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Reconsideration of the Electron-Neutron Scattering Length As Measured by the Scattering of Thermal Neutrons by Noble Gases*

V. E. Krohn and G. R. Ringo
Argonne National Laboratory, Argonne, Illinois 60439

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Our value for the electron-neutron scattering length has been corrected on the basis of new measurements of some neutron scattering lengths and now is $(-1.30\pm 0.03)\times 10^{-16}$ cm, which is 3% lower than our original result. (The equivalent figure in the Fermi convention is -3630 ± 70 eV and at $q=0$, $dG_{En}/dq^2=0.0189\pm 0.0004$ fm^2.) A check on the worrisome possibility of an H_2 impurity in the scattering gases showed that this is quite unlikely to be a significant source of error. The difference between our result and the Munich measurement and also the Foldy calculation thus continues unexplained.

I. INTRODUCTION

The nonmagnetic, electron-neutron scattering length has been measured with comparable precision by two groups, but the results are in significant disagreement. A group from Munich (Nucker,[1] Dilg and Vonach,[2] and Koester[3]) measured the index of refraction of bismuth (which gives the combined nuclear and electronic scattering lengths) and the free cross section of bismuth (which gives the nuclear length alone). Their result for the electron-neutron scattering length is $(-1.427\pm 0.023)\times 10^{-16}$ cm (-3965 ± 70 eV in the Fermi convention). The other is our measurement, completed in 1966,[4] which uses the Fermi and Marshall[5] method of measuring the angular distribution of the neutrons scattered by noble gases and finding the electron-neutron scattering length by its effect on the angular distribution via the atomic scattering factor. The result was $(-1.34\pm 0.03)\times 10^{-16}$ cm (-3720 ± 90 eV). This disagreement is made more interesting by the existence of the Foldy[6] term which comes from a very direct calculation, assuming only that the interaction is relativistically invariant and that the neutron has its observed mass, magnetic moment, and charge. This calculation gives a scattering length of -1.47×10^{-16} cm (-4080 eV), in near agreement with the scattering length measured by the Munich group. On the other hand, our measurements suggest that there may be an additional contribution to the electron-neutron interaction and this might have theoretical significance. Accordingly, we have corrected our 1966 result on the basis of recent measurements of scattering lengths, and have examined our experiment more critically for possible sources of systematic error.

II. CORRECTIONS FOR NEW VALUES OF SCATTERING LENGTHS

New measurements of the coherent scattering lengths of deuterium[7] and fluorine[8] require reconsideration of the values of the scattering lengths of krypton[4] and xenon.[9] First, the Oak Ridge result[9] for xenon (from Bragg reflection on XeF_4) must be modified to take account of the new fluorine value[8] (5.679 ± 0.014 fm). The xenon scattering length becomes 4.96 ± 0.03 fm. Our orginal result from a liquid xenon mirror[10] (5.10 ± 0.17 fm) is consistent with this, but when the mirror results are modified to take account of a number of changes[4] plus the new result for the deuteron (6.673 ± 0.007 fm), they become 5.29 ± 0.11 fm for xenon and 7.96 ± 0.15 fm for krypton. This revised xenon result differs from the revised Oak Ridge result by about three standard deviations. We are unable to account for the discrepancy but will use the modified Oak Ridge result (4.96 ± 0.03 fm) because it is of substantially higher precision than the mirror result, and it seems to come from a very straightforward experiment.

The aforementioned discrepancy indicates that the mirror result for xenon may be too high by about 6%, and this suggests that the mirror result for krypton might be too high by a comparable amount. This idea is reinforced by the fact that the total scattering cross section of krypton[4] limits the maximum value of the coherent scattering length to 7.90 ± 0.02 fm, which is 0.06 fm smaller than the mirror result. For the purpose of revising our results[4] for the electron-neutron interaction, we have used 7.7 ± 0.2 fm for the coherent scattering length of krypton.

It should be noted that the coherent scattering lengths we have given are all for bound nuclei (electron-neutron effects removed).

Our revised result for the electron-neutron interaction is −3630 ± 70 eV. Table I summarizes the revised results for the various scattering gases. It should be noted that, except for the somewhat arbitrary uncertainty given with the rather arbitrary value of the krypton scattering length, we quote standard deviations without any allowance for a possible systematic error.

III. INVESTIGATION OF THE HYDROGEN CONTAMINATION OF THE SCATTERING GASES

Since our value disagrees with that of the Munich group by about $4\frac{1}{2}$ standard deviations (and is even further from the Foldy value), we thought a reappraisal of our experiment would be desirable. In this reappraisal, the principal doubt raised in our minds was the possibility that the scattering gases might be contaminated with small amounts of H_2. Because of the large cross section and the great asymmetry of scattering by H_2, a concentration as small as one part in 100 000 might have been significant. The heavier hydrocarbons that might have been even more serious would certainly be destroyed by the 925° C titanium in our cleaning system, but it was not clear that H_2 itself was retained well enough by the hot titanium, and we had made no direct measurement of this. While there is literature that suggests the Ti is adequate under ideal conditions,[11] we felt that the purity could be affected by the details of the cleanup—in particular, by the amount of impurity removed from the gas, by the treatment of the Ti between uses, by its physical state, etc.—and indeed some of our fears were borne out. We accordingly decided to test the efficiency of our cleaning process at quite low levels of impurity by sending a test gas (a noble gas with an impurity of H_2 containing tritium as a tracer) through the same cleaning system, following the same procedure as was used for cleaning the gases in the scattering experiment.

In our cleaning system, Ti powder, with an average grain diameter of ~1 mm, was packed in approximately a 20-cm length of a stainless steel tube 2 cm in diameter. In the current tests, the Ti was at a temperature of 925° C, and the few liters of the test gas were passed through the tube at a pressure of about $1\frac{1}{2}$ atmospheres and at a rate of roughly 1 liter per min. Between passages, the hot Ti was usually kept in a vacuum system with a pressure $<10^{-4}$ Torr for a length of time indicated in Table II. In the scattering experiment, this time was usually several days.

TABLE I. Summary of results for the electron-neutron interaction.

Gas	$[dG_{En}/dq^2]_{q=0}$ (fm^2)	b (10^{-16} cm)	V_0 (eV)	Statistical weight
Neon	0.025 ± 0.007	−1.7 ± 0.5	−4800 ± 1300	0
Argon	0.0196 ± 0.0013	−1.36 ± 0.09	−3780 ± 250	0.07
Krypton	0.0190 ± 0.0007	−1.32 ± 0.05	−3670 ± 140	0.21
Xenon	0.0186 ± 0.0004	−1.29 ± 0.03	−3600 ± 80	0.72
Weighted mean	0.0188 ± 0.0004	−1.30 ± 0.03	−3630 ± 70	

The tritium concentration was measured by putting the gas under study in a proportional counter with a few percent CO_2 added to improve the counter performance. The counter efficiency was monitored by use of a ^{60}Co γ-ray source. The results of these tests are shown in Table II. It is clear that under these conditions, hot titanium is a very efficient getter and the H_2 left in the noble gases is far below levels significant for our e-n measurement.

IV. CONCLUSIONS

The discrepancy between our result and that of the Munich group is thus unexplained and the possibility that the interaction is not equal to the Foldy term seems still alive. As always there is a possibility that our unrecognized systematic error is substantially larger than the quoted error. Perhaps the strongest result to come out of this reconsideration is the recommendation that, if the experimental disagreement persists, measurements by methods independent of the two under discussion would be very desirable. At least preliminary data have become available for two of these,[12, 13] but we are not sure the work is continuing. We would like to emphasize the desirability of pushing such measurements to higher accuracy.

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TABLE II. The removal of H_2 containing tritium tracer from noble gases by Ti powder at 925 °C.

Test gas and treatment	Concentration of H_2 Initial (ppm)	Final (ppm)
Ar, 5 passes, 30 min total; Ti not pumped between passes.	15	<0.02
Xe, 3 passes, 10 min total; Ti pumped 3 h between 2nd and 3rd passes.	30 000	0.5 ± 0.2
Xe, 1 pass, 3 min total; Ti pumped 3 days before pass.	0.5	<0.01

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[1] Nicholas Nucker, Z. Phys. 227, 152 (1969).

[2] W. Dilg and H. Vonach, Z. Naturforsch. A26, 442 (1971).

[3] L. Koester, private communication.

[4] V. E. Krohn and G. R. Ringo, Phys. Rev. 148, 1303 (1966).

[5] E. Fermi and L. Marshall, Phys. Rev. 72, 1139 (1947).

[6] L. L. Foldy, Phys. Rev. 83, 688 (1951); Rev. Mod. Phys. 30, 471 (1958).

[7] W. Dilg, L. Koester, and W. Nistler, Phys. Lett. 36B, 208 (1971).

[8] L. Koester, private communication.

[9] J. H. Burns, P. A. Agron, and H. A. Levy, in *Noble Gas Compounds,* edited by H. H. Hyman (Univ. Chicago Press, Chicago, 1963), p. 211.

[10] M. F. Crouch, V. E. Krohn, and G. R. Ringo, Phys. Rev. 102, 1321 (1956).

[11] A. D. MacQuillan, Proc. R. Soc. Lond. A204, 309 (1950).

[12] Yu. A. Alexandrov, R. P. Ozerov, and N. V. Ranev, Zh. Eksp. Teor. Fiz. Pis'ma Red. 15, 398 (1972) [JETP Lett. 15, 280 (1972)]; Yu. A. Alexandrov and V. K. Ignatovich, Joint Institute of Nuclear Research Report No. E3-6294, 1972 (unpublished).

[13] C. G. Shull, private communication.

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Experimental Study of the Rare K^+ Decay Modes: $K^+\to\pi^+\pi^0\gamma$, $K^+\to\mu^+\pi^0\nu\gamma$, $K^+\to\pi^+\gamma\gamma$, $K^+\to\pi^+\nu\bar{\nu}$, $K^+\to\pi^0\pi^0e^+\nu$, and $K^+\to e^+\pi^0\nu\gamma$*

D. Ljung† and D. Cline

Physics Department, University of Wisconsin, Madison, Wisconsin 53706

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Six rare stopped-K^+ decays have been studied in the 40-inch heavy-liquid bubble chamber at Argonne National Laboratory. The chamber was filled with CF_3Br. Twenty-two radiative $K_{\pi2}$ events with three converted γ rays were analyzed. The experiment was sensitive to positive pions with kinetic energy 55 to 102 MeV. The strengths (γ and β) of the direct processes in the decay were determined to be $\gamma=-0.02^{+0.17}_{-0.43}$, $\beta=0.0\pm0.3$, and the branching ratio is $(1.5^{+1.1}_{-0.6})\times10^{-4}$ for $55<T_{\pi^+}<80$ MeV. These results are consistent with assuming the decay is dominated by internal bremsstrahlung. No events were found in the search for $K^+\to\mu^+\pi^0\nu\gamma$, and the upper limit on the branching ratio is reported as 6.1×10^{-5} for γ energies greater than 30 MeV. No examples of the $K^+\to\pi^+\gamma\gamma$ decay mode were found. The experiment was sensitive to pions with kinetic energy 6 to 102 and 114 to 127 MeV. The null result allowed us to discard several theoretical models which made branching-ratio predictions for this decay. Assuming a phase-space model for the pion spectrum, the upper limit is 3.5×10^{-5}. The upper limit on the neutral current decay $K^+\to\pi^+\nu\bar{\nu}$ is reported as 5.7×10^{-5} assuming a vector interaction. The decay $K^+\to\pi^0\pi^0e^+\nu$ was observed for the first time. Two events were found in which all four converted γ's were seen. These two events give a branching ratio of $(1.8^{+2.4}_{-0.6})\times10^{-5}$ for this decay. The form factor f_1 for the decay is $|f_1|=0.97^{+0.50}_{-0.19}$. These results are in good agreement with $\Delta I=\frac{1}{2}$ rule predictions. Seventeen $K^+\to e^+\pi^0\nu\gamma$ events were observed. The branching ratio is reported as $\Gamma(K^+\to e^+\pi^0\nu\gamma)/\Gamma(K^+\to e^+\pi^0\nu)=(0.48\pm0.20)\times10^{-2}$ for $E_\gamma>30$ MeV and $\cos\theta_{e\gamma}<0.9$.

I. INTRODUCTION

This paper presents the final results and details of a bubble-chamber study of six of the rare decay modes of the K^+ meson. Preliminary results have been published previously.[1-3] The decays studied (listed in order reported on in this paper) were $K^+\to\pi^+\pi^0\gamma$, $K^+\to\mu^+\pi^0\nu\gamma$, $K^+\to\pi^+\gamma\gamma$, $K^+\to\pi^+\nu\bar{\nu}$, $K^+\to\pi^0\pi^0e^+\nu(K_{e4'})$, and $K^+\to e^+\pi^0\nu\gamma$. The experiment was done in a heavy-liquid bubble chamber in which the γ conversion efficiency was high. Thus, rare K^+ decays that had π^0's or γ's as final-state products were chosen to be studied (or, as in the case of $K^+\to\pi^+\nu\bar{\nu}$, those decays in which the absence of γ's was important).

The physics involved was the study of basic weak-interaction assumptions, the determination of form factors, and the testing of theoretical models. Thus, for example, the search for $K^+\to\pi^+\nu\bar{\nu}$ tested the validity of the no-neutral-current rule, the radiative $K_{\pi2}$ study determined the form factors γ and β, and the search for $K^+\to\pi^+\gamma\gamma$ was able to test and discard several theoretical models.

The experiment has had several significant results. The decay $K^+\to\pi^0\pi^0e^+\nu$ was observed for