.49% ±0.09	1.57±0.28	1.79
1.49	0.29 ±0.03	0.26±0.06	0.35
2.19	0.68 ±0.10	0.78±0.16	0.91
0.1335	13.9 ±1.4	10.6 ±1.1	15.4

[a] These are also the transition abundances (except for the 134-kev case) since internal conversion is negligible.
[b] $4\pi\beta$ counting.
[c] Assume $134\alpha_K=0.49$.[8]
[d] Assume 134 level fed 22% of time [Phys. Rev. 96, 1276 (1954)].

[29] One cannot include the Compton distributions in the gamma channel if β-γ anisotropy exists because of the difficulty in making the β-γ anisotropy correction to the spectrum shape. Gammas scattered from particular regions of the spectrometer, the room, etc., have quite different β-γ correlations, but will not end up in the full energy peak of the gamma detector. We have seen changes in the 2.3-Mev group shape if much of the Compton distribution of the 697 kev γ is included in the gamma channel.

[30] Lindstrom, Siegbahn, and Wapstra, Proc. Phys. Soc. (London) **B66**, 54 (1953).

[31] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).

[32] We take advantage here of much work by a colleague of ours, Dr. D. W. Engelkemeir, who has determined the full energy peak efficiency for this crystal at several source distances by 4π beta

The low intensity of the gammas means that the same samples are not conveniently used for both β and γ counting. Diluting and aliquoting procedures used to make separate β and γ counting samples have been checked by repeating the procedures three times, and the consistency of the results (<2%) indicate the errors from this source are smaller than the γ efficiency uncertainties.

The 4π proportional counter samples are deposited from very dilute solutions onto 10–20 μg/cm² polyvinylstyrene (VYNS) films. This thickness included the ~7 μg/cm² gold coating which is vacuum volatilized onto the films. The 4π rates were ~15 000 counts/min, giving negligible dead-time losses.

The gamma spectra were taken with $2\frac{1}{2}$-inch diameter ×2-inch high NaI(Tl) crystal on Du Mont 6363 phototube at ~10% geometry, with no collimation. An absorber assembly of Be(2.00 g/cm²), Pb(1.21 g/cm²), Cu(0.93 g/cm²), and 0.18 g/cm² of Al+MgO of the crystal container, was used to stop the betas and lower the 134 kev γ intensity. The data were recorded on a 256 channel analyzer whose design insures that no counts can fall between channels. The counts under the full energy peaks were corrected for analyzer dead time (~6% correction), absorption (~50% for the 697 kev γ) and summing of the 0.7 and 1.48 gammas (~3–4%). The absorption correction was checked by running Cs^{137} and Na^{22} absolute standards with the same absorber and showing that the calculated efficiencies fell within 3% of the previously obtained[32] curve at 0.660, 0.511, and 1.28 Mev.

The 134 kev γ intensity was measured with a weaker source and with only the 2 g/cm² of Be absorber (plus the crystal container) present. A 3% escape peak correction[33] was applied.

The uncertainty in the efficiencies was estimated from the scatter of the points defining the curve and is the major source of error quoted for the present measurement in Table I.

With two $2\frac{1}{2}$-inch diameter by 2-inch high NaI(Tl) crystals and a fast-slow coincidence circuit of resolving time $2\tau = 80$ mμsec we have been unable to find the 1.1–1.7 Mev γ cascade and the 2.8 Mev cross-over reported by Firsov and Bashilov.[34] From a simple singles measurement using a low rate to minimize 2.2–0.7 accidental summing, any 2.8 full energy peak is less than 1.3×10^{-3} of the 2.19 full energy peak or less than 0.0009% abundant. We performed the same coincidence experiment reported by Firsov and Bashilov, namely with one gamma counter viewing the 1.1 full energy peak region, the coincidences with another gamma counter were displayed on the 256 channel analyzer. Some coincidences were observed to tail out beyond 700 full energy peak. If we take all the coincidences in the 1.7 photopeak region without any detailed chance analysis, the abundance of any 1.1–1.7-Mev cascade is less than 4×10^{-3} of the 1.49-Mev intensity or <0.0012% abundant. The efficiency and geometrical factors used in obtaining this limit are conveniently checked by the 0.697–1.49 Mev cascade itself and with Co^{60}. These limits are a factor of 10 or more lower than the abundances indicated by Firsov and Bashilov.

counting and by β-γ coincidence techniques using several established decays. These are Am^{241}, Hg^{203}, Au^{198}, Na^{22}, Cs^{137}, Sc^{46}, Co^{60}, and Tl^{208}.

[33] P. Axel, Rev. Sci. Instr. **25**, 391 (1954).

[34] E. I. Firsov and A. A. Bashilov, Izvest. Akad. Nauk S.S.S.R. Ser Fiz. **21**, No. 12, 1633 (1957) [Columbia Technical Translation, **21** No. 12, 1619 (1957)].

VI. THE 0− TO 0+ TRANSITION

A. Distortions

The shape of the abundant ground-state transition was obtained from the total spectrum by subtracting the known shapes of the inner groups in abundances given by the gamma ray intensity measurements. The errors introduced by the uncertainties in the inner group shapes and intensities are reduced by a factor of the order of 50 because of the low abundance of the inner groups. A much larger source of error for the ground-state-transition is the systematic uncertainty in the measurement of the total spectrum arising from scattering and baffle penetration.

While the arguments about *TP vs A* do not depend at all on removing the last few percent distortion in the shape, the ratio of the axial vector nuclear matrix elements which is determined in this case is very sensitive to small changes in the shape. For this reason (as well as the general interests of the continuing "shakedown" of this spectrometer) a considerable effort was made to find any sources of distortion. It is not appropriate to describe here in detail some thirty changes in the baffling and modes of operation of the spectrometer and the effects of the changes on the shape of the total spectrum of Pr^{144}, but we shall try to summarize what we have learned.

The most obvious fact brought out by our early measurements with this high-energy spectrum was that the low (1%) and high (5%) transition modes of operation showed different shapes, the high transmission mode giving the order of 5% more low-energy electrons than the low-transmission mode at $E_0/10$ with this 3-Mev spectrum. The problem was to find out whether this result was caused by increased scattering raising the low-energy points with the spectrometer baffles opened up for the high-transmission case or by penetration effects emphasizing the high-energy points when the baffles are closed down for the low-transmission case (or by a combination of the two effects). The answer is that the spectrum distortion occurs in the high transmission case. The following outline shows some of the places where we looked for trouble. "No effect" means less than 1% change in the spectrum shape.

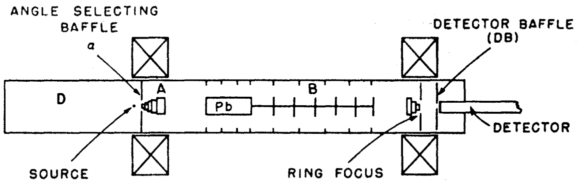

FIG. 5. A schematic view of the Argonne double lens beta ray spectrometer. The labels are used in the discussion of the search for distortions of the experimental spectrum shapes.

a. The eight $\frac{1}{8}$-inch $\times\frac{1}{8}$-inch legs which supported the Pb plug and axial baffle assembly were replaced by 0.010-inch diameter phosphor bronze wire—no effect on the spectrum.

b. The Al covering of the Pb plug was scored with $\frac{1}{4}$-inch deep *V* grooves running around the plug (other experiments showed this lowers the glancing angle scattering by 60% for the Pr^{144} betas)—no effect on the spectrum.

c. While it was already known that the outside rings and axial disk baffles in region *B* (see Fig. 5) were important in reducing the tail beyond the spectrum an increase in the number of rings and disks by a factor of 2 showed no effect on the spectrum.

d. Addition of outside ring baffles in region *A* showed no effect.

e. By closing the α defining baffle nearly tight the penetration effects at this baffle could be emphasized—no effect; similarly for the ring focus (RF) baffle.

f. The 200 $\mu g/cm^2$ Al foil backing for the sources for both modes of operation prior to these tests had been supported on $\frac{3}{4}$-inch diameter $\times\frac{1}{16}$ inch square cross section Al rings. They had been inserted on a 4-fingered Al holder about 1 inch long which was in turn supported by heavier brass rod and cylindrical centering supports which were the order of $1\frac{1}{2}$ to 2 inches away from the source position. All these were eliminated leaving region *D* clear and the 4-inch diameter ring and foil support described in Sec. IIc was used. A 3% decrease in the beta intensity at 300 kev was observed for the high-transmission mode. This result was checked by running in brass plates and cylinders behind and around the source and noting that indeed when the spectrometer transmission is "opened up" large brass objects must be kept at least three inches behind the source. (Beryllium can be closer; see Sec. IIb.)

g. A series of experiments involving the detector baffle (DB) in which the outer part of the axial focus image only was selected by use of a plug (which had the same rounded edge as the normal 5 mm hole in the DB used for low-transmission mode) showed that it was scattering rather than DB penetration that accounted for the last 2% difference between the modes. Further verification that the DB penetration effect was small came from the use of a platinum insert in the DB. Its greater density helps in the penetration problem ($\sim$ same radius of curvature for the edge as the brass one) and it can be made $\sim\frac{1}{3}$ as thick which should (according to some auxiliary experiments) actually decrease the net "in"-scattering from the edge. No change in the shape compared to the brass DB was noted.

In summary then we have been unable to shake the results in the low-transmission mode of operation of the spectrometer. This is the very same mode in which the P^{32} and Na^{24} measurements[11] were made. The high-transmission mode has some residual distortion ($\sim$2% at $E_0/10$ for $E_0=3$ Mev). This will not affect the measurement of the 2.3 Mev in coincidence since the spectrum is investigated only to $E_0/3$.[35]

B. Results

Figure 6 shows the experimental shape factor for the ground-state transition in the low transmission mode of the spectrometer. Of the several runs we have picked the one with the most points and the most counts. It happens to be one in which the gas proportional counter was used. We continue to find complete interchangeability as far as spectrum shapes are concerned between the gas counter and anthracene scintillation counter.[10,11] The spectrum was surveyed taking every other point with increasing current and the alternate points with decreasing current. Five such cycles constitute the run, the whole covering an elapsed time of 28 hours. Backgrounds at zero current and at 3.4 Mev, above the spectrum, are included in each cycle. The only points where the background of $\sim$10 c/m is an appreciable fraction of the count are the 2 or 3 nearest the end point; the background was 11% of the rate at the last

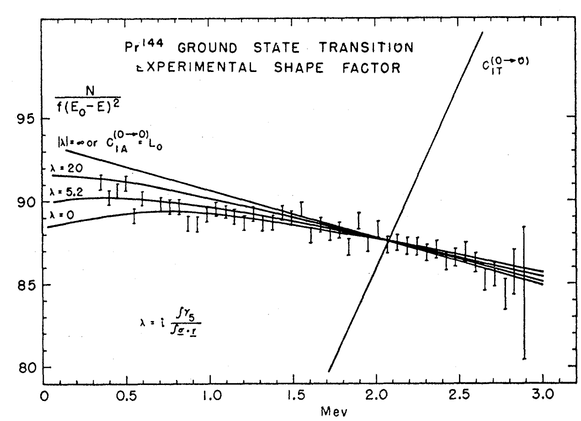

FIG. 6. Experimental shape factor for the abundant 2.996-Mev beta transition in Pr^{144}. The error flags (standard deviations) include contributions from the number of counts *and* the uncertainty in E_0 value. The solid curve $C_{1T}^{(0\rightarrow 0)}$ is the pure tensor prediction for a 0− to 0+ case. The solid curves labeled with various λ values are the pure axial vector predictions for 0− to 0+ transition where λ is the ratio of the two axial vector nuclear matrix elements which contribute in this case.

[35] The present work indicates the slight upturn at low energies which was observed in the Re^{186} inner group[10] may be an experimental distortion, i.e., the deviation from the allowed shape may be even more pronounced.

point. The peak rate was 3600/min so that dead time corrections were negligible. About 4×10^4 counts were collected for each point except the four near the end point. The 134-kev K line was run at the beginning and end of the experiment. From it the calibration factor and the first and second moments of the transmission-curve were obtained from which the resolution correction was made. It amounted to less than 0.2% up to 2600 kev where it increased to 7% at the last point.

From the total spectrum 1.20% by area of a unique ($\Delta I=2$, yes) spectrum of 2.3-Mev end point and 0.97% of an allowed shape of 807-kev end point were subtracted.

A Kurie plot of the points with $E\geq 2014$ kev was constructed [i.e., $\{N/(fL_0)\}^{\frac{1}{2}}$ *vs* E] and weighted least squares values for E_0 and $\sigma(E_0)$ obtained, the weights being the inverse of the variance of the points obtained from the total counts and, in the case of a few points near the end point, the background uncertainty. With this value of E_0(2993±0.5 kev for this particular run) the experimental shape factor was obtained. The error flags indicate a standard deviation *including* the error in E_0.

The results are in good agreement with those of Graham *et al.*,[8] but in disagreement with those of Laubitz.[7,36] Hamilton and Langer[37] have reported some counting of high statistical accuracy between 2.3 Mev and the end point which would rule out any large deviation from the allowed shape in that region of the spectrum.

Graham *et al.* have observed the P^{32} spectrum in the same spectrometer with which their Pr^{144} total spectrum was obtained. They find more deviation from the allowed shape in P^{32} than was found in the Argonne double lens by about 3% so that the agreement in the case of Pr^{144} may be fortuitous with some features of either or both spectrometers not fully understood within uncertainties of that order.

VII. DISCUSSION

The fact that tensor interaction alone cannot explain the 0− to 0+ shape is graphically illustrated [$C_{1T}^{(0\to 0)}$ in Fig. 6]. (The Fermi matrix elements make no contribution in 0− to 0+ case.) The difficulties *even with a TP* mixture in explaining the nearly allowed shape for a 0− to 0+ transition are evident in the discussions of Zirianova,[6] Graham *et al.*,[8] and Alaga *et al.*[38]

The VA version of beta decay interaction explains the shape easily. Two matrix elements $\int\gamma_5$ and $\int\boldsymbol{\sigma}\cdot\mathbf{r}$ make contributions. The $C_{1A}^{(0\to 0)}$ shape factor[4] can be written (see Sec. IIg for comments on notation and the evaluation of the functions)

$$C_{1A}^{(0\to 0)}\propto b[(\tfrac{1}{9}K^2L_0+M_0-\tfrac{2}{3}KN_0)+2\lambda(\tfrac{1}{3}KL_0-N_0)+\lambda^2L_0], \quad (8)$$

where $\lambda=i\int\gamma_5/\int\boldsymbol{\sigma}\cdot\mathbf{r}$, a real number, and b is just a constant used to normalize the expression to the data.

The expression (8) was compared with the experimental data and a weighted least squares[25] adjustment of the parameters (λ and b) gave

$$\lambda=5\pm2.$$

This standard deviation of course reflects only the internal consistency of the data. With the experimentalists' prerogative we can speculate that any as yet undetected systematic errors will probably not throw λ outside the range 0 to 20.

Theoretical estimates[39,40] give $\lambda\simeq0$ to -20, but the present experiments rule out negative values for λ. There is little ambiguity in the comparison of experiment and theory for the 0− to 0+ transitions because only a single parameter is involved. In contrast, the other nonunique first forbidden transition ($\Delta I=0$, 1, yes) requires 2 or 3 parameter fits and so far have yielded large flexibility in the sets of consistent parameters. Further, in the comparison of the beta polarization and spectrum shape in the first forbidden transitions[41] the 0− to 0+ cases may offer a less ambiguous test of the formalism again because of the single parameter.

If, for a reason as yet unseen, the specification of two component neutrino theory that $C_i=\pm C_i'(i=VASTP)$ should be dropped then the 0− to 0+ transition could play a role in determining the extent of T-A mixing. Without two components neutrino theory the pure G.T. allowed transition spectrum shapes and K capture to position ratios say[42] only that

$$C_AC_T+C_A'C_T'=0, \quad (9)$$

with an uncertainty the order of a few percent. The same coefficient (9) appears in the cross terms of the (T,A) shape factor for 0− to 0+ transition[43] but since the direct (pure) T and A terms have quite different shape factors (not so for the allowed transition) one still has a measure of the relative size of the coupling constants, $(C_T^2+C_T'^2)/(C_A^2+C_A'^2)$. It turns out to be a very poor measure when the experimental uncertainties are as large as the present case and further the result is blurred by the presence of a nuclear matrix

[36] See reference 8 for the probable explanation of Laubitz' results.

[37] J. H. Hamilton and L. M. Langer, Bull. Am. Phys. Soc. Ser. II, **3**, 208 (1958).

[38] Alaga, Sips, and Tadic, Glasnik mat. fiz. i Astron. Ser. II, **12**, 207 (1957).

[39] T. Ahrens and E. Feenberg, Phys. Rev. **86**, 64 (1952). We wish to thank Dr. Ahrens for confirming that indeed these theorectical estimates do not admit positive values for our λ.

[40] D. L. Pursey, Phil. Mag. **42**, 1193 (1951).

[41] Bincer, Church, and Weneser, Phys. Rev. Letters **1**, 95 (1958).

[42] We use the original T. D. Lee and C. N. Yang [Phys. Rev. **105**, 1671 (1957)] notation C_i and C_i'. (9) is the Fierz interference coefficient, e.g., b of Jackson, Treiman, and Wyld [Phys. Rev. **106**, 518 (1957)] where we assume T invariance, i.e., coupling constants are real.

[43] G. E. Lee-Whiting, Can. J. Phys. **36**, 1199 (1958).

element ratio. If condition (9) holds then the following expression can be compared with the experiment:

$$C_{1AT}^{(0\to 0)} \propto r(\tfrac{1}{9}K^2L_0+M_0+\tfrac{2}{3}KN_0) + (\tfrac{1}{9}K^2L_0+M_0-\tfrac{2}{3}KN_0)+2\lambda(\tfrac{1}{3}KL_0-N_0)+\lambda^2L_0$$

where, again, $\lambda = i\int\gamma_5/\int\boldsymbol{\sigma}\cdot\mathbf{r}$ and

$$r=\frac{C_T^2+C_T'^2}{C_A^2+C_A'^2}\frac{\left|\int\beta\boldsymbol{\sigma}\cdot\mathbf{r}\right|^2}{\left|\int\boldsymbol{\sigma}\cdot\mathbf{r}\right|^2}, \tag{10}$$

With the present data values of r from 0 to $\simeq 1$ are possible if λ takes on appropriate values from 5 to 60. Graham *et al.*[8] have obtained similar results with their data. From our graphical solution of the two parameter problem we estimate a decrease in the experimental uncertainties by a factor of 10 might serve to put an upper limit on $r \leq 0.01$, independent of λ. It is clear that other experiments such as recoil spectra[9] already give $(C_T^2+C_T'^2)/(C_A^2+C_A'^2) \leq 0.1$, and it seems unlikely the 0− to 0+ shapes will challenge this method.

There is the additional question of the presence of any pseudoscalar type shape factor in the 0− to 0+ transitions. There are various pseudoscalar shape factors and *PA* interference terms in the literature.[44,45,38,43] Graham *et al.*[8] have shown that the Pr^{144} spectrum is *not* a sensitive means of putting small limits on the quantities

$$\frac{C_PC_A+C_P'C_A'}{C_A^2+C_A'^2} \quad \text{and} \quad \frac{C_P^2+C_P'^2}{C_A^2+C_A'^2}. \tag{11}$$

They have used the two component theory assumption and the Rose-Osborne[45] treatment to demonstrate that C_P/C_A in the range from 0 to 1000 along with appropriate positive values of λ ranging from 0 to 200 are consistent with their data. We do not anticipate any marked difference with our data. They also point out that the *contribution* of the direct P part of the A, P shape factor to the total shape factor $C_{1AP}^{(0\to 0)}$, (i.e.,

$$(C_P^2+C_P'^2)\left|\int\boldsymbol{\sigma}\cdot\mathbf{r}\right|^2(S)\Big/C_{1AP}^{(0\to 0)}, \tag{12}$$

where S is the appropriate electron energy dependent factor) is very small, <1%, from the Pr^{144} spectrum (with Rose-Osborne formulation and including the AP interference terms) but the small magnitude of S in (12) allows only a large upper limit to be put on quantities (11).

We summarize the work on Pr^{144} by noting that the 0− assignment for Pr^{144} appears to be on firm ground (possibly only a direct attempt via atomic beam methods can improve the situation here) from the investigation of the 2.3-Mev β transition to the first excited state in Nd^{144}. The nearly allowed shape of the 3 Mev 0− to 0+ β transition is easily explained with a pure axial vector shape factor; in contrast, the *TP* formalism fails to reproduce the shape. The ratio of axial vector matrix elements $(i\int\gamma_5/\int\boldsymbol{\sigma}\cdot\mathbf{r})$ can be determined well from the shape, and while being the same absolute magnitude as the theoretical predictions, the experimental value has the opposite sign. The 0− to 0+ shape does *not* offer a sensitive measure of the relative sizes of P and A coupling constants although the net relative contribution of the direct pseudoscalar part of the shape factor is very small.

[44] T. Ahrens, Phys. Rev. **90**, 974 (1953).
[45] M. E. Rose and R. K. Osborne, Phys. Rev. **93**, 1315 (1954).

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