V^{48}. Considerably more detail is evident in Fig. 3 than in Fig. 2 because of the use of a thinner target.

Sheline and Stoughton[12] observed eight gamma rays in Co^{56} after bombardment of Fe^{54} by 39-Mev alpha particles. While an approximately 280-kev gamma ray may be attributed to a transition[9] from a level at 420 kev to the level at 160 kev, the origin of the gamma ray was not uniquely determined by the experiment.[13] The present experiment offers a possible alternative interpretation(see Fig. 6) of a 280-kev gamma ray as representing a transition to the ground state from the level corresponding to the 5734-kev threshold of Fig. 3.

[12] R. K. Sheline and R. W. Stoughton, Phys. Rev. **87**, 1 (1952).
[13] R. K. Sheline (private communications).

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Early phases of this work served to acquaint the research personnel of this laboratory with the operation of the Tandem Van de Graaff accelerator. Consequently, the authors are indebted to H. S. Adams, J. D. Fox, N. P. Heydenburg, R. K. Sheline and G. M. Temmer for their assistance in the measurements. The authors also wish to thank the many graduate students who helped to construct, test, and operate the equipment.

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Nuclear Spin of Gallium-70*

V. J. Ehlers,† W. A. Nierenberg,‡ and H. A. Shugart
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received November 10, 1961)

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 $^2P_{\frac{1}{2}}$ and the $^2P_{\frac{3}{2}}$ electronic states show that the nuclear spin is $I=1$.

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.[1-3] 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-min 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-hr 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 min after a 1-hr 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 radio-isotope 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 min.

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 ($\frac{3}{8}$-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 aligning it when placed in the atomic-

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† Presently on leave as a NATO Fellow at the Erstes Physikalisches Institut der Universität Heidelberg, Heidelberg, Germany.
‡ Presently on leave as Science Advisor to NATO, Paris, France.
[1] J. C. Hubbs, W. A. Nierenberg, H. A. Shugart, and J. L. Worcester, Phys. Rev. **105**, 1928 (1957).
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beam machine. The oven enclosed in a small polyethylene capsule filled with helium, was irradiated in the reactor for 1 hr. 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 alignment 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 min.

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

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

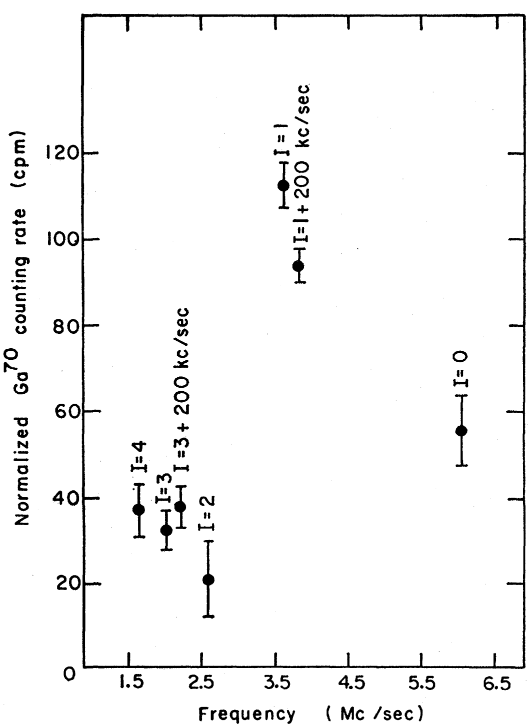

FIG. 1. Spin search conducted at a magnetic field of 3.227 gauss; normalized Ga^{70} counting rate.

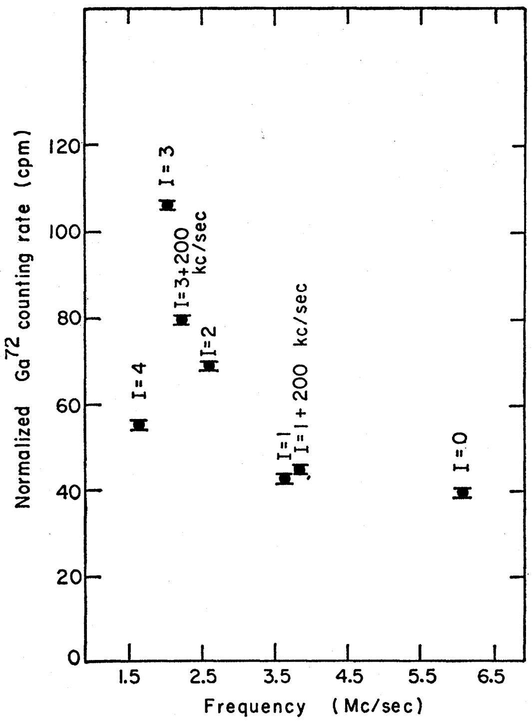

FIG. 2. Spin search conducted at a magnetic field of 3.227 gauss; normalized Ga^{72} counting rate.

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 $^2P_{\frac{1}{2}}$, with a fine-structure separation of only 826 cm^{-1} to the $^2P_{\frac{3}{2}}$ state. At the 1300°C operating temperature of the oven, the $^2P_{\frac{1}{2}}$ and $^2P_{\frac{3}{2}}$ levels are almost equally populated. The "flop-in" geometry employed in this experiment imposes the condition that only transitions with $m_J=\pm\frac{1}{2}\leftrightarrow m_J=\mp\frac{1}{2}$ are focused. Thus the only $\Delta F=0$ transitions observable for gallium are in the $F=I+J$ level of the $^2P_{\frac{1}{2}}$ state and in the $F=I+J$ and $F=I+J-1$ levels of the $^2P_{\frac{3}{2}}$ 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 radio-frequency 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 sec. The half-beam samples contain the high-velocity component of the beam which otherwise would have been stopped by the stop wire.

[5] For example, see W. A. Nierenberg, Ann. Rev. Nuclear Sci. 7, 349 (1957).

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.

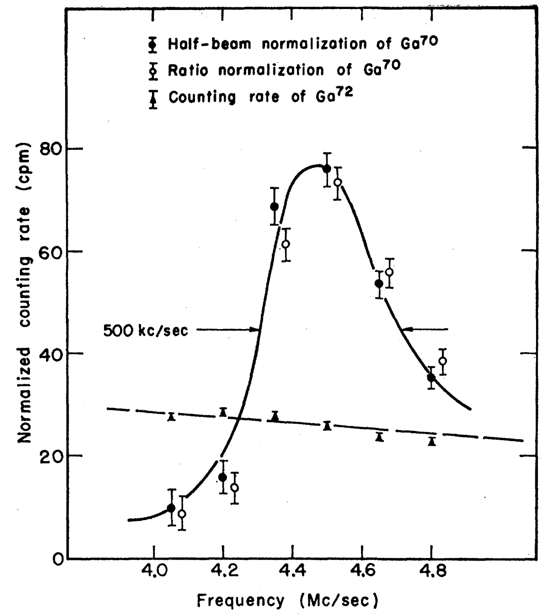

FIG. 4. Ga^{70} resonance obtained at a magnetic field of 3.987 gauss. The ratio-normalized points are shifted 25 kc/sec to the right for display purposes.

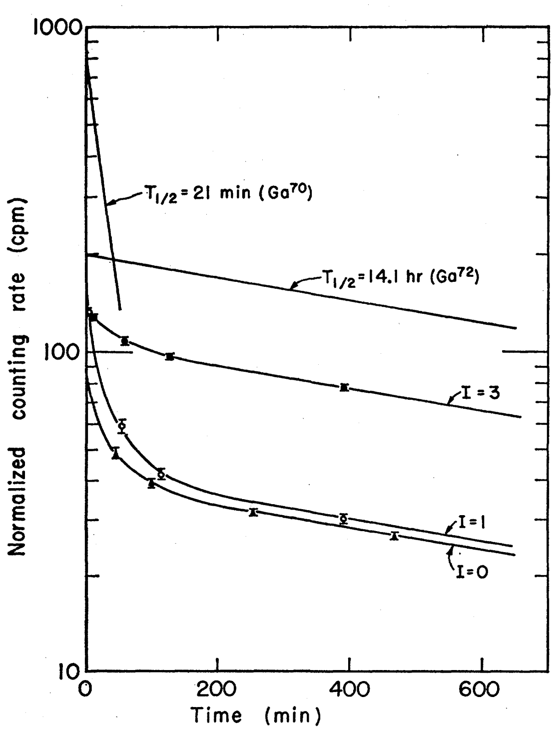

FIG. 3. Decay curves of three samples obtained during the spin search.

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 $F=\frac{5}{2}$ level of the $^2P_{\frac{3}{2}}$ 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 $^2P_{\frac{3}{2}}$, $F=\frac{3}{2}$ 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.

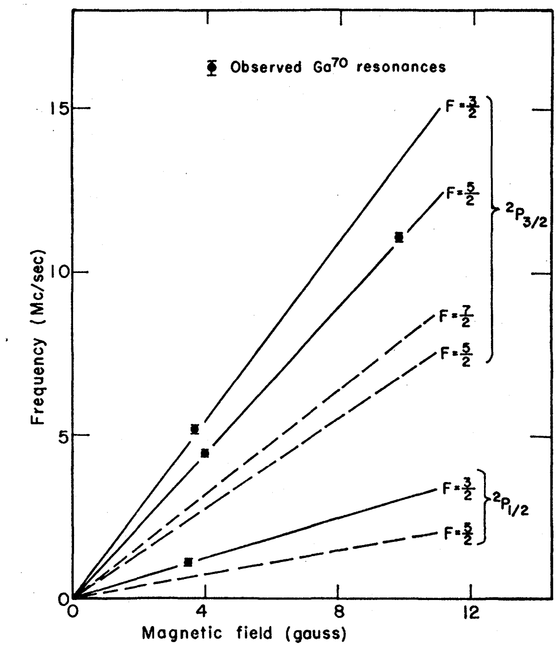

FIG. 6. Comparison of observed resonances to first-order resonance frequency. Solid lines for $I=1$, dashed lines for $I=2$.

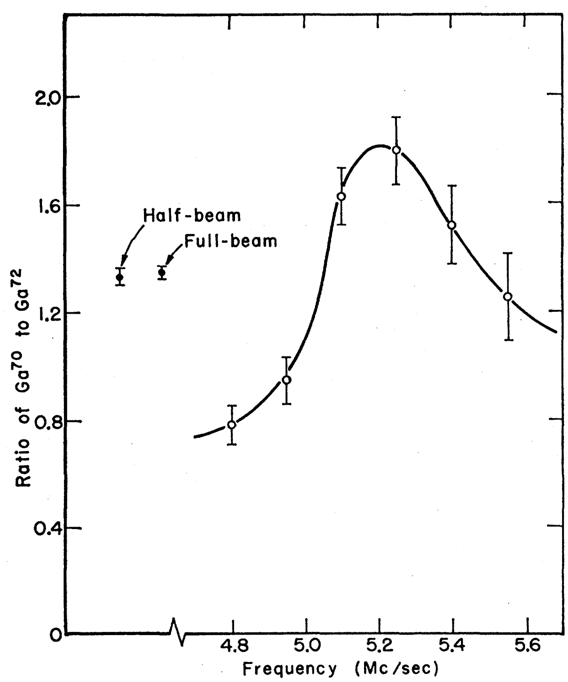

FIG. 5. Ga^{70} resonance obtained at a magnetic field of 3.696 gauss.

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 $p_{\frac{1}{2}}$ state, while the 31st proton is in the $p_{\frac{3}{2}}$ 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 $p_{\frac{1}{2}}$ neutron and the $p_{\frac{3}{2}}$ 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.

[6] See K. Way, R. W. King, C. L. McGinnis, and R. van Lieshout, *Nuclear Level Schemes*, *A*=*40*–*A*=*92*, compiled by K. Way, R. W. King, C. L. McGinnis, and R. van Lieshout, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

TABLE I. Summary of Ga^{70} Data.

Calibration frequency[a] (Mc/sec)	ν 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	$^2P_{3/2}$	$\frac{5}{2}$	3.227(53)		
1.867(30)	4.470(100)	$^2P_{3/2}$	$\frac{5}{2}$	3.987(64)	4.466	+0.004
1.633(25)	1.115(100)	$^2P_{1/2}$	$\frac{3}{2}$	3.490(53)	1.084	+0.031
1.730(25)	5.210(125)	$^2P_{3/2}$	$\frac{3}{2}$	3.696(53)	5.060	+0.150
4.616(25)	11.125(90)	$^2P_{3/2}$	$\frac{5}{2}$	9.815(53)	10.995	+0.130

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

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Anomalies in Yield Curves over the 992-kev $Al^{27}(p,\gamma)Si^{28}$ Resonance*

W. L. WALTERS,† D. G. COSTELLO, J. G. SKOFRONICK, D. W. PALMER, W. E. KANE, AND R. G. HERB
University of Wisconsin, Madison, Wisconsin
(Received October 30, 1961)

Gamma-ray yields from the $Al^{27}(p,\gamma)Si^{28}$ reaction have been investigated at the 992-kev resonance using H_1^+ and H_2^+ ions on thick and thin aluminum targets. Thick-target yield curves due to proton bombardment show a prominent peak a few hundred ev above the resonance energy. This structure was predicted by Lewis and is caused by the discrete nature of the energy losses suffered by the protons as they penetrate the target. A Monte Carlo calculation gives good agreement with the general form of the experimental curve. Diatomic ion thick-target yield curves are more complex in structure than those found with protons. The largest effect here is due to Coulomb repulsion between the two protons as they pass through the target. Internal kinetic energy of the ions makes a contribution to the structure. The Lewis effect also appears to contribute. Some information regarding the relative populations of the vibrational levels of the ions was obtained from H_2^+ ion thin-target yield curves.

I. INTRODUCTION

In previous published work, new features have been reported in thick-target gamma-ray yield curves from the $Al^{27}(p,\gamma)Si^{28}$ resonance at 992 kev. Curves taken with a proton beam of high-energy resolution have exhibited a maximum in the yield at an energy slightly above the resonance energy followed by a leveling off to a constant value at higher energies.[1] This structure was predicted by Lewis[2] and is due to the discreteness of the energy losses suffered by the protons as they penetrate the target.[3]

Dahl, Costello, and Walters[4] observed that yield curves obtained with H_2^+ ions from this resonance have a complex shape extending over a wide range of proton energies. Dahl *et al.* assumed that the binding electrons accompanying the ions are torn away immediately upon impact with the target. The ensuing Coulomb force between the protons results in large changes in the energies of the protons. Calculations based on this model succeeded in fitting thick-target yield curves taken with relatively low beam energy resolution.

In this paper results obtained with protons are

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† Present address: Department of Physics, University of Wisconsin—Milwaukee, Milwaukee, Wisconsin.
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