Nuclear Magnetic Moment of ^{85}Rb: Resolving a Discrepancy*

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(Received 18 September 1967)

The ratio of the nuclear g_I factor to the atomic g_J factor in ^{85}Rb has been measured by the atomic-beam magnetic-resonance technique to be $g_I(\text{uncorr})/g_J = -1.466478(22)\times10^{-4}$. This result is in excellent agreement with recent optical-pumping measurements but is lower than a previously reported atomic-beam result.

RECENT optical-pumping determinations of g_I/g_J for free ^{85}Rb atoms[1] are in considerable disagreement with an earlier atomic-beam measurement of the same ratio.[2] Because the discrepancy between the optical-pumping and atomic-beam results is nine times the larger experimental uncertainty, the question immediately arises whether this discrepancy is indeed real, or whether one of the measurements is in error. If the discrepancy were real, this would have had interesting implications for atomic theory.

In an attempt to resolve this question, we have remeasured the nuclear magnetic moment of ^{85}Rb, using the atomic-beam magnetic-resonance technique, and have obtained a result in agreement with the optical-pumping measurement. In an attempt to vary our technique from that used in Ref. 2, we have used the triple-loop method[3] in our measurements and have observed the $(F=3, m_F=-1)\leftrightarrow(3,-2)$ transition at its field-independent point at 2076.44 G. The frequency of this line is strongly dependent upon the value of g_I ($\partial\nu/\partial g_I=-2905$, where ν is in MHz and g_I is referred to the Bohr magneton), but depends less on the other parameters ($\partial\nu/\partial a=9.58$, $\partial\nu/\partial g_J=-0.43$) in the Breit-Rabi equation; thus this transition is well suited to a direct measurement of g_I.

A special triple hairpin, shown in Fig. 1, was constructed to observe this transition. The two end hairpins were constructed of standard rigid coaxial line and were used to induce the $(3,-2)\leftrightarrow(3,-3)$ transition. In use, the magnetic field was shimmed as necessary to make the transition frequency the same in both hairpins. The center hairpin, which was used to induce the $(3,-1)\leftrightarrow(3,-2)$ transition, was of a simple box-type construction with a center conductor shorted at the bottom of the hairpin. The center hairpin had a length of 4.5 in., resulting in a resonance linewidth of 5 kHz for this transition. This type of hairpin has been used and tested quite extensively by our group, and has yielded reliable results for frequencies up to about 700 MHz. A typical ^{85}Rb $(3,-1)\leftrightarrow(3,-2)$ resonance observed with this hairpin is shown in Fig. 2. The magnetic field was calibrated by measuring the frequency of the $(3,-2)\leftrightarrow(3,-3)$ transition with the center hairpin.

The center frequency of the resonance was determined by measuring the frequencies of three pairs of points symmetrically placed about the center of the resonance. These six points were taken at random heights varying from one-third to near full height for each resonance. We were careful to record each pair of symmetrically placed points as quickly as possible, to avoid errors introduced by random fluctuations of resonance height. The average of the three pairs was taken to be the center frequency of the resonance. In order to eliminate any discrepancies which might arise due to the direction of the magnetic field or the orientation of the hairpin, data were obtained for the four possible relative orientations and directions of the magnetic field and hairpin; 60 sets of data points were obtained for each orientation of the magnetic field and hairpin.

The data were analyzed by a least-squares fit to the Breit-Rabi equation. The results obtained for the four different orientations of magnetic field and hairpin are

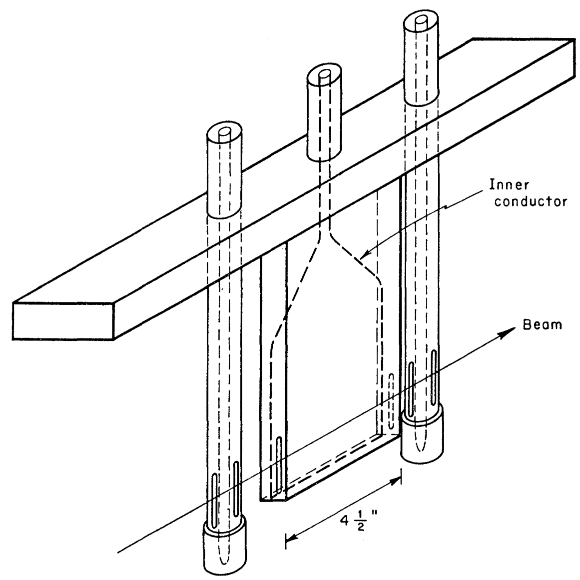

FIG. 1. Schematic drawing of the triple hairpin used in this experiment.

* Research supported by the U. S. Atomic Energy Commission.
† On summer leave from Calvin College, Grand Rapids, Mich.
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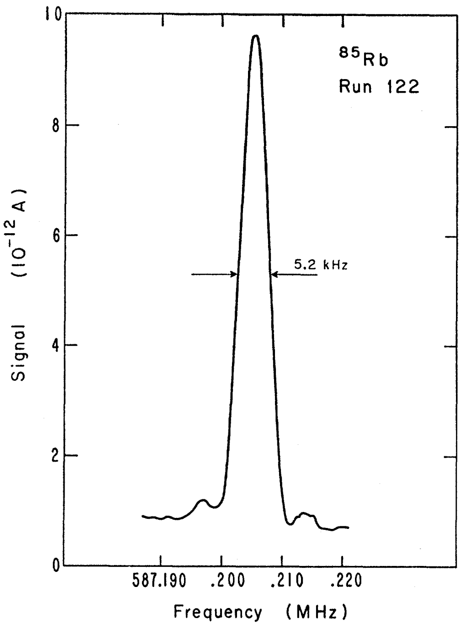

FIG. 2. A ^{85}Rb $(3, -1) \leftrightarrow (3, -2)$ resonance obtained at 2076 G.

shown in Fig. 3. Also shown is a least-squares fit of all data obtained for all four orientations.

It is clear from the figure that our experimental result is independent of the orientation of the hairpin, but that some type of systematic error is introduced by changing the direction of the magnetic field. At the moment we have no conclusive explanation for this shift. It is not a simple Millman effect, but may perhaps arise from the additional field inhomogeneities introduced when the field is in the reverse direction, opposite to the direction of the inhomogeneous deflecting fields. These inhomogeneities caused the calibration resonance linewidth to be twice as much for the reverse direction (≈ 600 kHz) as for the normal direction (≈ 300 kHz).

These measurements were repeated 4 G from the field-independent point, at 2080 G ($\partial\nu/\partial H = 0.175$ kHz/G). Ninety sets of data were taken at various orientations of the hairpin and magnetic field. As a test of possible systematic errors, no great care was taken in this measurement; the magnetic field was not degaussed and calibration linewidths varied from 600 kHz to 1 MHz. The least-squares result at this field was $g_I = 2.936290(85) \times 10^{-4}$. This result is lower than the result obtained precisely at the field-independent point, but is in agrement with it within the experimental uncertainty. This measurement does point out the necessity of using extreme care in the measurement and the desirability of working precisely at the field-independent point.

Our final result obtained at the field-independent point is $g_I = 2.936376(45) \times 10^{-4}$. The uncertainty we have attached is twice the uncertainty yielded by our least-squares analysis as shown in Fig. 3; it has been enlarged to include possible systematic errors. All nuclear g gactors in this paper are uncorrected for diamagnetic shielding.

This experiment essentially is a measurement of the ratio of g_I to g_J. The value of g_J used in the above analysis is -2.0023319; dividing this into our result for g_I, we obtain $g_I/g_J = -1.466478(22) \times 10^{-4}$. This latest measurement is in excellent agreement with recent optical-pumping determinations $-1.466496(10) \times 10^{-4}$ [Ref. 1(a)] and $-1.46648(8) \times 10^{-4}$ [Ref. 1(b)]; but disagrees with the previous atomic-beam measurement $-1.466764(30) \times 10^{-4}$ (Ref. 2).

Recently Figger, Schmitt, and Penselin have measured[4] the g_I of ^{87}Rb by atomic-beam techniques. Using their result, and the previously measured[5] nuclear-magnetic-resonance (NMR) ratio of $g_I(^{85}\text{Rb})/g_I(^{87}\text{Rb})$, we calculate $g_I(^{85}\text{Rb}) = 2.936436(40) \times 10^{-4}$, again in good agreement with the optical-pumping measurement and with our result.

The earlier atomic-beam measurement[2] was performed by observing the separation of the $(3, -1) \leftrightarrow (2, -2)$, $(3, -2) \leftrightarrow (2, -1)$ doublet components at their average field-independent point at 562.6 G. We attempted to repeat the doublet measurement, using the center hairpin shown in Fig. 1, but discovered that at the required frequency of 2612 MHz our measurements were not dependable. Although the resonance appeared symmetric, our measurements of the resonance frequency yielded a value of g_I 10 standard deviations different [$g_I = 2.9385(2) \times 10^{-4}$] from the more accurate value determined by using the triple-loop method. It was impossible to obtain a consistent least-squares fit of these doublet measurements to the Breit-Rabi equation, even when $\Delta\nu$ was allowed to be a variable in the analysis. It is quite clear that the rather simple design of this hairpin does not permit its use at such high

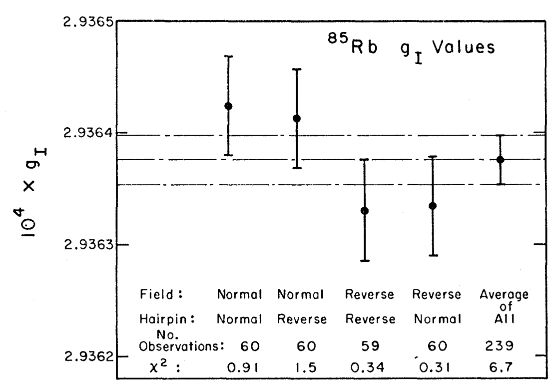

FIG. 3. The results of the least-squares analysis of our data, assuming $g_J(^{85}\text{Rb}) = -2.0023319$. The indicated errors represent one standard deviation.

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frequencies, most likely because of a shift or distortion of the resonance. In an attempt to support this conclusion, the doublet measurements were repeated using a 3-in.-long version of the same hairpin; the result [$g_I = 2.9367(2)\times10^{-4}$] from this shorter hairpin still gave an inconsistent least-squares fit, but was in much closer agreement with our triple-loop results.

It is difficult to understand why the result for g_I quoted in Ref. 2 differs from our results and those of Ref. 1. The data listed by Penselin *et al.* in Ref. 2 are very consistent, and a recalculation based on their data has given essentially the same result as quoted in their article. Furthermore, their results are internally self-consistent in that the mean value of their doublet frequency agrees with their zero-field measurement of the hyperfine-structure separation. An explanation of the disparity remains an open question at this time.

We express our appreciation to Professor Richard Marrus for bringing this discrepancy to our attention and for urging us to remeasure this ratio.

PHYSICAL REVIEW VOLUME 167, NUMBER 4 20 MARCH 1968

Atomic Masses of Fe^{56} and Fe^{57}†

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The 16-in. double-focusing mass spectrometer has been employed to remeasure the atomic masses of Fe^{56} and Fe^{57} in order to study a disagreement between earlier mass-spectroscopic results and nuclear reaction Q values. We find that the present results agree well with the nuclear reaction Q values. A test of the Einstein mass-energy relationship was made using the measured Fe^{57}–Fe^{56} isotopic difference and the $Fe^{56}(d,p)Fe^{57}$ reaction Q value. The mass-energy relationship was substantiated to an accuracy of 0.12%.

INTRODUCTION

THE University of Minnesota's 16-in. double-focusing mass spectrometer has been employed in a wide variety of atomic-mass measurements.[1–8] Improvements made in the instrument during the time of these measurements have caused significant increases in the precision of the measurements. A reduction of systematic errors, measured by improvements in the internal consistency of the data, has also occurred.[8]

Discrepancies between doublet measurements and Q-value mass differences have occurred at a number of isolated masses. It is for this reason that we have undertaken a program of remeasurement of a number of mass doublets. This paper reports a series of measurements which resolve a discrepancy in the Fe^{57}-Fe^{56} mass difference.

† Supported by Contract No. Nonr-710 (58) with the U. S. Office of Naval Research.

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MEASUREMENT

An instrument description and a discussion of the technique of measurement have been recently reported by Benson and Johnson.[8] No change in the instrument has been made for these measurements except that a higher resolution, about 170 000, was employed. The section of the mass spectrum employed for the measurements is shown in Fig. 1. Fragment ions containing iron atoms were obtained from ferrous chloride. Doublets yielding the Fe^{57}-Fe^{56} mass difference could be measured at three different positions in this spectrum. The results of these measurements are listed in Table I. In addition, the mass of Fe^{57} was measured using the C_7H_8-$Fe^{57}Cl^{35}$ doublet. This result is also listed in Table I. In Fig. 2, the consistency of the three different methods of determining the Fe^{57}-Fe^{56} mass difference is shown.

RESULTS

In order to calculate the resultant Fe^{57}-Fe^{56} mass difference, each run of the various doublets which determine this mass difference was given equal weight. This final result together with the associated error is listed in Table II. The mass of Fe^{57} was calculated from the hydrocarbon doublet result using the following two known masses:

$$C^{12} = 12.000\,000\,00\ \text{u}\,,$$

$$H^1 = 1.007\,825\,22 \pm 3\ \text{u}\,.^{8}$$

This mass was combined with the measured Fe^{57}-Fe^{56}