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NUCLEAR SPINS, NUCLEAR MOMENTS, AND HYPERFINE STRUCTURE OP *>9(}e AND T5(je, AND 3p2 HYPERFINE STRUCTURE OF ^Ge

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NUCLEAR SPINS, NUCLEAR MOMENTS, AND HYPERFINE STRUCTURE OF ^{69}Ge AND ^{75}Ge, AND $^{3}P_{2}$ HYPERFINE STRUCTURE OF ^{71}Ge *

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ABSTRACT

The atomic-beam magnetic-resonance method has been used to measure the nuclear spin I and the hyperfine structure constants a and b in the $^{3}P_{1}$ atomic state of 38-hr ^{69}Ge and 82-min ^{75}Ge and in the $^{3}P_{2}$ atomic state of ^{75}Ge and 11-day ^{71}Ge. From these measurements, the nuclear moments μ_I and Q_I are deduced. The results are: for ^{69}Ge, I = 5/2, $a(^{3}P_{1}) = \pm 23.39(3)$ MHz, $b(^{3}P_{1}) = \mp 8.28(8)$ MHz, μ_I(uncorr) = $\mp 0.733(7)$ μ_N, and Q_I(uncorr) = $\mp 0.028(6)$ barn; for ^{71}Ge, $a(^{3}P_{2}) = +360.54(6)$ MHz; and for ^{75}Ge, I = 1/2, $a(^{3}P_{1}) = -81.05(8)$ MHz, $a(^{3}P_{2}) = +335.94(9)$ MHz, and μ_I(uncorr) = $+0.509(5)$ μ_N.

I. INTRODUCTION

Germanium (Z = 32) has seven odd-mass isotopes. Until recently, nuclear spins and moments and atomic hyperfine structures (hfs) had been measured for only ^{71}Ge[1] and ^{73}Ge.[1-3] This paper is a report on the measurement of the ground state nuclear spins and multipole moments for two more germanium isotopes: ^{69}Ge and ^{75}Ge. It is part of a continuing study by the Berkeley Atomic Beam Group on the atomic and nuclear properties of radioactive isotopes. Hopefully, such measurements for several isotopes of an element can aid in understanding the effects of changing neutron number on the nuclear structure. It is also interesting to note that there have recently been measurements of the nuclear magnetic moments in excited nuclear states of two odd-mass germanium isotopes.[4,5]

We briefly describe the principles and techniques used in these measurements. The results are presented along with a discussion of the contributions to the hfs constants from relativistic corrections and configuration interaction calculated by the effective Hamiltonian technique of Sandars and Beck.[6] Finally, the values obtained for the nuclear moments are compared with the predictions of several nuclear models.

In addition to the above, we also present the results of a measurement improving the $^3P_2$ hfs of ^{71}Ge.

II. GENERAL PRINCIPLES

The Hamiltonian $\mathcal{H}$ for a free atom in an external magnetic field H is given by[7]

$$\mathcal{H} = \mathcal{H}_{hfs} + \mathcal{H}_Z \qquad (1a)$$

where

$$\mathcal{H}_{hfs} = ha\ \underset{\sim}{I}\cdot\underset{\sim}{J} + hb\ \frac{[3(\underset{\sim}{I}\cdot\underset{\sim}{J})^2 + (3/2)(\underset{\sim}{I}\cdot\underset{\sim}{J}) - I(I+1)J(J+1)]}{2I(I-1)J(2J-1)} \qquad (1b)$$

and

$$\mathcal{H}_Z = -g_J\ \mu_o\ \underset{\sim}{J}\cdot\underset{\sim}{H} - g_I\ \mu_o\ \underset{\sim}{I}\cdot\underset{\sim}{H} \quad . \qquad (1c)$$

In Eqs. (1b) and (1c) $\underset{\sim}{I}$ and $\underset{\sim}{J}$ are the vector nuclear and electronic angular momentum operators, respectively, and $g_I = (\mu_I/I)$ and $g_J = (\mu_J/J)$ are the nuclear and electronic g-factors expressed in Bohr magnetons. The hyperfine structure constants a and b are related to the nuclear magnetic dipole moment μ_I and the nuclear electric quadrupole moment Q_I by the relations

$$ha = -\frac{\mu_I He}{IJ} \qquad (2a)$$

$$hb = e^2 q_J Q \qquad (2b)$$

where He is the magnetic field produced by the electrons at the nucleus, and q_J is the atomic electronic field gradient at the nucleus.

In the absence of an external field, $\underset{\sim}{I}$ and $\underset{\sim}{J}$ are strongly coupled by the hfs interaction to form a total angular momentum $\underset{\sim}{F} = \underset{\sim}{I} + \underset{\sim}{J}$. An atomic level specified by the quantum number J is split by $\mathcal{H}_{hfs}$ into levels specified by the different possible values of F. In an external field, $\mathcal{H}_Z$ splits each F level into (2F+1) sublevels specified by the quantum numbers $M_F = -F, (-F+1), \cdots, (F-1), F$.

At low magnetic fields where $\mathcal{H}_{hfs} \gg \mathcal{H}_Z$, F and M_F are the good quantum numbers. At high magnetic fields where $\mathcal{H}_{hfs} \ll \mathcal{H}_Z$, I and J are decoupled and I, M_I and J, M_J are the good quantum numbers. These experiments were done at low and intermediate fields, and the hyperfine levels are specified in terms of the asymptotic zero-field quantum numbers (F, M_F).

III. EXPERIMENT

A. Apparatus

The atomic beam apparatus used for these measurements is the classic flop-in type.[7] A detailed description of our apparatus is given in Ref. 8. A beam of neutral atoms emerges from a well-defined source, passes successively through three magnetic fields designated in order by letters A, C, and B, and then strikes the detector. The A and B magnets have strong inhomogeneous fields with the direction of the gradients parallel to each other and parallel to the direction of the fields. In order for an atom to reach the detector it must undergo equal and opposite deflections as it passes through the A and B fields. This is only possible if its effective magnetic moment reverses sign in the intermediate C field region. In this region, the atom interacts with a weak rf field whose frequency corresponds to the difference in energy between Zeeman hyperfine sublevels of the atom. This necessary reversal of sign leads to the machine selection rule $M_J(A) = -M_J(B)$, where A and B refer to the inhomogeneous magnets.

B. Isotope Production and Detection

Both ^{75}Ge and ^{71}Ge were prepared by neutron irradiation of germanium metal spheres sealed in quartz capsules. The Berkeley TRIGA Mark III reactor, with a flux of 10^{13} cm^{-2}-sec^{-1}, was used to produce 83-min ^{75}Ge while the GETR at Vallecitos, California, with a higher flux of

10^{14} cm^{-2}-sec^{-1}, was used to produce 11-day ^{71}Ge.

The neutron-deficient isotope 38-hour ^{69}Ge was produced by the cyclotron reaction[9] $^{70}Ge(p,2n)^{69}As \xrightarrow{15\ min} {}^{69}Ge$. Both the 88" cyclotron at Berkeley and the Crocker 76" cyclotron at Davis were used to produce ^{69}Ge. The cyclotron target was a 0.078 in. thick germanium disc in an aluminum holder. A total bombardment of about 300 μA-hr was necessary for a good run.

In all three cases, the atomic beam was produced by electron bombardment of a tantalum oven with a graphite liner containing the germanium metal.

Germanium has an electronic ground state configuration $\cdots(4s)^2(4p)^2$. In order of increasing energy, the states arising out of this configuration are: $^3P_0$, $^3P_1$, $^3P_2$, $^1D_2$, and $^1S_0$. At the oven temperature of 1500°C the Boltzmann factors of the $^3P_1$ and $^3P_2$ states are large enough to make transitions between the hyperfine levels of these states observable.

Germanium-69 presented more experimental difficulties than the reactor-produced isotopes. The cyclotron target was made from natural germanium which has five stable isotopes; a number of (p,2n) reactions take place simultaneously, producing several other arsenic isotopes in addition to ^{69}As. Rather than perform a chemical separation of germanium from arsenic, we used the difference in vapor pressure of the two elements at a given temperature to effect a separation. At 500°C the vapor pressure of arsenic is about 120 mm Hg, while the vapor pressure of germanium is essentially zero.[10] The scheme was to increase the oven temperature gradually from about 500°C to the operating temperature of 1500°C. In this way it was possible to drive off the arsenic isotopes from the germanium sample. This procedure took about 30 minutes. Unfortunately, rather than being pumped away and out of the oven chamber of the machine, a good deal of the arsenic appeared to condense on the cooler parts of the oven loader and oven chamber. When the source temperature was raised to 1500°C or so, this arsenic reevaporated and acted as a broad atomic beam source. Because of this broad source effect, the signal-to-background ratio for ^{69}Ge was only half of that of ^{71}Ge or ^{75}Ge.

All three isotopes were detected by means of their radioactivity. The atomic beam was collected on clean sulfur-coated brass buttons which were exposed to the beam for five minutes, removed from the vacuum system, and then sent to the counting area where their radioactivity was measured. Germanium-75 decays by β^- emission and ^{69}Ge decays by β^+ emission; the beta particles were detected by low background Geiger counters. The third isotope, ^{71}Ge, decays by electron capture. Thin NaI(Tl) crystals mounted on photomultipliers were used to detect the 9.2 keV gallium x-ray resulting from this decay.

To normalize the beam intensity, two buttons were exposed simultaneously. One button was placed on the center of the machine to collect the flopped-in beam while the other button was placed off-axis and collected the flopped-out beam. The signal is the ratio of the activity of the center button to that of the side button. A resonance curve is obtained by plotting this ratio versus the applied radio frequency.

C. Spin Measurement

The nuclear spins of ^{69}Ge and ^{75}Ge were measured by observing rf transitions between low-field Zeeman levels in the hfs states with $F = I + J$. The frequency of such transitions is given approximately by

$$\nu = -g_J[J/(I+J)](\mu_0/h)H_0 \quad .$$

For germanium, whose atoms have integral J values, single-quantum transitions changing M_F by ± 1 violate the machine selection rule $M_J(A) = -M_J(B)$. However, at low fields where the Zeeman sublevels are almost equally spaced, a double-quantum transition with $\Delta M_F = \pm 2$ can be induced. At least one of these transitions will satisfy the machine selection rule. The applied frequency is one-half that corresponding to the splitting of the two levels. Usually the rf power required to induce such transitions is much larger than that required for equivalent single-quantum transitions.

Figures 1 and 2 show the results of the spin searches for ^{69}Ge and ^{75}Ge. One can easily see the enhanced signal-to-noise ratio at the $I = 5/2$ points for ^{69}Ge and at the $I = 1/2$ point for ^{75}Ge. To confirm these values, complete resonance curves were also obtained at these low fields.

To help identify the isotopes, a decay analysis of the spin buttons was made. Half-lives of 38 hours and 83 minutes were obtained for the $I = 5/2$ and $I = 1/2$ buttons respectively, identifying the isotopes as ^{69}Ge and ^{75}Ge. For ^{69}Ge, the γ ray spectrum of the cyclotron target, shown in Fig. 3, was taken with a Ge (Li) detector. This spectrum agrees with that in Ref. 11 and the ^{69}Ge peaks can be easily identified.

D. Hfs Measurements

Energy level diagrams for the $^3P_1$ states of ^{69}Ge and ^{75}Ge are shown in Figs. 4 and 5. All the observed transitions are labelled, i.e., α ($\Delta F = 0$, $\Delta M_F = \pm 2$), β ($\Delta F = \pm 1$, $\Delta M_F = \pm 1$), γ,δ ($\Delta F = 0$, $\Delta M_F = \pm 1$), and ε,η ($\Delta F = \pm 1$, $\Delta M_F = \pm 1$).

The general procedure for determing a by ABMR is to follow one of the $\Delta F = 0$ transitions up in field from the low field Zeeman region until the error in a is small enough to permit the observation of a direct $\Delta F = \pm 1$ transition. The double-quantum transition α, used in measuring the spin, was observed at several values of H_0, up to about 25 G. It was observable as long as the two single-quantum component transitions γ and δ differed by less than a few MHz.

When the difference in frequency of the two component transitions γ and δ became too large to allow us to observe the double-quantum transition α, it was necessary to use a two-frequency technique.[12] This technique involves the superposition of two rf fields whose frequencies match those of the two single-quantum transitions γ and δ. One component of the rf field induces transition δ $[(F,M_F)\leftrightarrow(F,M_F+1)]$ and the other component induces transition γ $[(F,M_F+1)\leftrightarrow(F,M_F+2)]$. An atom which makes transitions δ and γ in succession will then satisfy the criterion $M_J(A) = -M_J(B)$. A resonance signal is observed by fixing one of the rf generators at the correct frequency for one transition and then varying the other. Figure 6 illustrates two single-quantum transitions observed in ^{75}Ge at 12.8 G.

After each run, a least-squares fit of the data to Eq. (1) was made, treating a and b as variable parameters. These values of a and b were then used to predict the frequency of the $\Delta F = 1$ β-transition, which was subsequently observed. Figure 7 shows the $\Delta F = 1$ resonance for ^{75}Ge at 1 gauss while Fig. 8 shows the β-transition resonance for ^{69}Ge at its field-independent point, 4 gauss.

The $\Delta F = 1$ observations were combined with the $\Delta F = 0$ data to yield more precise values of a and b. For ^{75}Ge with $I = 1/2$, $b = 0$ the observation of the β-transition completely determines a. The zero-field hyperfine splitting is given by $\Delta\nu = (3/2)a$. For ^{69}Ge, however, with $I = 5/2$, one needs to measure both the ($F = 7/2 - F = 5/2$) and ($F = 5/2 - F = 3/2$) hfs intervals to determine a and b uniquely. Unfortunately, transitions between levels with $F = 5/2$ and $F = 3/2$ violate the machine selection rules and are not directly observable. One can again circumvent this difficulty by superimposing two rf fields in the C-field region. One rf field induces transitions between the $F = 7/2$ and $F = 5/2$ levels, and the other induces transitions between the $F = 5/2$ and $F = 3/2$ levels. This method allows an unambiguous determination of a and b. The transitions observed in this experiment are labeled η and ε in Fig. 4.

When the value of $a(^3P_1)$ was known for ^{75}Ge and ^{71}Ge,[1] the Fermi-Segrè law could be used to predict the values of $a(^3P_1)$ for these isotopes by comparing them to ^{73}Ge for which $a(^3P_2)$ was previously known.[2] Direct $\Delta F = 1$ transitions were observed in the $^3P_2$ state for both ^{71}Ge and ^{75}Ge. The observed frequencies of these transitions were in agreement with the predicted values. Figure 9 shows the $\Delta F = 1$ resonance for the $^3P_2$ state of ^{71}Ge.

IV. RESULTS

A. Summary

Table I lists the quantum numbers of the observed transitions and Tables II, III, and IVa and IVb summarize the data for ^{69}Ge, ^{71}Ge, and ^{75}Ge, respectively.

A least-squares fit of the data to Eq. (1) by a computer routine yielded the results shown in Table V for the hfs constants a and b. This table also lists the nuclear moments deduced from the hfs constants and the χ^2 for each of the fits. The number in parentheses is the uncertainty in the least significant figure, and represents two standard deviations for a and b. Preliminary values of these results were reported earlier.[13]

The magnetic moments were determined by using the Fermi-Segrè relation to compare ^{75}Ge and ^{69}Ge to the stable isotope ^{73}Ge. The hyperfine structure constants and nuclear moments for this isotope have all been measured previously.[2,3] The uncertainties in the values of the nuclear magnetic moments have been taken to be 1% to allow for a possible hfs anomaly. The results for the quadrupole moment of ^{69}Ge are discussed below.

Childs and Goodman[2] have measured a positive sign for a($^3P_1$) for ^{73}Ge. Since it is known that μ_I for this isotope is negative, one would expect a and μ_I to have the opposite sign for all germanium isotopes. To determine the sign of μ_I for ^{75}Ge, we followed the β-transition up to higher fields where the center of the resonance curve depends significantly upon the sign of the nuclear moment. These further observations made the difference in χ^2 between the fits for $\mu_I < 0$ and $\mu_I > 0$ sufficiently pronounced to justify assigning a positive sign to $\mu_I(^{75}\text{Ge})$. This implies that for ^{75}Ge, $a(^3P_1)$ is negative and $a(^3P_2)$ is positive. For ^{69}Ge the data were insufficient to allow a determination of the signs of the nuclear moments, but nuclear theory strongly supports a positive sign for the nuclear magnetic moment.

The data for $a(^3P_2)$ of ^{71}Ge were analyzed in two ways. First, our $\Delta F = 1$ observations alone were fitted by the computer routine, and second, these data were combined with the $\Delta F = 0$ data of Childs and Goodman[1] and another fit was made. Both procedures gave the same results.

B. $a(^3P_1)$ for Ge Isotopes

For pure non-relativistic L-S coupling of two p-electrons to $^3P_1$, one finds $a(^3P_1) = 0$ in contrast to the non-zero experimental values. These non-zero values may be attributed primarily to two sources: relativistic effects and configuration-mixing or core-polarization effects. Sandars and Beck[6] have shown that relativistic effects in magnetic dipole hfs can be taken into account with a three-parameter Hamiltonian

$$\mathcal{H}_{hfs}(M1) = \sum_i 2\mu_o^2\, g_I \langle r^{-3}\rangle_{av}\{\underset{\sim}{\ell}_i F_{orb} - (10)^{1/2}\, (\underset{\sim}{s}\underset{\sim}{C}^{(2)})_i^{(1)} F_{sd} + \underset{\sim}{s}_i F_c\}\cdot \underset{\sim}{I} \quad (3)$$

where the F's are relativistic corrections which will be discussed below. Core-polarization effects can be represented by a term

$$\mathcal{H}_{cp} = C\, \underset{\sim}{S}\cdot\underset{\sim}{I} \quad (4)$$

and will appear as an additive constant to both $a(^3P_1)$ and $a(^3P_2)$ for a particular isotope. Since Eq. (4) has the same form as the last term in Eq. (3) the authors of Ref. 6 point out that it may be difficult to distinguish between these two effects.

One can analyze our measurements for ^{75}Ge, for example, in two ways. If one assumes that the F's in Eq. (3) are each independent parameters to be determined by experiment, then with only two measurements it is impossible to determine the values of these radial parameters or to effect a separation between relativistic or core polarization effects. On the other hand, if one assumes that the F's are given correctly by the formulas of Ref. 6 and the tables of Ref. 14, then one can use the two measured quantities $a(^3P_1)$ and $a(^3P_2)$ to obtain an estimate of $\langle r^{-3}\rangle_{av}$ and the relative contributions of relativistic effects and core polarization effects to $a(^3P_1)$. In this case we can write

$$a(^3P_1;\text{expt}) = a_{cp} + A(^3P_1)\langle r^{-3}\rangle_{av} \qquad (5a)$$

$$a(^3P_2;\text{expt}) = a_{cp} + A(^3P_2)\langle r^{-3}\rangle_{av} \qquad (5b)$$

where a_{cp} is the contribution to a from core polarization, and the A's represent the contribution to a from all the terms in Eq. (3) except $\langle r^{-3}\rangle_{av}$.

For ^{75}Ge we find that a_{cp} = -54 MHz, or about 67% of the total $a(^3P_1)$ with the other 33% coming from relativistic effects. The core polarization term makes $a(^3P_2)$ about 14% smaller than it would be in the absence of this effect. Equations (5) give $\langle r^{-3}\rangle_{av} = 6.4\ a_o^{-3}$. In the absence of any hfs anomalies, the relative contributions of the various sources to the hfs interaction and the value of $\langle r^{-3}\rangle_{av}$ should be the same for all germanium isotopes.

C. Quadrupole Moment of ^{69}Ge

The quadrupole moment Q of ^{69}Ge can be obtained from the constant b by the relation of Eq. (2b). The non-relativistic value of q_J is given by $q_J = 0.2\langle r^{-3}\rangle$. Although relativistic corrections, calculated by the methods of Ref. 6, change the value of q_J by only about 2%, Sternheimer corrections (which we ignore here) could change its value by as much as 15%. From the measured value of b and the value $\langle r^{-3}\rangle$ deduced above, we then obtain the value Q(^{69}Ge) = 0.028(6) barn shown in Table V. The 20% uncertainty in Q results from the theoretical problem of extracting Q from b.

Equation (2b) and our value of $\langle r^{-3}\rangle$ imply that Q(^{73}Ge) = -0.173(26) barn, a value which differs from that in Ref. 2 by about 40%. Through a private communication,[15] W. J. Childs has informed us that he agrees that there was an error in Ref. 2, and that this new value is the correct one.

V. DISCUSSION

The measured spins I = 5/2 for ^{69}Ge and I = 1/2 for ^{75}Ge agree with the predictions of the single-particle (S-P) shell model. On the basis of this model one would expect to find the odd neutrons in ^{69}Ge in the $1f_{5/2}$ shell and the last odd neutron in ^{75}Ge in the $2p_{1/2}$ or the $1g_{9/2}$ shell. It should also be noted that indirect measurements of the spin of ^{69}Ge based on the β-decay[11] of ^{69}Ge and a study of the ^{70}Ge(^{3}He,α)^{69}Ge reaction[15] had previously indicated the value I = 5/2 for this isotope.

One can make a comparison of the measured values of the magnetic moments with the theoretical predictions of various nuclear models. This comparison is shown in Table VI.

For ^{69}Ge, as one might expect, the predictions of the S-P shell model (the Schmidt value) do not agree well with experiment. If one assumes that the sign of the moment should be positive, then the other models all predict values which are much closer to the experimental value. The uncertainties of the theoretical values are at least 0.1 μ_N and probably larger. Within these limits, the predictions of the three more complicated models all agree about equally well with experiment.

As mentioned above, the last odd neutron in ^{75}Ge is in a $p_{1/2}$ state. For a neutron in such a state, both the configuration-mixing approach and Migdal's quasiparticle method (as well as the S-P shell model) predict that the magnetic moment is equal to the Schmidt value. This value, 0.64 μ_N, is in good agreement with experiment. The pairing-plus-quadrupole model prediction includes contributions to the magnetic moment from collective excitations of the nucleus. With these extra contributions, this model predicts a value for the moment which differs from the Schmidt value, but one which gives poorer agreement with experiment than the others.

Finally, one can compare the measured quadrupole moment of ^{69}Ge with the predictions of the various nuclear models. However, the very small value of the ^{69}Ge quadrupole moment and the large experimental uncertainty limit one to only a qualitative comparison. If the sign of the magnetic moment is taken to be positive, then our measurements give a small positive quadrupole moment Q = 0.028(6) barns for ^{69}Ge. The S-P shell model predicts a zero quadrupole moment for all odd neutron nuclei including ^{69}Ge. Both Migdal's quasiparticle theory[16] and the configuration-mixing approach[17] predict a small positive quadrupole moment in agreement with experiment.

Thus, it appears that the nuclear spins and moments of ^{69}Ge are quite well described by some of the more sophisticated versions of the shell model, and that the nuclear magnetic moment of ^{75}Ge is, as expected, close to the Schmidt value.

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Table I. Quantum numbers of observed resonances.

Isotope	Transition Type	J	Quantum Numbers F_1	M_1	F_2	M_2
^{69}Ge	α	1	7/2	7/2	7/2	3/2
	δ	1	7/2	7/2	7/2	5/2
	γ	1	7/2	5/2	7/2	3/2
	β	1	5/2	5/2	7/2	3/2
	ε	1	3/2	-3/2	5/2	-5/2
	η	1	5/2	-5/2	7/2	-7/2
^{75}Ge & ^{71}Ge	α	1	3/2	3/2	3/2	-1/2
	δ	1	3/2	3/2	3/2	1/2
	γ	1	3/2	1/2	3/2	-1/2
	β	1	1/2	-1/2	3/2	-1/2
	β'	2	5/2	1/2	3/2	-1/2

Table III. Observed resonances in ^{71}Ge; I = 1/2, J = 2.

Run No.	Calibration Isotope	Calibration Frequency (MHz)	Field (Gauss)	Ge^{71} Frequency (MHz)	Type†	Residuals (kHz)
GC 5 *	^{133}Cs	24.958	70.006	236.666(5)	α	- 25
GC 4 *	^{133}Cs	18.450	52.004	175.300(6)	α	- 0.1
GC 3 *	^{133}Cs	13.789	39.003	131.200(15)	α	- 9
GC 2 *	^{133}Cs	7.035	20.001	67.100(25)	α	- 2
GC 1 *	^{133}Cs	.350	1.000	4.896(15)	α	-126
1086	^{85}Rb	.463(15)	.991(32)	903.400(200)	β	- 16
1087	^{85}Rb	.869(58)	1.859(124)	905.300(200)	β	62
1088	^{85}Rb	1.863(15)	3.979(32)	909.800(200)	β	98
1116	^{85}Rb	1.815(15)	3.877(32)	909.500(100)	β	14
1117	^{85}Rb	.451(15)	.966(32)	903.400(100)	β	37
1118A	^{85}Rb	.946(15)	2.024(32)	905.500(100)	β	- 83
1118B	^{85}Rb	.941(15)	2.013(32)	905.550(50)	β	- 11

* From the work of Goodman and Childs (Ref. 27).

† See Table I.

Table II. Observed resonances in ^{69}Ge; I = 5/2, J = 1.

Run No.	Calibration Isotope	Calibration Frequency (MHz)	Field (Gauss)	^{69}Ge Frequency (MHz)	Type*	Residuals (kHz)
1126	^{85}Rb	.469(20)	1.004(42)	1.200(100)	α	-26
1135	^{133}Cs	1.069(20)	3.053(57)	3.800(100)	α	-59
1140	^{133}Cs	2.083(30)	5.945(85)	7.800(200)	α	-90
1140A	^{133}Cs	2.779(20)	7.925(57)	10.800(200)	α	-69
1141	^{133}Cs	2.458(20)	7.011(57)	9.500(100)	α	28
1141A	^{133}Cs	1.675(20)	4.780(57)	6.200(100)	α	-22
1141B	^{133}Cs	2.470(20)	7.048(57)	9.600(100)	α	73
1142	^{133}Cs	3.096(20)	8.829(57)	12.200(100)	α	-90
1142A	^{133}Cs	3.064(20)	8.737(57)	12.100(100)	α	-44
1143	^{133}Cs	3.849(20)	10.970(57)	15.800(100)	α	-12
1146	^{133}Cs	5.149(30)	14.659(85)	22.400(100)	α	-4
1153	^{133}Cs	5.319(20)	15.143(57)	23.300(100)	α	-20
1153A	^{133}Cs	6.373(20)	18.126(57)	29.200(100)	α	-25
1156	^{133}Cs	8.812(20)	25.018(56)	44.600(100)	α	-19
1157	^{133}Cs	8.836(30)	25.087(85)	24.200(200)	δ	-297
1157A	^{133}Cs	8.836(30)	25.087(85)	20.500(300)	γ	213
1163	^{133}Cs	8.760(20)	24.872(56)	89.300(100)	β	-124
1168	^{133}Cs	24.677(20)	69.234(55)	89.100(100)	γ	89
1172	^{133}Cs	3.577(25)	10.196(71)	90.700(100)	ε	-1
1172	^{133}Cs	3.577(25)	10.196(71)	89.800(100)	η	74
1172	^{133}Cs	3.556(18)	10.137(51)	90.600(100)	ε	18
1173	^{133}Cs	3.577(20)	10.196(57)	89.600(100)	η	-25
1174	^{133}Cs	8.803(20)	24.993(56)	20.200(100)	γ	11
1174B	^{133}Cs	8.813(30)	25.022(85)	89.400(100)	β	-275
1175B	^{133}Cs	1.488(20)	4.248(57)	72.600(100)	β	58
1178	^{133}Cs	1.550(20)	4.425(57)	72.550(500)	β	78
1180	^{133}Cs	1.507(20)	4.303(57)	79.100(100)	ε	7

* See Table I.

Table IVa. Observed resonances in ^{75}Ge; I = 1/2, J = 1.

Run No.	Calibration Isotope	Calibration Frequency (MHz)	Field (Gauss)	Ge^{75} Frequency (MHz)	Type*	Residuals (kHz)
975	^{85}Rb	.868(8)	1.858(18)	5.100(144)	α	-131
977	^{85}Rb	1.858(8)	3.968(17)	11.200(250)	α	- 45
981	^{133}Cs	2.773(10)	7.908(29)	22.600(280)	α	- 76
985	^{133}Cs	2.782(16)	7.935(46)	22.600(144)	α	-154
986	^{133}Cs	4.477(10)	12.752(28)	37.100(200)	α	- 16
1001A	^{85}Rb	5.968(15)	12.661(32)	17.900(200)	γ	- 14
1001B	^{85}Rb	5.968(15)	12.661(32)	18.900(200)	δ	- 26
1001C	^{85}Rb	5.968(15)	12.661(32)	36.800(200)	α	- 40
1006A	^{85}Rb	9.434(28)	19.904(58)	30.700(200)	δ	16
1006B	^{85}Rb	9.434(28)	19.904(58)	28.600(200)	γ	39
1007A	^{85}Rb	14.278(30)	29.890(61)	47.800(200)	δ	34
1007B	^{85}Rb	14.278(30)	29.890(61)	44.000(200)	γ	- 17
1010A	^{85}Rb	24.250(20)	49.973(40)	84.400(200)	δ	77
1010B	^{85}Rb	24.250(20)	49.973(40)	78.100(200)	γ	- 20
1011A	^{85}Rb	24.226(15)	49.926(30)	78.000(100)	γ	- 35
1011B	^{85}Rb	24.226(15)	49.926(30)	84.150(100)	δ	- 84
1012A	^{85}Rb	37.100(16)	74.955(31)	124.850(100)	γ	-108
1012B	^{85}Rb	37.110(10)	74.974(19)	132.300(100)	δ	- 80
1014	^{85}Rb	.516(6)	1.104(13)	123.900(100)	β	- 23
1094	^{85}Rb	.455(15)	.974(32)	123.650(50)	β	7
2229	^{85}Rb	50.515(15)	100.029(28)	450.400(100)	β	- 15
1121	^{85}Rb	50.507(15)	100.015(28)	450.400(100)	β	39
1016	^{85}Rb	.979(6)	2.094(13)	126.050(50)	β	- 3

* See Table I.

Table IVb. Observed resonances in ^{75}Ge; I = 1/2, J = 2.

Run No.	Calibration Isotope	Calibration Frequency (MHz)	Field (Gauss)	^{75}Ge Frequency (MHz)	Type*	Residuals (kHz)
1111A	^{85}Rb	.452(15)	.968(32)	841.900(200)	β'	37
1111B	^{85}Rb	.936(200)	2.002(427)	843.800(200)	β'	-235
1111C	^{85}Rb	2.337(15)	4.988(32)	850.400(100)	β'	66
1111D	^{85}Rb	2.334(15)	4.981(32)	850.300(200)	β'	-17
1111E	^{85}Rb	.961(15)	2.056(32)	844.000(200)	β'	-148

*See Table I.

Results: $a(^3P_2;\ ^{75}Ge) = +335.94(9)$

$\chi^2 = 0.55$

Table V. Results.

Isotope	Spin	hfs Constants	Nuclear Moments	χ^2
^{69}Ge	5/2	$a(^3P_1) = \pm 23.39(3)$ MHz	$\mu_I = \mp 0.733(7)\ \mu_N$	7.97 (a>0)
		$b(^3P_1) = \mp 8.28(8)$ MHz	$Q_I = \mp 0.028(7)$ barn	8.14 (a<0)
		$b/a < 0$		
^{71}Ge		$a(^3P_2) = +360.54(6)$ MHz [a]		0.47
		$a(^3P_2) = +360.54(6)$ MHz [b]		0.55
^{75}Ge	1/2	$a(^3P_1) = -81.05(8)$ MHz	$\mu_I = +0.509(5)\ \mu_N$	2.23
		$a(^3P_2) = +335.94(9)$ MHz		

[a] From our ($\Delta F = 1$) transitions alone.

[b] From our ($\Delta F = 1$) transitions and ($\Delta F = 0$) transitions in Ref. 1.

Table VI. Comparison of the experimentally measured values of the magnetic moments with the predictions of several nuclear models.

Model	^{69}Ge	^{75}Ge
Single-Particle Shell	+1.37	+0.64
Configuration Mixing [a]	+0.80	+0.64
Pairing Plus Quadrupole [b]	+0.64 [c]	+0.91
Quasiparticle [d]	+0.90 [c]	+0.64
Experiment	±0.733(7)	+0.509(5)

[a] A. Arima and H. Horie, Prog. Theoret. Phys. (Kyoto) 12, 623 (1954).

[b] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. 35, 853 (1963).

[c] This is actually an estimate of the magnetic moment for ^{67}Zn but should be very close to the expected value for ^{69}Ge.

[d] M. A. Troitskiĭ and V. A. Khodel, Sov. J. Nucl. Phys. 1, 143 (1965).

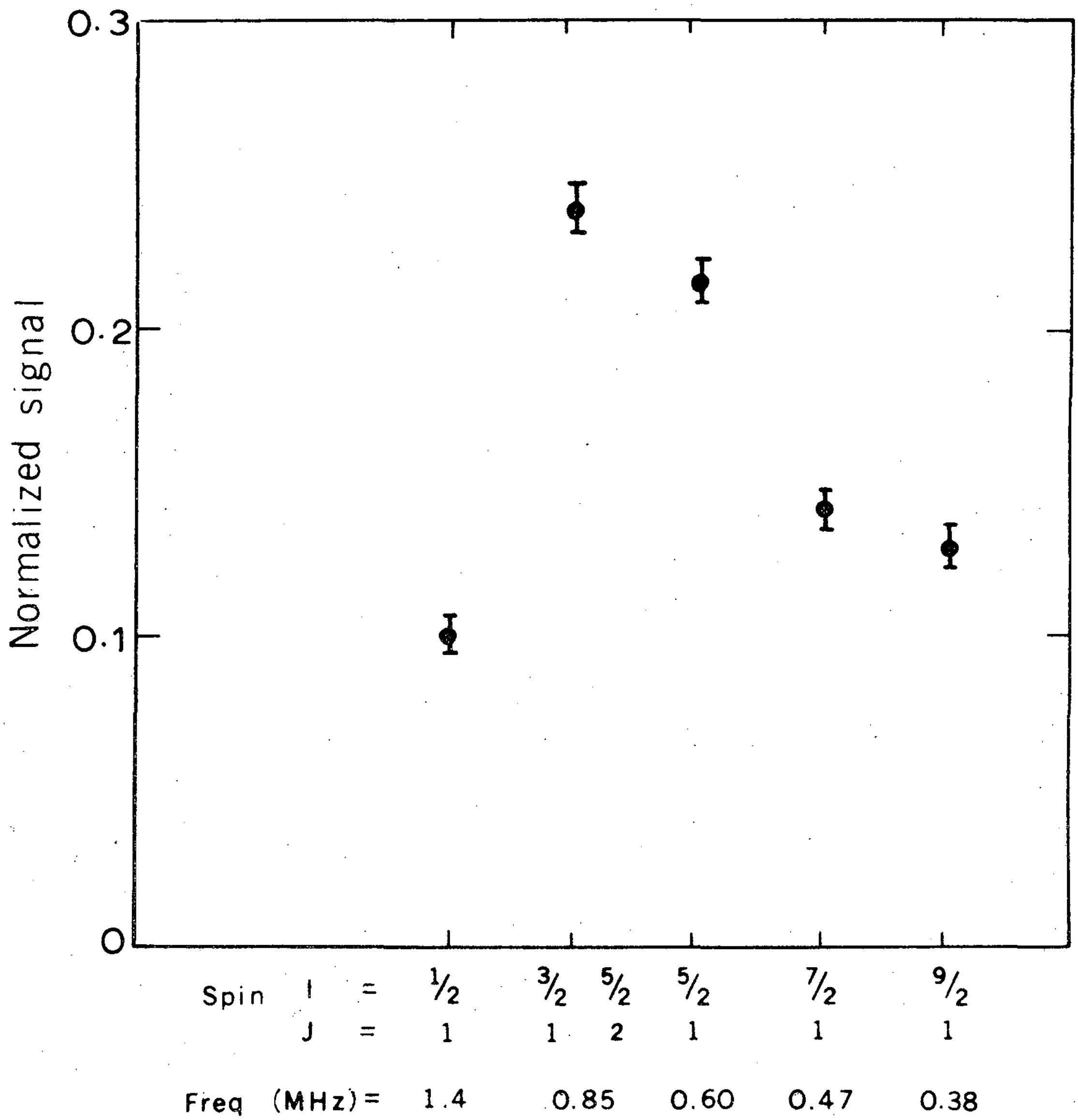

Fig. 1. Results of the spin search for ^{69}Ge.

XBL 699 4906

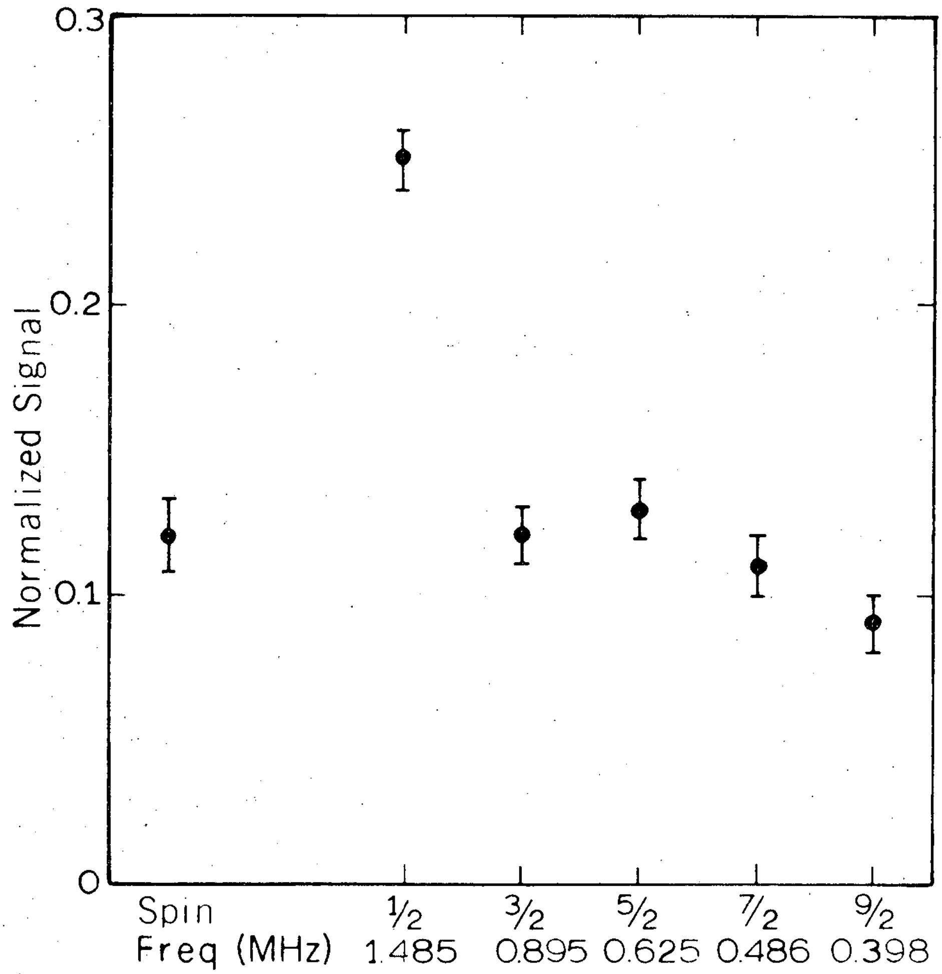

Fig. 2. Results of the spin search for ^{75}Ge.

XBL 699 4900

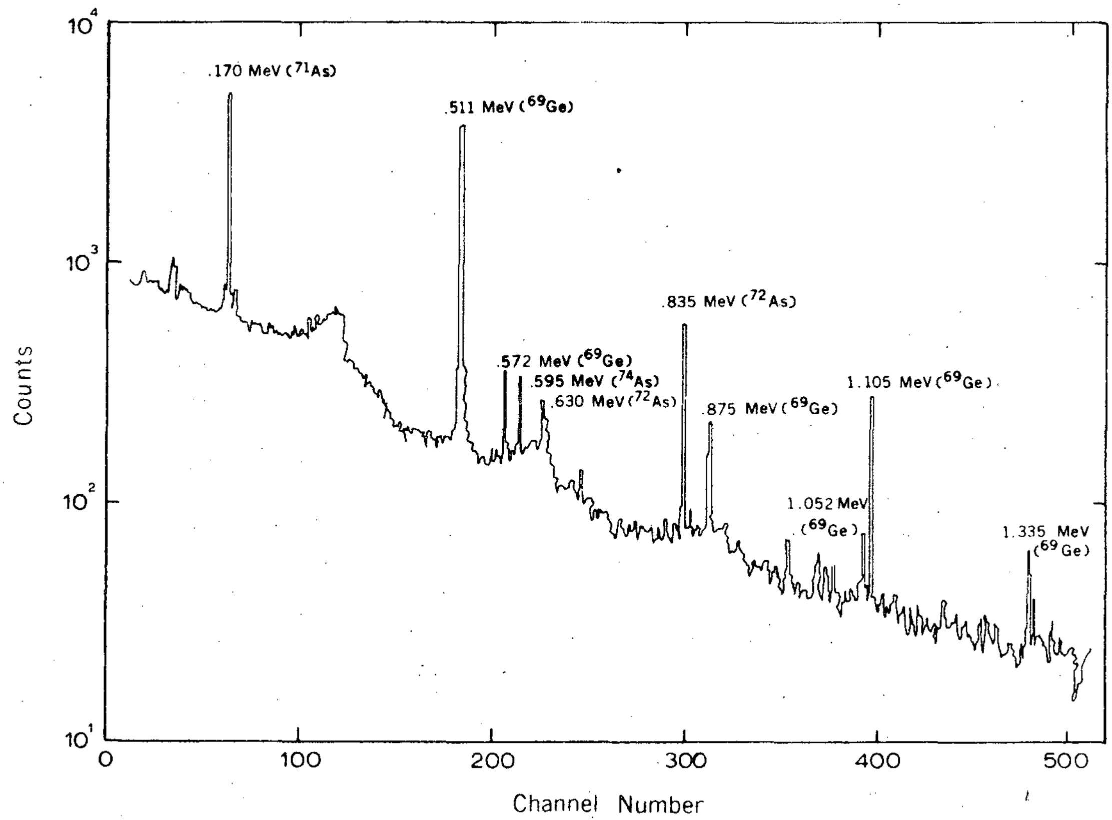

Fig. 3. γ-ray spectrum of the cyclotron target used to prepare ^{69}Ge.

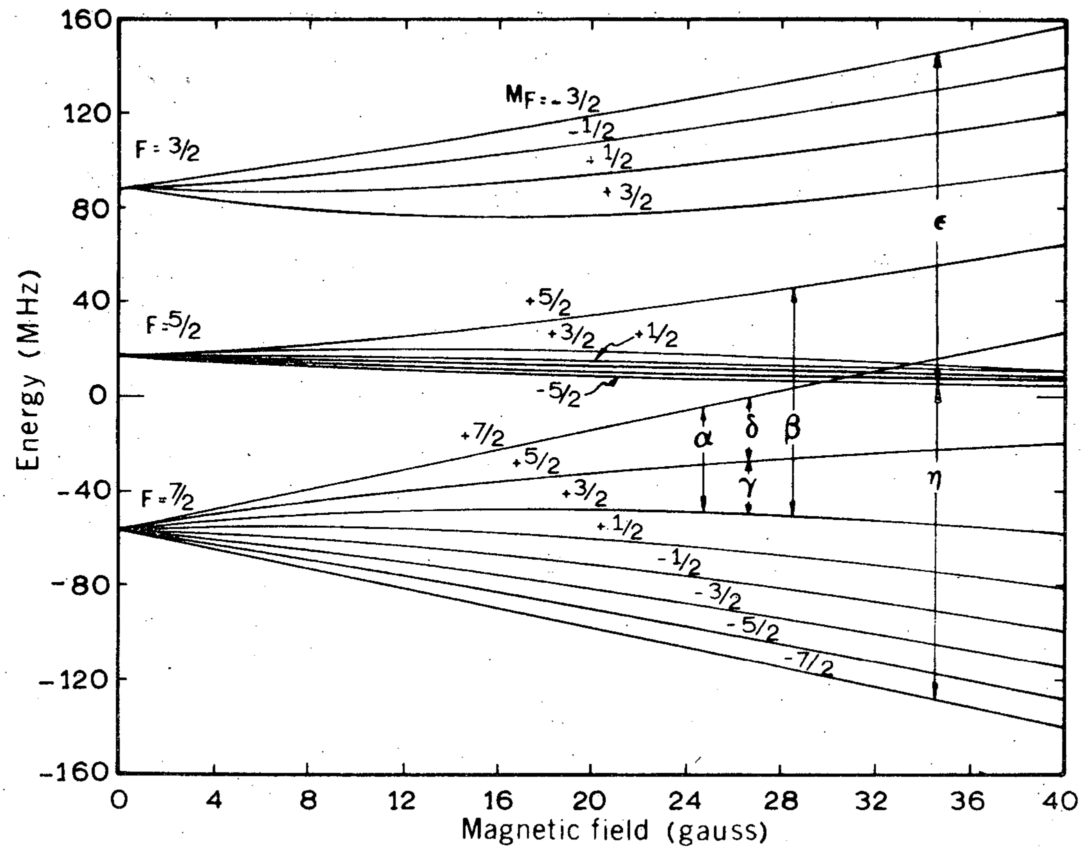

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Fig. 4. Energy level diagram for the $^3P_1$ hfs levels of ^{69}Ge. The diagram is drawn for hfs constants a<0 and b>0.

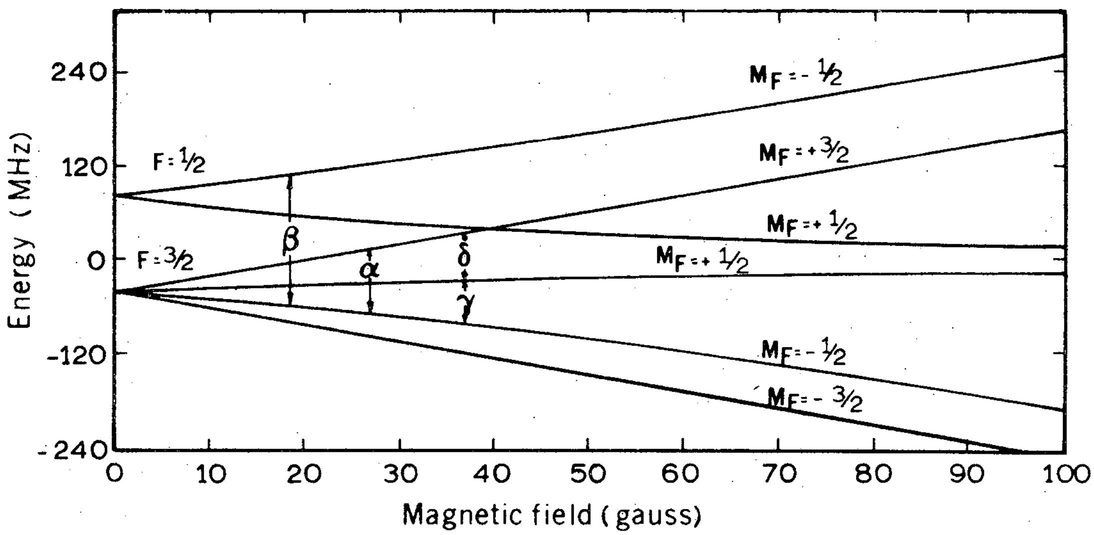

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Fig. 5. Energy level diagram for the $^3P_1$ hfs levels of 83-min ^{75}Ge with a<0.

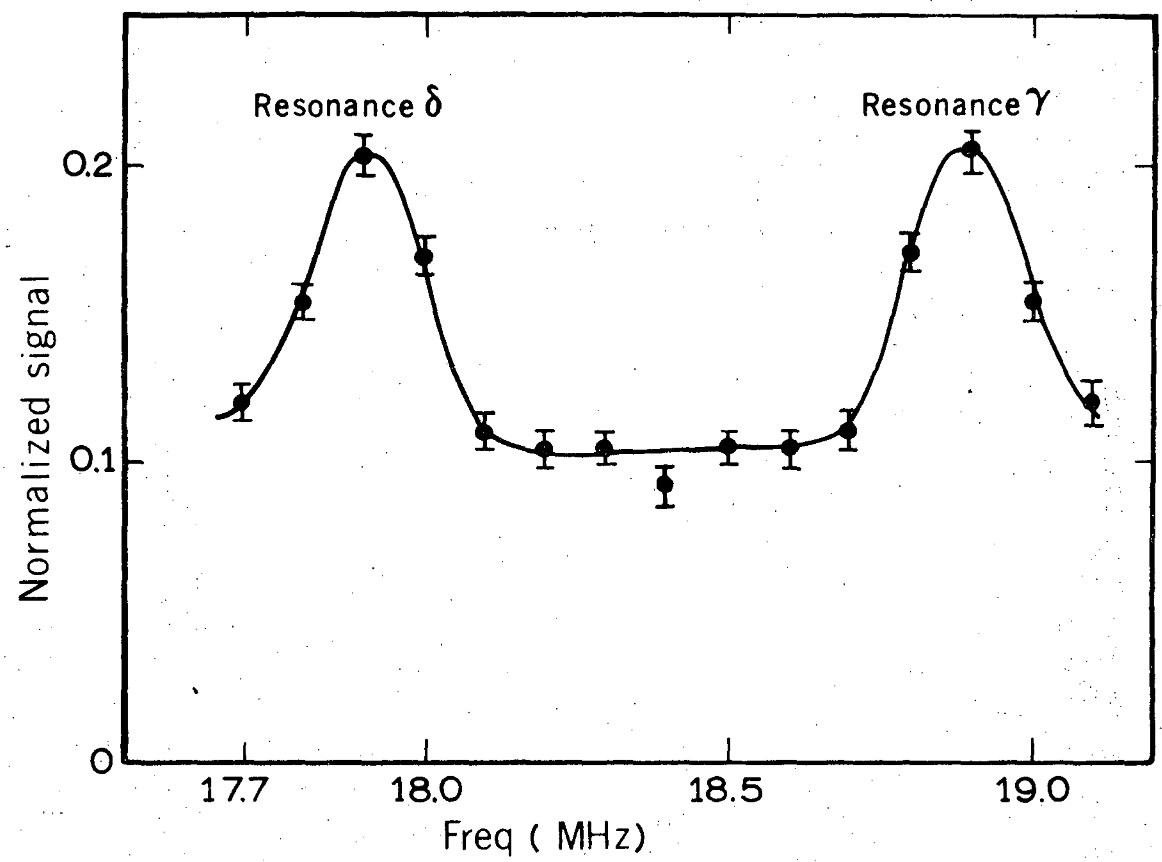

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Fig. 6. Two single-frequency resonances at ∿12.8 gauss. The levels connected in δ are (F = 1.5, M_F = 0.5) and (F = 1.5, M_F = -0.5). Those in γ are (1.5, -0.5) and (1.5, -1.5).

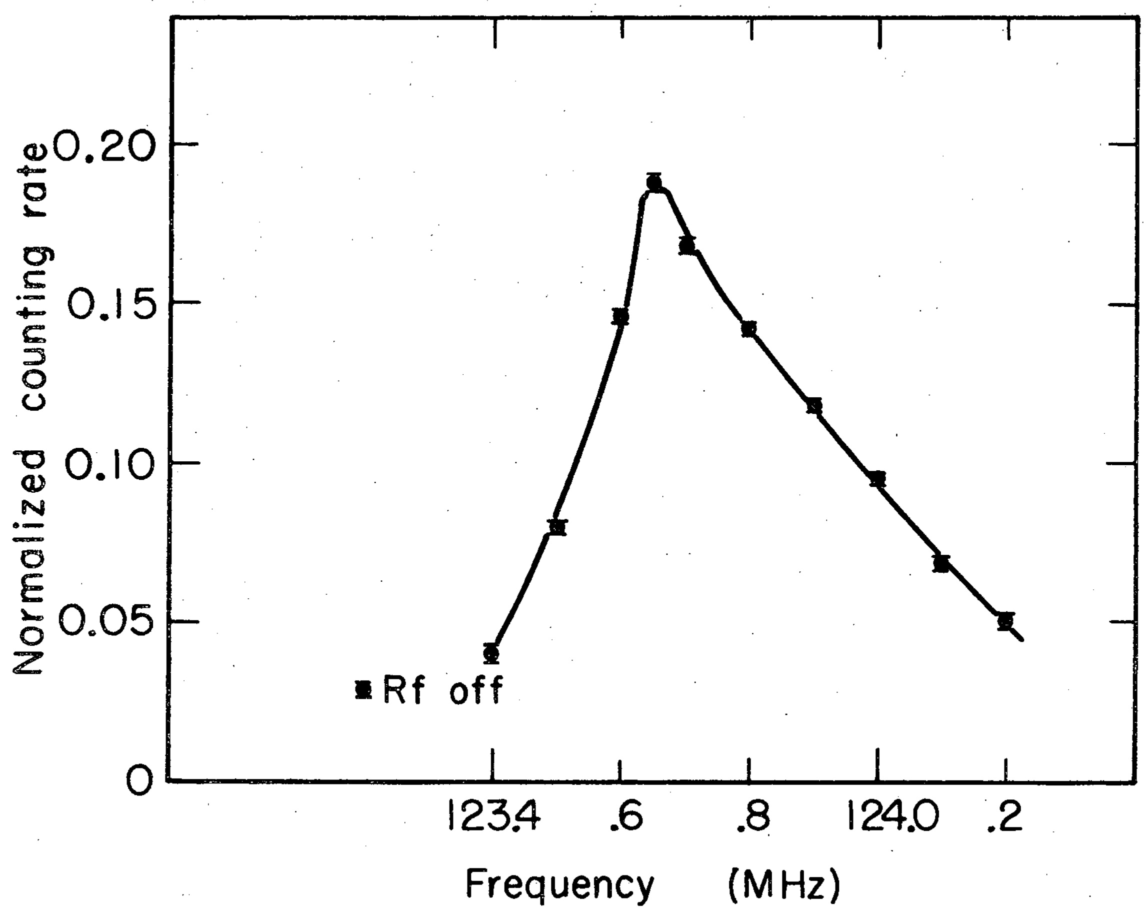

Fig. 7. $\Delta F = 1$, β transition in ^{75}Ge ($^3P_1$) at 1 gauss.

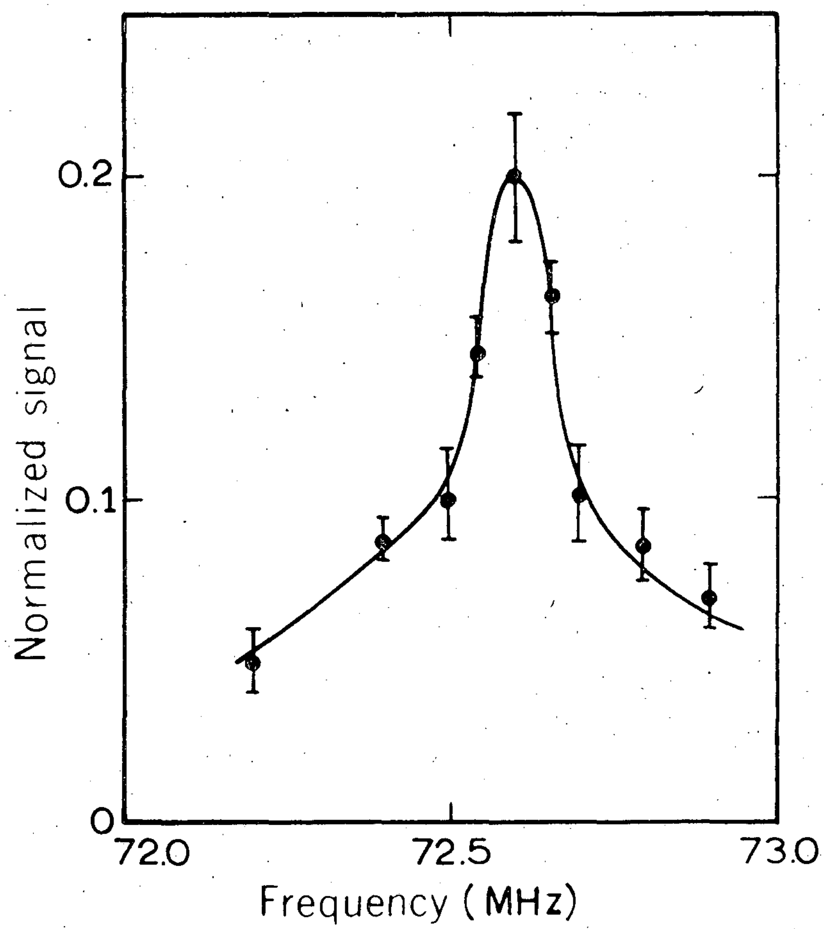

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Fig. 8. $\Delta F = 1$ transition in ^{69}Ge at its field-independent point at ~4.3 gauss.

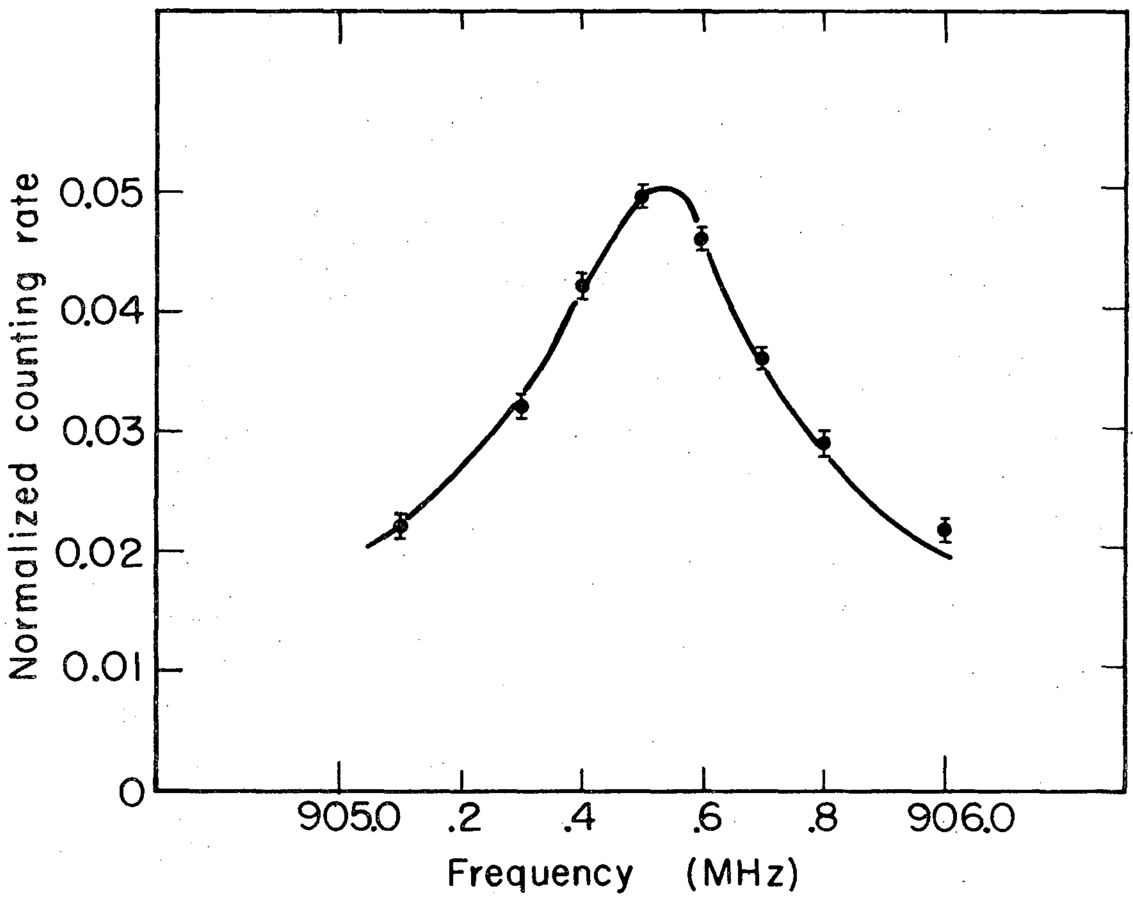

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Fig. 9. $\Delta F = 1$ transition in ^{71}Ge ($^3P_2$) at 1 gauss.

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