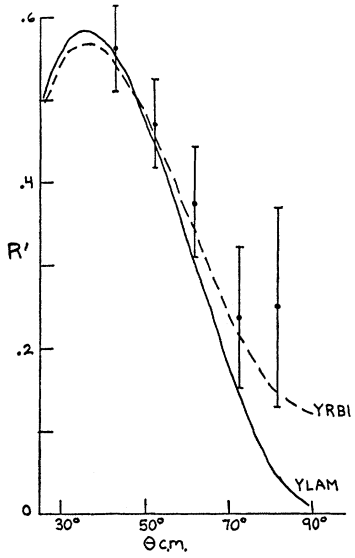

FIG. 2. R' (137½ MeV) for proton-proton scattering versus center-of-mass scattering angle. Shown also are two predictions of the Yale group[7] at 140 MeV.

At four of the five scattering angles the measurements differed by one standard deviation or less. All of the measurements differed by less than two standard deviations.

The final results of R' are listed in Table III and plotted in Fig. 2. The results are in agreement with

TABLE III. R' values at 137½ MeV.

θ_2 (lab)	R'
20° 50′	0.562±0.052
25° 26′	0.472±0.054
30° 8′	0.376±0.068
35° 16′	0.238±0.084
39° 55′	0.251±0.121

phase shift analyses from preexisting data. Shown in Fig. 2 are two predictions of the Yale group[7] calculated at 140 MeV. YLAM represents the best fit to the data between 9.5 MeV and 345 MeV. The data of this experiment seem to favor YRB1, however. Presumably this indicates that minor adjustments must still be made to the fit.

ACKNOWLEDGMENTS

E. H. Thorndike participated in the early stages of this experiment. M. Sobel and R. Vedam assisted in the data taking. We would like to express our gratitude to the entire staff of the Cyclotron Laboratory, especially to A. M. Koehler and R. Sette.

[7] G. Breit, M. H. Hull, K. Lassila, and K. D. Pyatt, Phys. Rev. **120**, 2227 (1960).

PHYSICAL REVIEW VOLUME 132, NUMBER 5 1 DECEMBER 1963

Recoil Energy Spectrum of the Sodium Ions Following the β^- Decay of Ne^{23}

THOMAS A. CARLSON
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received 29 July 1963)

Following the beta decay of Ne^{23}, the sodium ions have a recoil energy distribution which is dependent on the nature of the decay. A precise measurement has been made of the recoil spectrum from 100 to 500 eV. From these data the electron-neutrino angular correlation coefficient α has been determined to be -0.33 ± 0.03, in good agreement with V-A interaction. The quoted error includes an uncertainty of only 2% due solely to the recoil measurements. The principal uncertainty in α arises from the errors quoted by Penning and Schmidt for their measurements of the β^--ray intensities to the ground and first excited states. If it is assumed that V-A interaction is valid and hence $\alpha=-1/3$, the β^--ray intensities to the ground and first excited states of Na^{23} may be calculated from the recoil data. Such calculations were made and the results are, respectively, (67 ± 1)% and (32 ± 1)%. From the end point of the recoil spectrum, the decay energy to the ground state has been determined to be 4.383 ± 0.008 MeV.

I. INTRODUCTION

A NUMBER of measurements have been made on the recoil energy spectra of ions resulting from the beta decay of rare gases.[1,2] Data have also been obtained, making use of both β and recoil particles in coincidence.[3,4] The purpose of both sets of measurements was to elicit information on the angular correlation between the beta particle and the neutrino. Some uncertainty was present in the initial experiments, but later results established that the (V,A) interaction is dominant in beta decay.

The recent work of Johnson, Pleasonton, and Carlson[2] on He^6 has greatly increased the precision of recoil spectrometry. Advantage was taken of the knowledge

[1] J. S. Allen, R. L. Burman, W. B. Herrmannsfeld, P. Stahelin, and T. H. Braid, Phys. Rev. **116**, 134 (1959).
[2] C. H. Johnson, F. Pleasonton, and T. A. Carlson, Phys. Rev. **132**, 1149 (1963).
[3] For summary of early work, see J. S. Allen, *The Neutrino* (Princeton University Press, Princeton, New Jersey, 1958), Chap. 5.
[4] B. W. Ridley, Nucl. Phys. **25**, 483 (1961).

gained in this experiment[2] in order to make a precision measurement of the recoil spectrum of the Na^{23} ions formed in the decay of Ne^{23}.

II. EXPERIMENTAL

Neon-23 was prepared from the reaction, $Na^{23}(n,p)Ne^{23}$, by bombarding approximately 100 g of sodium aluminum silicate in the core of the Oak Ridge research reactor. The large surface area of the material permitted effective emanation; and the radioactive gas, which decays with a half-life of 40 sec, was swept continuously by water vapor into the laboratory. An ice-water trap removed most of the water vapor. Two more cold traps and a Cu-CuO oven helped purge the neon of contaminating gases. The neon-23 was then allowed to decay in a source volume. Some of the ions that were formed following β^- decay emerged from the conical volume as a beam, and were analyzed for their charge and energy by means of magnetic and electrostatic analyzers in tandem. A precision voltage supply was available for biasing the potential of the source volume either positively to accelerate the emerging ion beam before analysis or negatively to prevent the beam from entering the spectrometer at all. Background measurements were normally taken under the latter condition. The ions that passed through both analyzers were counted with an electron multiplier.

The accuracy of the present experiment is based to a large extent on a previous thorough investigation[2,5,6] of the spectrometer; however, a few points peculiar to the present work should be mentioned.

First, a small uncertainty, $\pm 0.2\%$ of the value for the angular correlation coefficient, arose in the He^6 experiment because the source volume was not completely shielded from stray magnetic fields. This uncertainty was eliminated in the present experiment by wrapping the volume with Co-Netic magnetic shielding.

Second, the pressures of the residual gases were 6×10^{-6} Torr in the source volume and 1×10^{-6} Torr in the analyzers. Possible errors in the recoil spectrum that might result from elastic and inelastic scattering from gas molecules are small compared to the major errors in this experiment. Examination of a portion of the Na^{23} recoil spectrum was made at several pressures, and it was determined that the change in the observed relative abundances for ions with recoil energies from 100 to 500 eV is less than 0.5% because of pressure effects. That pressure is not a major problem in the present experiment is confirmed by Bracewell's study[7] on the dependence of Na^+ transmission as a function of recoil energy and pressure, in which he finds that the transmission is only weakly dependent on recoil energy above 100 eV.

Third, the ions before entering the multiplier were accelerated by a negative potential, which was adjusted to keep the total kinetic energy of the ions striking the multiplier constant. The present experiment was operated under conditions[8] where the measured spectrum was essentially independent of the focusing that results from this acceleration.

III. RESULTS

The relative abundances $N(E)$ of the singly charged Na^{23} ions have been measured as a function of their recoil energy. Actually, the measured values are proportional to $N(E)\cdot E$ since the resolution width of the spectrometer is a fixed fraction of the energy of the ions being analyzed. As previously reported,[9] the recoil spectrum from the decay of Ne^{23} has a negligible dependence on the charge of the sodium ion, and it is not necessary to sum the contributions from all the charge states. The only important corrections to the data were for background. Dead time corrections for the counter were negligible. Corrections for the effect on the spectrum of the spectrometer's finite resolution were negligible for measurements below 500 eV, although the intensity measured at 500 eV needed to be increased 0.2%. In two runs the ions were pre-accelerated before they entered the analyzers, while in four runs they were not. The spectra obtained under both conditions were the same, and the weighted averages of the data from all six runs are listed in Table I. Use has been made of data obtained in the course of the He^6 experiment to calibrate the spectrometer, and the energies quoted are accurate to $\pm 0.25\%$. The errors quoted for the relative intensities are from counting statistics. There was no strong evidence for random fluctuations outside counting statistics; and, as is noted in Sec. V, the least-squares fit of the data in Table I to theory is consistent with the errors quoted. The data are displayed in Fig. 1, together with measurements taken near the maximum recoil energy. The theoretically determined spectral shapes for complete axial-vector and complete tensor interaction are also given in Fig. 1. The experimental data are obviously in

TABLE I. Relative intensities of Na^{23} ions measured as a function of recoil energy.

E (eV)	$N(E)\cdot E$ (arbitrary units)
497.0	1185±9
447.3	1361±5
397.6	1454±6
367.8	1484±6
347.8	1461±6
298.2	1299±6
247.5	1098±6
198.1	856±4
148.5	608±4
99.0	356±3

[5] C. H. Johnson, F. Pleasonton, and T. A. Carlson, Nucl. Phys. **41**, 167 (1963).
[6] T. A. Carlson, F. Pleasonton, and C. H. Johnson, Phys. Rev. **129**, 2220 (1963).
[7] K. H. Bracewell, Phys. Rev. **54**, 639 (1938).
[8] See grid transmission for 3-grid case, Fig. 10 in Ref. 2.
[9] T. A. Carlson, Phys. Rev. **130**, 2361 (1963).

excellent agreement with the predictions for axial-vector interaction.

IV. THEORY

The decay scheme for Ne^{23} is given in Fig. 2. We discuss, in order, the contributions to the recoil spectrum of transitions to the ground state, and the first two excited states. Transitions to still more highly excited states are less than 0.25% and are neglected.

The principal contribution to the recoil energy spectrum comes from the β^- transition to the ground state. The recoil energy spectrum for an allowed transition is given by

$$N(E)=AF(E)[N_1(E)+\alpha N_2(E)], \qquad (1)$$

where A is a proportionality constant and α is the angular correlation coefficient. The terms $N_1(E)$ and $N_2(E)$ are functions of the recoil energy and the maximum β^- energy, and are defined by Eqs. (A1) and (A2) as given in our previous paper.[2] The factor $F(E)$, which is derived from the usual Fermi-Coulomb function $F(Z,W)$, has been estimated from tables of Rose[10] as described earlier.[2] Since beta decay to the ground state is a pure Gamow-Teller transition ($\Delta I=-1$, no change in parity), α may take on values from $-1/3$ for axial-vector interaction to $+1/3$ for tensor interaction. It is assumed that the Fierz interference term is zero[11] and that second-order effects are negligible.[12]

The contribution to the recoil spectrum from the transition to the first excited state has been calculated, also assuming pure G-T interaction. Fermi interaction is allowed, but has been estimated[13] to be less than 0.1%. Formulas for obtaining the recoil energy spectrum from beta decay followed by gamma emission have been derived by Rose[14] on the assumption that the γ ray is emitted isotropically. Before these formulas were used, the proper limits of integration were substituted and the Fermi-Coulomb correction was included.

The small contribution from the second excited state, which decays by two γ rays, has been estimated by treating the two γ's as one. Calculation of the recoil spectrum was made by using first the sum and then the difference in the energies of the γ's. The mean of these two results has been used in the present analysis.

The spectral shapes from the three contributions are normalized, and the final shape is obtained by weighting the contributions according to the relative beta ray intensities as given by Penning and Schmidt.[15]

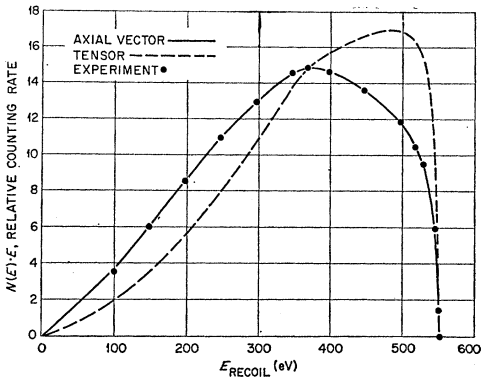

FIG. 1. Recoil spectrum of $(Na^{23})^+$ following the β^- decay of Ne^{23}. The experimental data are compared with special shapes as calculated for axial-vector and tensor interaction.

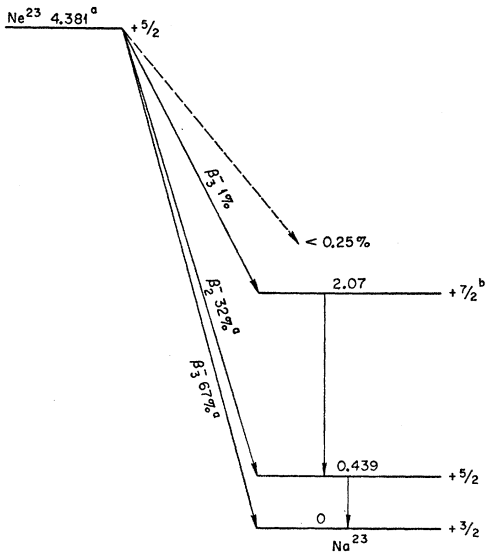

FIG. 2. Decay scheme for Ne^{23}. Energies are in units of MeV. Most of the data are taken from J. R. Penning and F. H. Schmidt, Phys. Rev. **105**, 647 (1957). See also (a) the present paper, (b) D. W. Braben, L. L. Green, and J. C. Willmott, *Proceedings of the Rutherford Jubilee International Conference* (Heywood and Company Ltd., London, 1961), p. 265.

V. ANALYSIS

Before comparison of the experimental data can be made with theory, it is necessary to have a good value for the decay energy of Ne^{23}. *Nuclear Data Sheets*[16] give 4.380 ± 0.006 MeV. The decay energy was also assigned, as described earlier,[5] by matching the data near the end point to the theoretical shape, which had been smeared by the experimental resolution function. The decay

[10] M. E. Rose, in *Beta and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), pp. 273–291.

[11] Ramaswamy found that the Fierz interference term is -0.004 ± 0.012; M. K. Ramaswamy, Indian J. Phys. **33**, 285 (1959).

[12] For a discussion of second-order effects in beta decay, see Ref. 2 and the following: M. Gell-Mann, Phys. Rev. **111**, 362 (1958); and **112**, 2139 E (1958); M. Morita, Nucl. Phys. **14**, 106 (1959); J. N. Huffaker and E. Greuling, Phys. Rev. **132**, 738 (1963).

[13] B. W. Ridley, Nucl. Phys. **6**, 36 (1958).

[14] M. E. Rose, ORNL-1593 (1953) (unpublished).

[15] J. R. Penning and F. H. Schmidt, Phys. Rev. **105**, 647 (1957).

[16] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.).

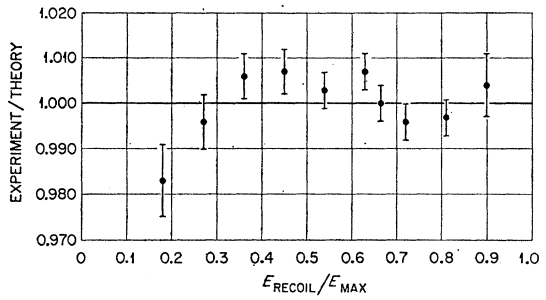

FIG. 3. Comparison of the experimentally determined recoil spectrum of $(Na^{23})^+$ with theory, where $\alpha=-0.329$, $E_{max}=553$ eV, and the beta-ray intensities are those given in Fig. 2.

energy from the present experiment is 4.383 ± 0.008. For purpose of analysis the weighted average of the two values is used to obtain the maximum recoil energy of 553 ± 1 eV.

A least-squares fit of the theoretical shape as determined in Sec. IV is made to data in Table I by using α and the proportionality constant as parameters. The value of -0.329 ± 0.005 is obtained for the angular correlation coefficient, and the ratio of experiment to theory as a function of recoil energy is plotted in Fig. 3. The value of $\chi^2/N-2$, as commonly defined,[17] is 1.6, and without the datum at 100 eV is 1.2. The goodness of the "chi-square test" is consistent with the errors quoted from the data in Table I. Systematic errors have been considered by making use of the detailed evaluation of errors associated with the spectrometer as reported earlier.[2] In the present experiment only errors in the end-point and those due to pressure effects are of importance. They amount, respectively, to errors in α of ±0.004 and ±0.003. By combining in quadrature the error from the least-squares fit with the systematic errors, one arrives at the total error in α that results solely from the measurement of the recoil spectra (±0.007). The result of the present work may be compared with the best previous measurement on Ne^{23}, $\alpha=0.37\pm0.04$, by Allen *et al.*[1] Their value does not contain any consideration of the contribution from the second excited state and does not include the error in the measurement of the relative β^--ray intensities.

[17] For example, see: A. H. Wapstra, G. J. Nijgh, and R. Van Liesboat, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), pp. 10–14.

The error in α from the uncertainty in the treatment of transitions to states higher than the first excited state is estimated to be ±0.003. This gives a net error of ±0.008, excluding the uncertainty of the β^--ray intensities to the ground and first excited states.

The beta-ray intensities to the ground and first excited states are given by Penning and Schmidt as $(67\pm3)\%$ and $(32\pm3)\%$. Unfortunately, the uncertainty in these values constitutes the largest error in the evaluation of α, and the final analysis of α yields -0.33 ± 0.03.

A multiparameter fit was attempted by varying values for the beta-ray intensities as well as α and the proportionality constant, but the error determined for α was no smaller than that given in the above paragraph. One may, however, use the recoil data to assign a better value to the β^--ray intensities, by assuming the *V-A* theory[18] so that $\alpha=-1/3$, and neglecting second order effects.[12] These assumptions are supported by the He^6 experiment,[2] which gives the angular correlation coefficient as -0.3343 ± 0.0030. From a least-squares fit of the Ne^{23} data using $\alpha=-1/3$, the beta-ray intensities to the ground and first excited states are found to be $67\pm1\%$ and $32\pm1\%$.

VI. CONCLUSION

A precise measurement of the recoil energy spectrum following the decay of Ne^{23} has been made. The agreement between the experimental data and theory based on *V-A* interaction is good. Unfortunately, the uncertainty of the beta-ray intensities to the ground and first excited states prevents a close comparison of the parameters involved in beta decay. An accurate reevaluation of the beta intensities in the decay of Ne^{23} is urgently needed.

ACKNOWLEDGMENTS

The author would like to thank Miss Frances Pleasonton of the Oak Ridge National Laboratory for her help and advice in the experimental part of this work. He would also like to express his appreciation to Dr. Eugene Greuling of Duke University for help in clarifying certain aspects of the theoretical interpretation.

[18] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).