UCRL-9879

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

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October 3, 1961

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Abstract

The atomic-beam magnetic-resonance method has been used to determine the nuclear angular momentum of 21-minute Ga^{70}. Measurements performed in both the $^2P_{1/2}$ and the $^2P_{3/2}$ electronic states show that the nuclear spin is $I = 1$.

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Introduction

Previous measurements of the nuclear spins and moments of odd-odd gallium isotopes have yielded several interesting results. The nuclear spins of Ga^{66}, Ga^{68}, and Ga^{72} were found to be 0, 1, and 3 respectively.[1,2,3] Also, the nuclear magnetic moments of both Ga^{68} and Ga^{72} were observed to be small, causing an inversion of the hyperfine-structure energy levels.[3,4] Previously the shortest-lived isotope of gallium investigated by atomic beams possessed a 68-minute half life. This paper describes the spin measurement of 21-minute Ga^{70}.

Isotope Production and Transportation

Ga^{70} is produced most easily by thermal-neutron activation of 60.1%-abundant Ga^{69}, using the $Ga^{69}(n, \gamma)Ga^{70}$ reaction. However, 14.1-hour Ga^{72} is produced simultaneously by the same reaction on 39.9%-abundant Ga^{71}. Because radioactive decay is used for detection, the Ga^{72} causes an undesirable background in the Ga^{70} measurements. Calculations based on the thermal-neutron-capture cross sections and relative half lives of these isotopes indicated that the expected activity of Ga^{70} would be approximately four times that of Ga^{72} 30 minutes after a 1-hour bombardment. Experimentally the ratio was observed to be slightly smaller. Although the presence of Ga^{72} made the experiment more difficult, it was still possible through decay analysis to distinguish the

two isotopes by their different half lives.

The highest-flux nuclear reactor for use in producing the radioisotope in the vicinity of Berkeley is at the General Electric Vallecitos Atomic Laboratory, approximately 40 miles away. Because of this distance, rapid transportation of the bombarded sample presented a major problem. With the assistance of the U. S. Office of Naval Research, arrangements were made to deliver the sample by Navy helicopter. This method reduced the transportation time to 17 minutes.

Because of the short half life, all planning for the experiment centered around making every operation as rapid as possible. In order to avoid wasted time in transferring the bombarded material to the oven container, the entire graphite oven (3/8-in. cube) was bombarded with the gallium already enclosed. This was possible because of the low neutron-capture cross section of carbon. Typically, about 30 mg of Ga was irradiated. In addition, the oven contained 4 mg of CsF to aid in lining it up when placed in the atomic-beam machine. The oven enclosed in a small polyethylene capsule filled with helium, was irradiated in the reactor for 1 hour. Immediately after the bombardment the radioactive capsule was transferred to a 120-lb lead-uranium container and flown to Berkeley. Upon arrival in Berkeley the polyethylene capsule was sliced open with a hot nichrome wire, and the irradiated oven was loaded into the atomic-beam apparatus. The few mg of CsF present in the oven allowed rapid oven line-up by the use of a tungsten hot-wire ionization detector. The CsF caused no interference during the remainder of the experiment because it was quickly evaporated as the oven was heated by electron bombardment to the temperature of 1300°C necessary to produce a beam of gallium atoms. The elapsed time between removal of the radioactive capsule from the reactor and exposure of the first samples was usually about 30 minutes.

Experimental Method

The first-order field dependence of the resonance frequency for an atom undergoing a transition with $\Delta F = 0$, $\Delta m = \pm 1$ is[5]

$$\nu_0 = g_F (\mu_0 H)/h, \tag{1}$$

where

$$g_F = g_J [F(F+1) + J(J+1) - I(I+1)] / 2F(F+1),$$

and terms involving the nuclear moment are neglected. Since g_J and J are known for Ga, the measurement of the resonant frequency ν_0 at low magnetic fields gives an unambiguous determination of I, the nuclear spin. Second-order effects enter at higher magnetic fields and cause deviations from Eq. (1). These deviations can be used to determine the hyperfine-structure separations and thus the nuclear moments of the isotope in question.

The electronic ground state of gallium is $^2P_{1/2}$, with a fine-structure separation of only 826 cm^{-1} to the $^2P_{3/2}$ state. At the 1300°C operating temperature of the oven, the $^2P_{1/2}$ and $^2P_{3/2}$ levels are almost equally populated. The "flop-in" geometry employed in this experiment imposes the condition that only transitions with $m_J = \pm 1/2 \leftrightarrow m_J = \mp 1/2$ are focused. Thus the only $\Delta F = 0$ transitions observable for gallium are in the $F = I + J$ level of the $^2P_{1/2}$ state and in the $F = I + J$ and $F = I + J - 1$ levels of the $^2P_{3/2}$ state.

Standard techniques used in radioactive atomic-beam work[5] were modified slightly in this experiment because of the short half life involved. The samples collected with the stop wire in place and the radiofrequency field on (traditionally called spin samples) were exposed for 2.5 min each, whereas the samples taken with stop wire out and with the radio-frequency

off (half-beam samples used for normalization purposes) were exposed for 30 seconds. The half-beam samples contain the high-velocity component of the beam which otherwise would have been stopped by the stop wire. The total number of samples taken during a run was limited by two factors; first, the short half life, which required that the entire experiment be completed within one or two half lives; second, the presence of the Ga^{72}, which required obtaining a good decay curve for each sample in order to distinguish between the Ga^{70} and Ga^{72} decay components. In general, six or seven spin samples were exposed during each run. These, together with a half-beam sample, were cycled through continuous-flow Geiger counters a sufficient number of times to obtain good decay curves. Each decay curve was analyzed with a digital computer program, using a least-squares method. The output of this routine gave the relative amount of each isotope present on each sample at an arbitrarily chosen zero time.

Although the beam of gallium atoms appeared to possess short-term stability, it was subject to long-term variations. Thus it was necessary to normalize the counting rates of the spin samples to correct for changes in beam intensity. Two methods of normalization were used. The first, and perhaps more usual, is called half-beam normalization. This method assumes that the beam intensity during the exposure of a spin sample is equal to the average of the beam intensities indicated on the half-beam samples exposed immediately before and after the spin sample in question. The other method of normalization, possible only when there is more than one radioactive isotope in the beam, is called ratio normalization. This method assumes that the amount of the background isotope on a spin sample is proportional to the beam intensity during exposure of that particular sample. Thus, in this experiment, it is necessary only to calculate the ratio of Ga^{70} to Ga^{72}

on a sample in order to obtain the normalized Ga^{70} counting rate. Both methods of normalization were used and were found to yield consistent results.

Results

A "spin search" was performed during the first experimental run. The procedure consisted of exposing spin samples at frequencies corresponding to the various possible nuclear spins. In Fig. 1 we have plotted the normalized Ga^{70} counting rate of the spin samples obtained. The results clearly indicate $I = 1$ for this isotope. If we plot the Ga^{72} counting rate of the same samples, we obtain Fig. 2. This indicates $I = 3$ for Ga^{72}, in agreement with previous observations.[3] In Fig. 1 we note that the sample exposed 200 kc/sec above the frequency for the $I = 1$ transition has a lower count rate than the $I = 1$ sample, indicating that any deviations from the first-order frequency are relatively small at this magnetic field. The decay curves for several samples obtained during the spin search are shown in Fig. 3. The relative enrichment of Ga^{70} and Ga^{72} on the $I = 1$ and $I = 3$ samples, respectively, is readily apparent.

During the next experimental run an attempt was made to obtain a resonance curve for the observable transition in the $F = 5/2$ level of the $^2P_{3/2}$ state. The result is shown in Fig. 4. We note that the Ga^{72} counting rate is essentially constant whereas the Ga^{70} counting rate indicates a good resonance. Also demonstrated in this figure is the equivalence of the two methods of normalization. The points agree well within their respective limits of error; virtually the same curve could be drawn through each of the two separate sets of points.

Each of the observable $\Delta F = 0$ transitions was observed at least once in the succeeding runs. Figure 5 shows the result obtained for the $^2P_{3/2}$,

$F = 3/2$ transition. In this figure, which shows the ratio-normalized Ga^{70} counting rate, is also shown the ratio of Ga^{70} to Ga^{72} present on the half-beam (A and B magnets on) and the full-beam (A and B magnets off) samples. We should expect these samples to possess a Ga^{70}-to-Ga^{72} ratio equal to that of the background (off-resonance) buttons, but we note it is higher. This effect was observed in all the runs. Although the presence of the extra short-lived component in the half-beam samples is not fully understood, it should have no effect on the results of these experiments. The unknown activity most likely arises from initial impurities in the gallium or CsF or in the carbon oven.

All the Ga^{70} data obtained are summarized in Table I. We have also listed the identification of the various resonances observed, and the first-order frequency ν_0 at which they should be expected for $I = 1$. We note that the difference between the observed frequency and the first-order frequency is slightly larger than the experimental uncertainty in two cases, indicating that second-order effects are becoming noticeable around 10 gauss. In Fig. 6 are plotted the observed resonance frequencies as a function of magnetic field. In addition we have shown ν_0 vs H for $I = 1$, and also for the possible case $I = 2$. We see clearly that $I = 1$ fits the data very well.

Discussion of Results

The observed nuclear spin $I = 1$ for Ga^{70} is in agreement with earlier observations employing β-ray spectroscopy.[6] The result indicates that the 39th neutron is in a $p_{1/2}$ state, while the 31st proton is in the $p_{3/2}$ state. According to the simple shell model, these particles then couple according to the strong rule to give the observed spin $I = 1$.

Although small second-order effects may be appearing in the higher-field resonances, more data are needed to establish quantitative information concerning the nuclear moments of this isotope. The observed shifts tend to indicate that the moments are relatively large when compared with those of the other odd-odd gallium isotope. Using the shell model and j-j coupling of the $p_{1/2}$ neutron and the $p_{3/2}$ proton, we obtain calculated values of the magnetic moment of + 1.4 nm if the empirical proton and neutron g factors of neighboring odd-proton and odd-neutron nuclei are used, and +2.8 nm if theoretical g values for a free proton and neutron are used. Both these calculated values greatly exceed the magnetic moments of the other odd-odd gallium nuclei; however, a quantitative comparison in Ga^{70} must await further investigation.

Acknowledgements

We wish to thank Dr. W. B. Ewbank, Dr. F. R. Petersen, Miss B. M. Dodsworth, Mr. F. S. Baker, and Mr. J. Bowen for the help given during the critical phases of the experiment. We are also grateful to the Health Chemistry Division of the Lawrence Radiation Laboratory and the operators of the Test Reactor at Vallecitos Atomic Laboratory for their extremely rapid and careful handling of the radioactive sample. Especially, we would like to thank LCDR R. E. Roby, his crew, and the United States Navy for providing the helicopter transportation of the bombarded sample.

Footnotes and References

*Supported in part by the U. S. Atomic Energy Commission and the U. S. Office of Naval Research.

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5. For example, see W. A. Nierenberg, Ann. Rev. Nuclear Sci. 7, 349 (1957).
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Table I. Summary of Ga^{70} Data

Calibration frequency[a] (Mc/sec)	Ga^{70} frequency (Mc/sec)	Electronic state	F	Magnetic field[b] (gauss)	Calculated first-order frequency ν_0 for I=1 (Mc/sec)	$\nu - \nu_0$ (Mc/sec)
1.510(25)	Spin = 1	$^2P_{3/2}$	5/2	3.227(53)		
1.867(30)	4.470(100)	$^2P_{3/2}$	5/2	3.987(64)	4.466	+.004
1.633(25)	1.115(100)	$^2P_{1/2}$	3/2	3.490(53)	1.084	+.031
1.730(25)	5.210(125)	$^2P_{3/2}$	3/2	3.696(53)	5.060	+.150
4.616(25)	11.125(90)	$^2P_{3/2}$	5/2	9.815(53)	10.995	+.130

[a]Calibration in terms of the Rb^{85} (3, -2) $\leftrightarrow$ (3, -3) transition.

[b]Calculated from the calibration frequency.

Figure Captions

Fig. 1. Spin search conducted at a magnetic field of 3.227 gauss; normalized Ga^{70} counting rate.

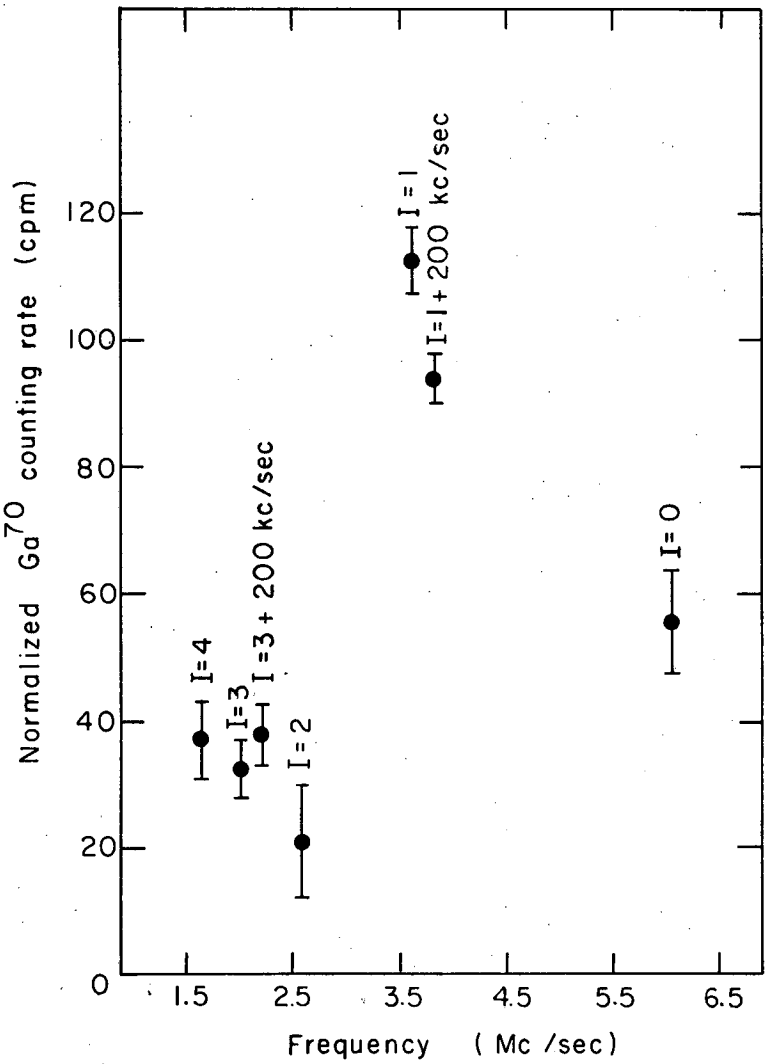
Fig. 2. Spin search conducted at a magnetic field of 3.227 gauss; normalized Ga^{72} counting rate.

Fig. 3. Decay curves of three samples obtained during the spin search.

Fig. 4. Ga^{70} resonance obtained at a magnetic field of 3.987 gauss. The ratio-normalized points are shifted 25 kc/sec to the right for display purposes.

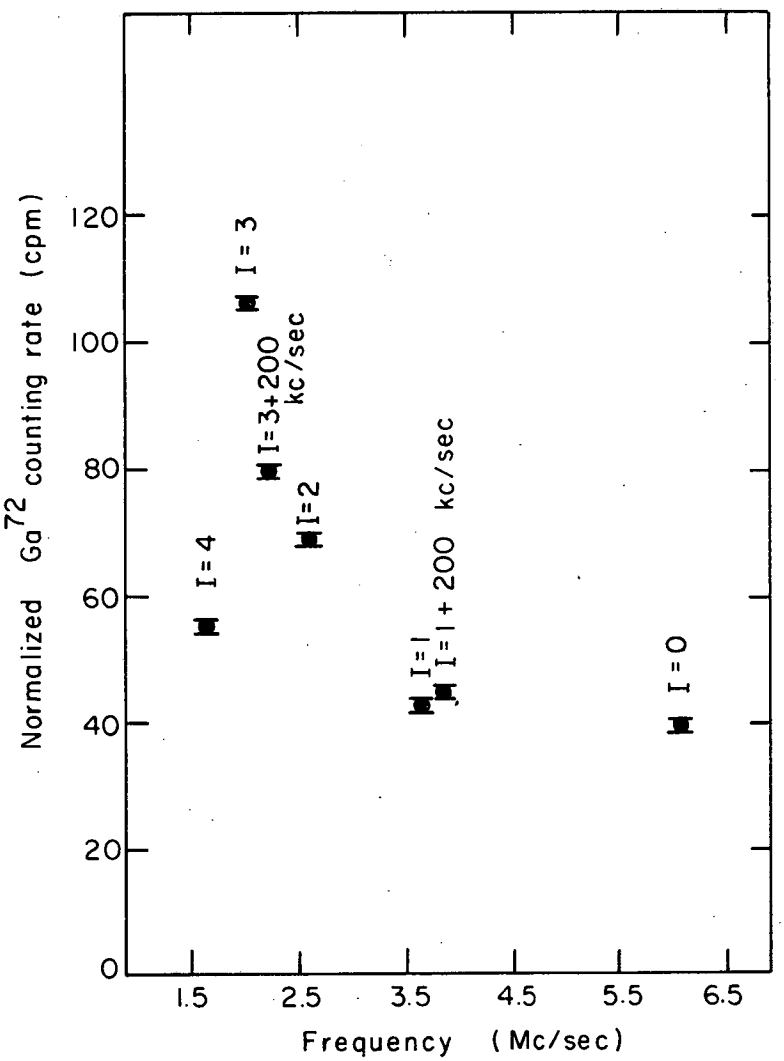
Fig. 5. Ga^{70} resonance obtained at a magnetic field of 3.696 gauss.

Fig. 6. Comparison of observed resonances to first-order resonance frequency. Solid lines for $I = 1$, dashed lines for $I = 2$.



MU-19578

Fig. 1



MU-19579

Fig. 2

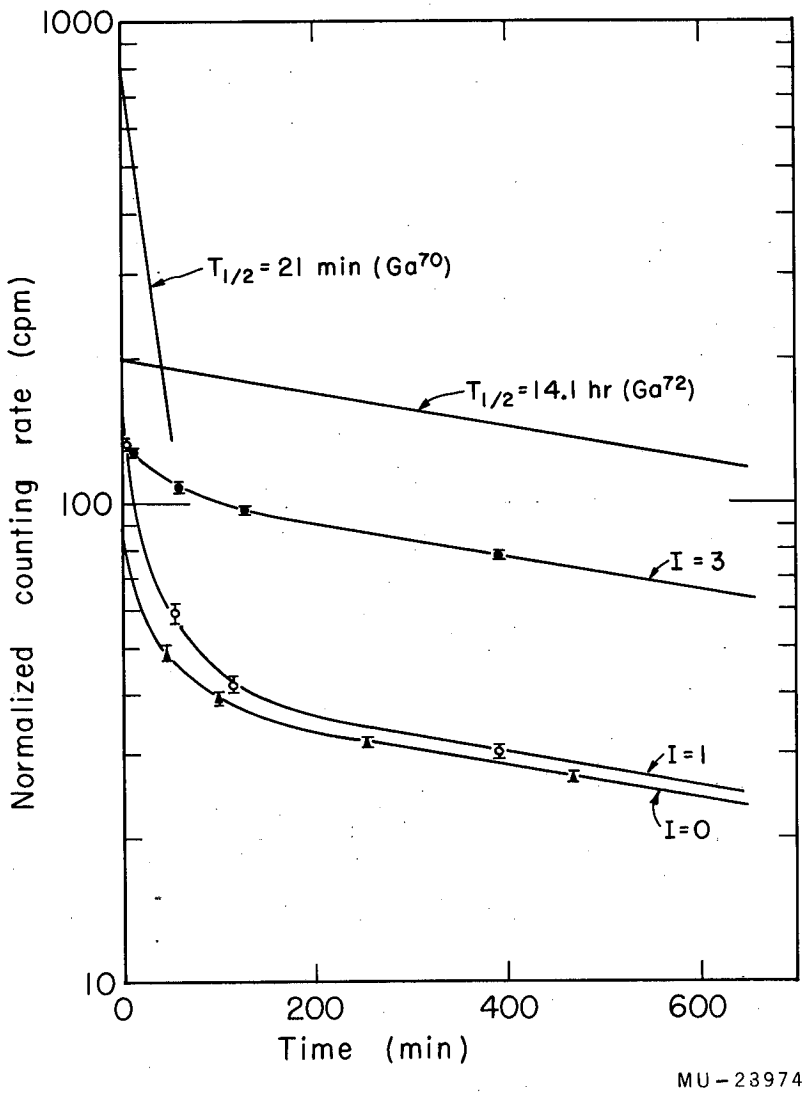

1000
100
10
0
200
400
600
Time (min)
Normalized counting rate (cpm)
$T_{1/2}$ = 21 min (Ga^{70})
$T_{1/2}$ = 14.1 hr (Ga^{72})
I = 3
I = 1
I = 0
MU-23974

Fig. 3

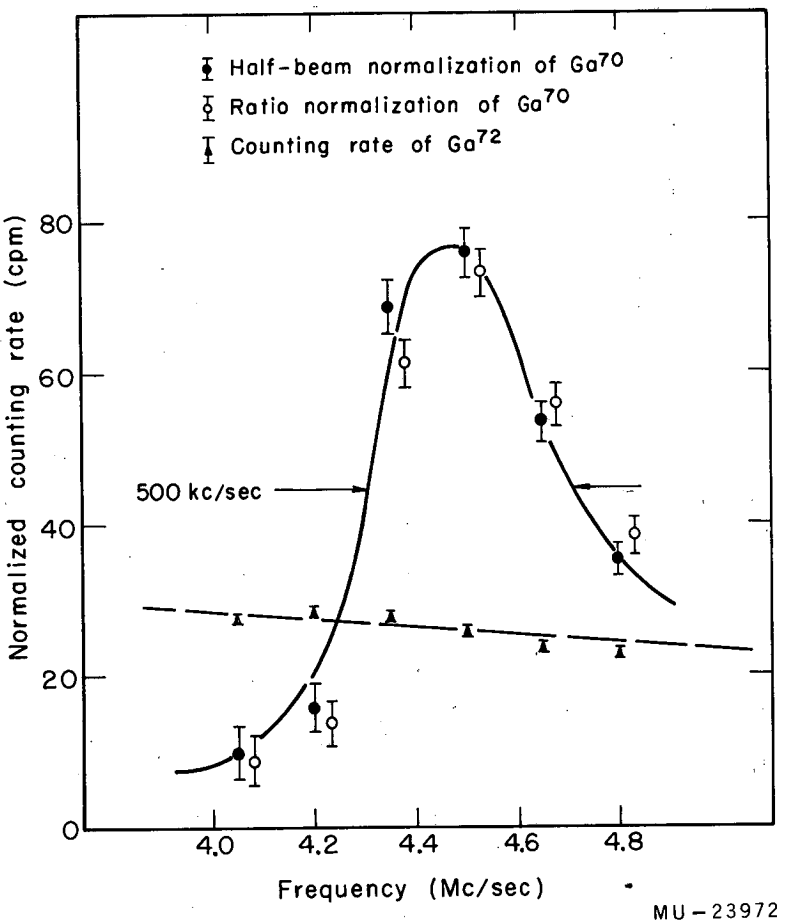

Half-beam normalization of Ga70
Ratio normalization of Ga70
Counting rate of Ga72
500 kc/sec
Normalized counting rate (cpm)
0
20
40
60
80
4.0
4.2
4.4
4.6
4.8
Frequency (Mc/sec)
MU-23972

Fig. 4

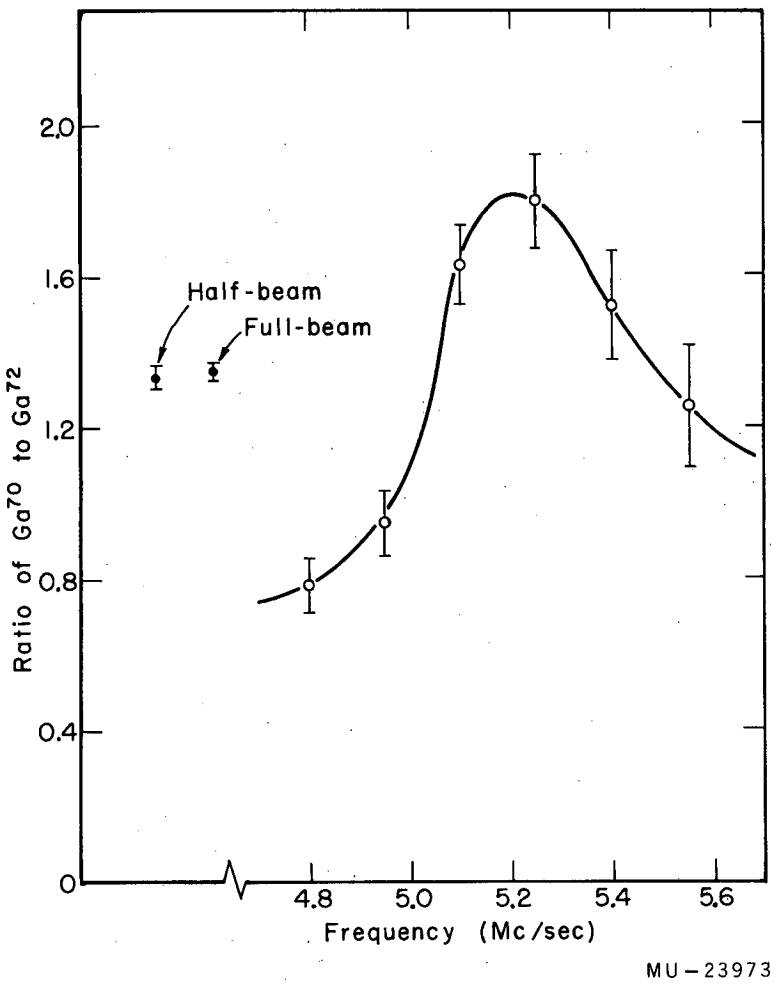

2.0
1.6
1.2
0.8
0.4
0
Ratio of Ga^{70} to Ga^{72}
Half-beam
Full-beam
4.8
5.0
5.2
5.4
5.6
Frequency (Mc/sec)
MU-23973

Fig. 5

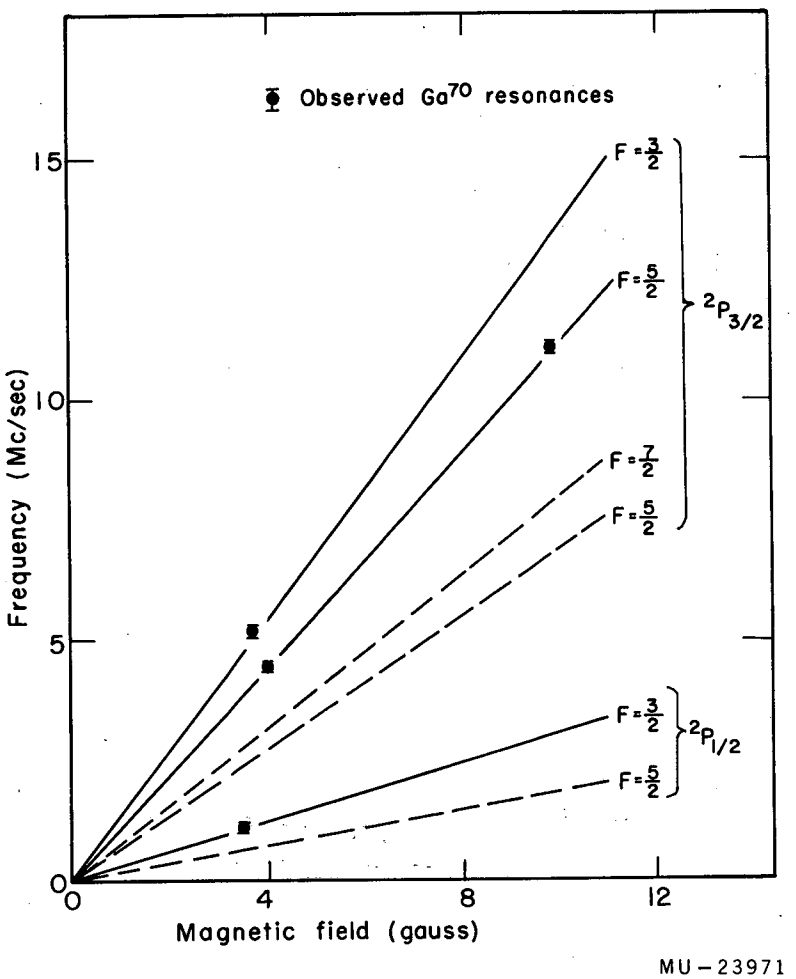

Observed Ga70 resonances
F = 3/2
F = 5/2
F = 7/2
F = 5/2
2P3/2
F = 3/2
F = 5/2
2P1/2
Frequency (Mc/sec)
0
5
10
15
0
4
8
12
Magnetic field (gauss)
MU-23971

Fig. 6

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