Magnetic Moment of the First Excited State in ^{83}Kr by the Mössbauer Effect*

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The magnetic moment of the 9.3-keV first excited state in ^{83}Kr has been measured by use of the Mössbauer effect. Source and absorber were solid krypton at 4.2°K with the absorber in a longitudinal magnetic field of 77.8 kOe from a superconducting solenoid. The ratio R of the g factor of the $\frac{7}{2}^+$ excited state to that of the $\frac{9}{2}^+$ ground state is found to be $+1.249\pm0.002$, from which $\mu(\frac{7}{2}^+)=-(0.939\pm0.002)\mu_N$ without diamagnetic correction. If the ground state could be considered a pure configuration of three $g_{9/2}$ neutron holes coupling to $J=\frac{9}{2}$ and the excited state a recoupling within the same configuration, then $R=1$. Furthermore, the $M1$ transition matrix element would vanish. The transition is indeed retarded. It appears from the work of Noya, Arima, and Horie that a modest admixture into each state of the configuration obtained by promoting one $g_{9/2}$ neutron to $g_{7/2}$ can in the main account for both the observed transition rate and the excess in R.

INTRODUCTION

THE ground state of ^{83}Kr has $J_\pi=\frac{9}{2}^+$. Its first excited state at 9.3 keV has $J_\pi=\frac{7}{2}^+$. The simplest shell model configuration involved is three $g_{9/2}$ neutron holes coupling to $\frac{9}{2}^+$ for the ground state and to $\frac{7}{2}^+$ for the excited state.[1] Nearby nuclei with $N=43$, 45, and 47 show the low-lying $\frac{7}{2}^+$ state, while for $N=49$ one sees only the $\frac{9}{2}^+$ state, in agreement with the idea that the $\frac{7}{2}^+$ state arises principally from recoupling in the ground-state configuration. Two consequences follow from a pure recoupling description. The first is that the $M1$ transition between the two states is forbidden, and the second is that the g values are identical for the two states. The transition is indeed slow, being retarded by a factor of $\sim$60 with respect to the Weisskopf single-particle estimate. The second point is the subject of the present investigation. We have measured the g factor of the excited state by means of the Mössbauer effect. The technique is similar to that employed in earlier work in this and other laboratories, namely, to apply as large a field as one can conveniently obtain from a superconducting magnet and to depend on curve fitting to decode the resulting broadened velocity spectrum.

The properties of ^{83}Kr appropriate for work with the Mössbauer effect are given in Table I. The radioactive parent is 1.9-h ^{83m}Kr produced by neutron capture in the 11.56% isotope ^{82}Kr. The absorber is natural Kr in which ^{83}Kr has a relative abundance of 11.55%. The magnetic moment of the ground state is seen to be about half of the Schmidt value, which is that of a single neutron $(-1.91\mu_N)$. The transition is nearly pure $M1$, as may be ascertained by the ratio of the estimated $E2$ single-particle width to the radiative part of the observed width. The quantity α is the internal-conversion coefficient and σ_0 the Breit-Wigner cross section at resonance. The mean life of 212 ± 6 nsec corresponds to the natural linewidth $\Gamma_0=0.10$ mm/sec. Twice this value is the smallest that can in principle be observed. The column labeled E_r is the recoil energy expressed in °K. With a Debye temperature of 63°K for solid krypton,[2] this value of E_r leads to a recoil-free fraction $f=0.86$ at 4.2°K, where all of our experiments took place.

EXPERIMENTAL METHOD

Most of the experiments were performed with absorbers of solid krypton contained in small nylon cylinders with thin walls top and bottom. The sources were also solid krypton. The absorber was mounted at the position of maximum field in a superconducting solenoid. Above the magnet was a pair of spaced soft iron shields which served to reduce the stray field at the source position to 1.5 kG under the condition of maximum current. The fields in different runs ranged from 73.7 to 77.8 kOe in the persistent-current mode. The constancy of the field with time was verified by monitoring with an external magnetometer. The source, in the same liquid helium as that which bathed the magnet and the absorber, was moved by means of the mechanical velocity spectrometer described in earlier work. The γ radiation was detected in a beryllium-window proportional counter with an argon-methane filling.

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[1] B. H. Flowers, Proc. Roy. Soc. (London) **212**, 248 (1952); **215**, 398 (1952).

[2] J. de Boer, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland Publishing Co., Amsterdam, 1957), Vol. 2, p. 10.

TABLE I. Properties of the transition in 1.9-h ^{83}Kr.

Rel. abund. (%)	Energy (keV)	$J^{\pi}_{exc} \to J^{\pi}_{gr}$	μ_{gr}	$E2/M1$	α	σ_0 (cm^2)	Mean life (nsec)	Γ_0 (mm/sec)	E_r (°K)
11.55	9.3	$\frac{7}{2}^+ \to \frac{9}{2}^+$	$-0.96707(4)$[a]	Small	11 ± 2[b]	1.89×10^{-18}	212 ± 6[b]	0.100	6.49

[a] H. Korsching, Z. Physik **109**, 349 (1938); E. Brun, J. Oeser, H. H. Staub, and C. G. Telschow, Helv. Phys. Acta **27**, 173A (1954). (Without diamagnetic correction.)
[b] S. L. Ruby, Y. Hazoni, and M. Pasternak, Phys. Rev. **129**, 826 (1963).

Figure 1 shows a typical pulse-height spectrum as transmitted through the absorber.

The magnet was calibrated in several ways, the most accurate of which was by means of a Rawson rotating-coil magnetometer whose calibration was checked against an air-core solenoid with agreement within 0.3%. The other methods of calibration employed the Mössbauer effect itself. In one experiment an absorber of (diamagnetic) sodium ferrocyanide was placed in the magnet and the splitting was observed with a ^{57}Co source. In the second experiment a magnetic sample consisting of a thin foil of ^{57}Fe was placed in the magnet and the hyperfine field was determined as a function of the coil current. These last two field determinations agreed with the former within 1.5%. As we shall see from analysis of the data, the precision of the magnetic field is not very important in determining the ratio of the g values.

In our experimental arrangement it is necessary to observe the radiation along the field direction. In this case the spectrum contains 16 lines. These are incompletely resolved in the field available and it is therefore necessary to apply some constraints in the fitting process to obtain a useful result. The most obvious constraint consists in requiring that the line positions satisfy pure magnetic Hamiltonians for the ground and excited states. The assumption that there is negligible quadrupole splitting is predictable both from the cubic structure of the solid krypton and from our own results.

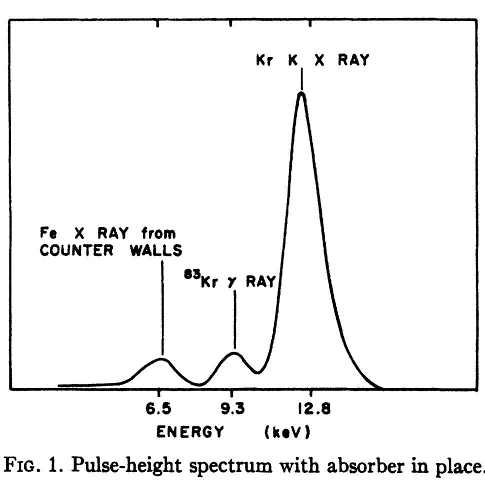

FIG. 1. Pulse-height spectrum with absorber in place.

In the preliminary curve fitting it was assumed that all lines had the theoretical intensities appropriate to a thin absorber and that all widths were equal.

In a subsequent fitting this was modified by applying to the absorption maxima and to the widths first-order corrections based on the thickness of the sample. The overlap between two lines was estimated from the preliminary fit and the theoretical line area was assumed to be intermediate between those calculated for the cases of zero and complete overlap, by linear interpolation, and Lang's formula[3] for the extreme cases. The width corrections were made in a similar way and then the absorption dips adjusted to give the calculated areas. In the subsequent refitting of the data, the ratios of the dips were constrained by use of these values, and the calculated differences among the widths were maintained (Table II). Although the corrections to the dips were sizable, one finds that applying the corrections or omitting them makes only a small difference in the results. Their utilization did, however, improve the value of χ^2 by 12%.

TABLE II. $M1$ Zeeman intensities in a longitudinal magnetic field.

Transition[a] $m_j(\frac{7}{2}^+)\to m_i(\frac{9}{2}^+)$	Theoretical relative line areas for a thin absorber	Relative maximum absorption after correction for thickness and overlap[b]	Additive correction to width[b] (mm/sec)
$+\frac{7}{2}\to+\frac{5}{2}$	1	1	0.0025
$+\frac{5}{2}\to+\frac{3}{2}$	3	2.88	0.0066
$+\frac{3}{2}\to+\frac{1}{2}$	6	5.63	0.0127
$+\frac{1}{2}\to-\frac{1}{2}$	10	8.45	0.0208
$-\frac{1}{2}\to-\frac{3}{2}$	15	11.31	0.0310
$-\frac{3}{2}\to-\frac{5}{2}$	21	14.29	0.0432
$-\frac{5}{2}\to-\frac{7}{2}$	28	17.42	0.0575
$-\frac{7}{2}\to-\frac{9}{2}$	36	20.62	0.0679

[a] One-half of the spectrum is indicated. Exchanging + for − gives the other half.
[b] This applies only to the experiment with solid Kr absorber having a thickness of 1.2 mg/cm^2 of ^{83}Kr. This absorber gave the most accurate value of $R=g_{7/2^+}/g_{9/2^+}$.

[3] G. Lang, Nucl. Instr. Methods **24**, 425 (1963).

TABLE III. Summary of results.

Absorber	Thickness (mg/cm^2 of ^{83}Kr)	H (kOe)	Γ (mm/sec)	R $(=g_{7/2}/g_{9/2})$
Clathrate	0.7	73.4	0.76[a]	1.26±0.01
Solid Kr	0.6	77.7	0.27±0.03[b]	1.245±0.003
Solid Kr	1.2	77.8	0.47±0.04[b]	1.248±0.002
			0.38±0.03[c]	1.251±0.002
		(77.2±0.9)[d]	0.37±0.02[c]	1.251±0.002
Best value	$R=+1.249\pm0.002$			
	$\mu(\frac{7}{2}^+)=+(0.939\pm0.002)\mu_N$ without diamagnetic correction			

[a] This width was constrained to be invariant during the fitting process. Here Γ is the width of the narrowest line.
[b] Fitted without thickness corrections to intensities and widths.
[c] Fitted with corrected relative intensities and widths from Table II.
[d] Here the field was permitted to be a free parameter to be determined by the fit.

RESULTS

Figure 2 shows a velocity spectrum at zero field. The source and absorber each contained 3.5 mg/cm^2 of krypton having the ordinary isotopic abundance. Each had a thickness $t\equiv n\sigma_0 f=4.7$, with n the number of ^{83}Kr nuclei/cm^2. For this, one calculates an expected linewidth $\Gamma_{calc}=0.45\pm0.08$ mm/sec, while the observed linewidth $\Gamma_{obs}=0.50\pm0.02$ mm/sec agrees within error. Thus there is no discernible quadrupole coupling.

Figure 3 shows a velocity spectrum and least-squares fit with the absorber in a field of 77.8 kOe. This absorber contained 10.2 mg/cm^2 of ordinary krypton, which in the case of zero field would correspond to a thickness $t=15.3$; but t is, of course, greatly reduced by the splitting. The source was identical with that of Fig. 2. A summary of results is found in Table III. The ratio R of the excited $\frac{7}{2}^+g$ factor to that of the ground $\frac{9}{2}^+$ is seen to be 1.251±0.002 when fitted with corrected intensities and widths, while use of uncorrected parameters gives the same answer within statistical error. A thinner sample is seen from Table III to give the value $R=1.245\pm0.003$.

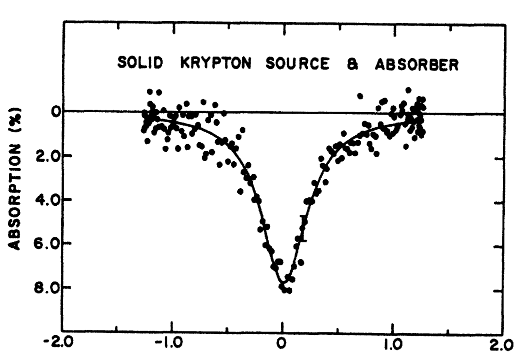

FIG. 2. Velocity spectrum in zero field.

An experiment was also done with the hydroquinone clathrate of krypton as absorber. Here, as also observed by others,[4] the line is broadened by quadrupolar effects and the deduction of detail from the unresolved spectrum is less trustworthy. In order to obtain a useful result, the quadrupolar effects were assumed merely to cause a broadening of the components of a pure nuclear Zeeman pattern. The lack of structure in the spectrum also made it necessary to specify an invariant width for each line. With the width deduced from the results of a zero-field experiment, we obtained $R=1.26\pm0.01$, in agreement with the measurements on the solid Kr samples.

To obtain the results discussed thus far, the strength of the applied field was inserted as a constraint between line positions by use of the known magnetic moment of the ground state. On the other hand, if the spectrum were well enough resolved, this would not be necessary and the field could be deduced from the observed line positions. It turns out that, appearances to the con-

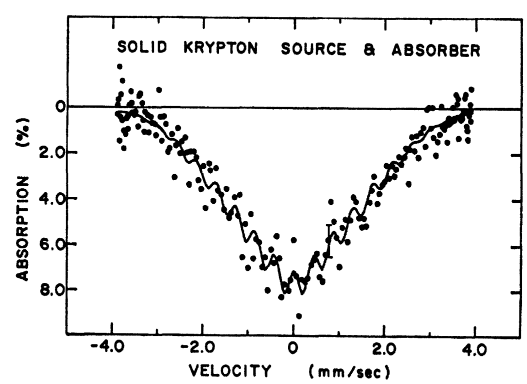

FIG. 3. Velocity spectrum in 77.8 kOe.

[4] Y. Hazoni, P. Hillmann, M. Pasternak, and S. Ruby, Phys. Letters 2, 337 (1962).

trary, the data of Fig. 3 are good enough to obtain a value for the magnetic field. In this way we obtained $H=77.2\pm0.9$ kOe, which is to be compared with the actual value 77.8 kOe. The resulting value for R remained unchanged.

Other tests performed upon the fitting process were as follows. An incorrect value of H which differed from the actual field by 3% was used in the fitting process. The resulting value of R differed by less than 0.1%. In another test the spectrometer constant relating channel number to velocity was altered by 1%. R was observed to change by only 0.02%. From all this it is apparent that the determination of the dimensionless quantity R is virtually independent of moderate errors in the experimental parameters. Hence the small indicated error, although determined by statistics alone, appears to be realistic.

The weighted average of results from the two samples of solid krypton gives the final value $R=+1.249\pm0.002$ quoted in Table III. The sign of R is immediately determined by the clustering of the strength toward the center of the spectrum; the negative sign would put the high-intensity lines toward the periphery. The magnetic moment of the $\frac{7}{2}^+$ state then becomes $(-0.939\pm0.002)\mu_N$ without diamagnetic correction. With the ground-state moment $\mu_g=-0.967$, also uncorrected for diamagnetic effect, it appears that the two magnetic moments rather than the two g values are nearly equal.

DISCUSSION

If the ground state and excited state of ^{83}Kr can be represented by the pure j-j coupled wave functions $(g_{9/2})^7{}_{J=9/2}$ and $(g_{9/2})^7{}_{J=7/2}$, the two moments should be -1.91 and $-1.49\mu_N$ in contrast to observed values of -0.967 and $-0.939\mu_N$. Now Blin-Stoyle and Perks[5] have shown that small admixtures of the other component of the spin-orbit doublet can lead to drastic reductions in the magnetic moment, the reduction being linear in the admixed amplitude. Noya, Arima, and Horie[6] have extended their work and have shown that for the $\frac{9}{2}$ state, configuration mixing due to residual interactions between particles can reduce the moment to the observed value. Several admixed configurations of neutrons and protons contribute to this reduction, but it can be shown that the major contribution comes from the $[(g_{9/2})^6(g_{7/2})^1]_{J=9/2}$ component whose amplitude is about 23%. Although their paper does not enable similar calculations to be carried out for the $\frac{7}{2}^+$ state, it seems probable that a comparable reduction will arise and that the important admixed component comes from the $g_{7/2}$ state.

In the absence of these admixtures, the $M1$ transition probability between these states is zero. With admixtures, the transitions will proceed but with a probability proportional to the square of the admixed amplitude and therefore slower than the single-particle value by a factor of about 10.

We conclude, therefore, that admixture of the $g_{7/2}$ neutron configuration in the ground state and first excited state is probably responsible for the large deviations between the observed moments and the simple prediction and that these admixtures are also responsible for the rate of the $M1$ transition.

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[5] R. J. Blin-Stoyle and M. A. Perks, Proc. Phys. Soc. (London) **A67**, 885 (1954).

[6] H. Noya, A. Arima, and H. Horie, Progr. Theoret. Phys. (Kyoto) Suppl. **8**, 33 (1958).