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Nuclear Gyromagnetic Ratios. III

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The super-regenerative oscillator techniques described in earlier reports have been modified by introduction of a tuned narrow band amplifier with chart recorder and by improvements in magnetic-field regulation. Magnetic resonance frequencies of various nuclei have been compared with the resonance frequencies of H^1, D^2, Li^7, and Sc^{45}, which have been used as "standards." Ratios of the observed resonance frequencies to the proton resonance frequency in the same magnetic field are given for the following nuclear species: Be^9, B^{11}, F^{19}, Na^{23}, Al^{27}, P^{31}, V^{51}, Mn^{55}, Cu^{63}, Cu^{65}, Br^{79}, Br^{81}, Rb^{87}, Nb^{93}, I^{127}, Cs^{133}, La^{139}, Tl^{203}, and Tl^{205}. The nuclear magnetic moments of these species have been determined in terms of the proton moment from the known spins and the observed frequency ratios after making diamagnetic corrections; values for the nuclear magnetic moments are listed.

IN earlier reports from this laboratory[1,2] super-regenerative oscillator techniques for observing nuclear magnetic resonance phenomena have been described. The present paper gives a brief description of certain modifications of the earlier techniques and gives a tabulation of the results obtained for various nuclei by means of the improved techniques.

EXPERIMENTAL METHODS

In Fig. 1 is shown a block diagram of the apparatus employed. The coil of the tank circuit of a super-regenerative oscillator is located between the poles of a large electromagnet. In searching for a magnetic resonance, a sample containing the nuclei of interest is placed in the coil and the magnetic field is varied slowly by means of a clockdrive operating a potentiometer in the control circuit of the magnet-current regulator; the regulator circuit employs electronic regulation of the current supplied through hard tubes to the high resistance magnet windings. At resonance

$$h\nu = g\mu_n H \tag{1}$$

the amplitude of oscillation of the super-regenerative circuit decreases. This amplitude change is observed by means of a narrow-band amplifier tuned to the 45-cycles/sec frequency of the magnetic-field modulator shown in the figure. The output of this narrow-band amplifier is applied to a recorder and to an oscilloscope, which is employed as a monitoring device.

After the resonance corresponding to the central frequency of the oscillator spectrum has been located, the magnetic field is held constant by means of the regulator while the oscillator frequency is carefully measured by means of the heterodyne frequency meter shown in Fig. 1. With the magnetic field unchanged, the frequency of the oscillator is changed until a resonance is observed for one of the nuclear species employed as "standards." The nuclear g-factor g_x of the nucleus being studied can then be determined in terms of the standard g_s by the relation

$$g_x = g_s(\nu_x/\nu_s), \tag{2}$$

where ν_x and ν_s are resonance frequencies for the two nuclear species in the same magnetic field.

Tests have shown that the regulator is capable of maintaining the magnet *currents* constant to 1 part in 30,000 for several hours. Operational experience indicates that the magnetic field itself can be held constant to at least 1 part in 20,000; this conclusion is based on observations of signal constancy obtained when the magnetic field is adjusted for a narrow resonance peak and for a position on the sharply rising shoulder of a resonance line. It is probable that improvement in regulation could be obtained by using the proton resonance to control the field, but this has not yet been done.

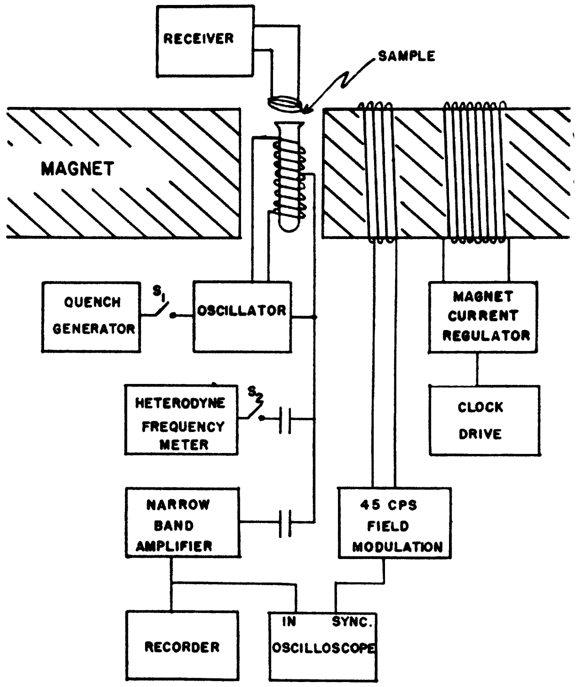

FIG. 1. Block diagram of apparatus.

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[1] J. R. Zimmerman and D. Williams, Phys. Rev. 76, 350 (1949).

[2] W. H. Chambers and D. Williams, Phys. Rev. 76, 638 (1949).

TABLE I. Resonance frequency ratios.

Nuclei compared	Resonance frequency ratio	Sample
Be^9 to D^2	0.915 475±0.000 07	$\mathrm{BeCl_2}$, $\mathrm{D_2O+NiCl_2}$
B^{11} to Li^7	0.825 615±0.000 04	$\mathrm{Na_2B_2O_4}$, $\mathrm{LiC_2H_3O_2+Mn(C_2H_3O_2)_2}$
F^{19} to H^1	0.940 86±0.000 05	HF
Na^{23} to Sc^{45}	1.088 83±0.000 05	$\mathrm{Na_2B_2O_4}$, $\mathrm{ScCl_3}$
	1.088 72±0.000 06	NaBr, $\mathrm{ScCl_3}$
Al^{27} to Sc^{45}	1.072 61±0.000 05	$\mathrm{AlCl_3}$, $\mathrm{ScCl_3}$
P^{31} to Li^7	1.041 82±0.000 05	$\mathrm{H_3PO_4+CuCl_2}$, $\mathrm{LiC_2H_3O_2+Mn(C_2H_3O_2)_2}$
V^{51} to Sc^{45}	1.081 56±0.000 05	powdered $\mathrm{V_2O_5}$, $\mathrm{ScCl_3}$
Mn^{55} to Sc^{45}	1.020 28±0.000 05	$\mathrm{Ca(MnO_4)_2}$, $\mathrm{ScCl_3}$
Cu^{63} to Sc^{45}	1.091 25±0.000 06	powedered $\mathrm{Cu_2Cl_2}$, $\mathrm{ScCl_3}$
Cu^{65} to Sc^{45}	1.169 51±0.000 06	powdered $\mathrm{Cu_2Cl_2}$, $\mathrm{ScCl_3}$
Cu^{65} to Cu^{63}	1.071 78±0.000 05	powdered $\mathrm{Cu_2Cl_2}$
Br^{79} to Sc^{45}	1.031 45±0.000 05	NaBr, $\mathrm{ScCl_3}$
Br^{81} to Sc^{45}	1.111 65±0.000 06	NaBr, $\mathrm{ScCl_3}$
Br^{81} to Br^{79}	1.077 75±0.000 05	NaBr
Rb^{87} to Al^{27}	1.255 29±0.000 06	$\mathrm{Rb_2CO_3+CuCl_2}$, $\mathrm{AlCl_3}$
Nb^{93} to Sc^{45}	1.006 13±0.000 05	$\mathrm{Nb_2O_5+HF}$, $\mathrm{ScCl_3}$
I^{127} to D^2	1.303 17±0.000 06	KI, $\mathrm{D_2O+NiCl_2}$
Cs^{133} to D^2	0.854 49±0.000 04	$\mathrm{CsCl+CuCl_2}$, $\mathrm{D_2O+NiCl_2}$
La^{139} to D^2	0.920 25±0.000 06	$\mathrm{LaCl_3+CuCl_2}$, $\mathrm{D_2O+NiCl_2}$
Tl^{205} to Tl^{203}	1.009 83±0.000 05	$\mathrm{TlC_2H_3O_2+Mn(C_2H_3O_2)_2}$
Tl^{203} to H^1	0.577 02±0.000 03	$\mathrm{TlC_2H_3O_2+Mn(C_2H_3O_2)_2}$, $\mathrm{H_2O+FeCl_2}$

The radiofrequencies employed in the present work were in the 5 to 10 mc/sec range, and the quench frequency was usually in the range 5 to 15 kc/sec. The theory of the super-regenerative oscillator and a more detailed description of the circuits are being published elsewhere.

DISCUSSION OF RESULTS

In Table I are listed the observed ratios of resonance frequencies of various nuclei in the same applied magnetic field. Each value listed is the mean of at least eight careful independent determinations. The uncertainties given are in some cases the statistically most probable errors and in other cases the instrumental uncertainty of 1 part in 20,000 imposed by the limitations of the magnet current regulator. In each case the larger of these uncertainties is listed. The samples used are also listed in Table I; all samples were aqueous solutions except the ones used for V and Cu. In samples containing magnetic catalysts, the concentration of the catalyst was kept as low as possible and was of the order of 0.03 molar.

Since the recent precise measurements[3] of the absolute value of the proton moment, it has become conventional to use the proton moment as a "primary standard" in work on nuclear resonance absorption and to express the results of measurements in terms of ratios of resonance frequencies of various nuclei to the resonance frequency of the proton in the same magnetic field. In the present work, it was convenient in making frequency measurements to use the deuteron D^2, Li^7, and Sc^{45} as "secondary standards." The ratios of the resonance frequencies of these nuclei to the resonance frequency of the proton are listed in Table II. The results obtained by various investigators are given in the second column of this table and the values used as "standard" are given in the last column.

Through the use of the secondary frequency standards listed in Table II, it is possible to express the observed resonance frequencies for the nuclei listed in Table I in terms of the proton resonance frequency. This has been done; and the results are presented in Table III along with corresponding ratios obtained by other methods, which are included for purposes of comparison.

A few brief comments concerning the results obtained for the various nuclear species are given below:

Be^9: Considereable difficulty was encountered in matching the beryllium signal with that of the deuteron, since there appeared to be a significant difference in line shape. The result obtained is considerably higher than that given in our earlier work[2] but is in excellent agreement with the work of Dickinson.[4]

TABLE II. Resonances used as standards.

Ratio	Value resonance frequency ratio	Reference	Value used as standard
D^2 to H^1	0.153 507 5	a	
	0.153 505 9 ±0.000 000 8	b	
	0.153 506 69±0.000 000 25	c	
	0.153 506 06±0.000 000 05	d	0.153 506
Li^7 to H^1	0.388 625 ±0.000 04	e	
	0.388 62 ±0.000 02	f	
	0.388 611 ±0.000 017	g	0.388 617±0.000 017
Sc^{45} to H^1	0.242 90 ±0.000 03	h	
	0.242 95 ±0.000 02	i	
	0.242 939 ±0.000 003	j	0.242 939±0.000 003

[a] Reference 20.
[b] E. C. Levinthal, Phys. Rev. **78**, 204 (1950).
[c] G. Lindstrom, Phys. Rev. **78**, 817 (1950).
[d] Smaller, Yasaitis, and Anderson, Phys. Rev. **80**, 137 (A) (1950).
[e] Reference 5.
[f] Reference 1.
[g] Reference 8.
[h] W. G. Proctor and F. C. Yu, Phys. Rev. **78**, 471 (1950).
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[j] D. M. Hunten, Phys. Rev. **78**, 806 (1950).

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[3] Hipple, Sommer, and Thomas, Phys. Rev. **76**, 1877 (1949).

[4] W. C. Dickinson and T. F. Wimett, Phys. Rev. **75**, 1769 (1949).

TABLE III. Frequency ratios to the proton frequency.

Nucleus	Sample	Value	Uncertainty (%)	Intermediate standard	Reference
Be^9	BeF_2	0.140 5187±0.000 0020	(0.002)		4
	$BeCl_2$	0.140 34 ±0.000 07	(0.050)		2
	$BeCl_2$	0.140 531 ±0.000 011	(0.008)	D^2	Present study
B^{11}	BCl_3(?)	0.320 85 ±0.000 06	(0.019)		5
	$Na_2B_2O_4$	0.320 76 ±0.000 09	(0.028)		1
	$K_2B_2O_4$	0.320 827 ±0.000 004	(0.001)		6
	$Na_2B_2O_4$	0.320 848 ±0.000 021	(0.007)	Li^7	Present study
F^{19}	$C_2F_3Cl_3$	0.940 934 ±0.000 015	(0.002)		8
	HF*	0.940 816			
	HF	0.940 77 ±0.000 10	(0.011)		9
	SbF_3	0.940 86 ±0.000 17	(0.018)		1
	HF*	0.940 75			
	HF	0.940 86 ±0.000 05	(0.005)		Present study
Na^{23}	NaI or NaCl	0.264 50 ±0.000 03	(0.011)		5
	$NaAsO_2$	0.264 54 ±0.000 07	(0.026)		1
	$Na_2B_2O_4$	0.264 518 ±0.000 014	(0.005)	Sc^{45}	Present study
	NaBr	0.264 492 ±0.000 015	(0.006)	Sc^{45}	Present study
Al^{27}	$AlCl_3$	0.260 56 ±0.000 03	(0.011)		5
	$AlCl_3$	0.260 62 ±0.000 11	(0.042)		1
	$AlCl_3$	0.260 579 ±0.000 013	(0.005)	Sc^{45}	Present study
P^{31}	P_2O_5 or P	0.404 96 ±0.000 09	(0.022)	Na^{23}	10
	P_2O_5(?)	0.404 81 ±0.000 04	(0.010)		5
	H_3PO_4+cat	0.404 98 ±0.000 11	(0.027)		2
	H_3PO_4+cat	0.404 869 ±0.000 026	(0.006)	Li^7	Present study
V^{51}	V_2O_5, HCl	0.262 91 ±0.000 02	(0.008)	Na^{23}	12
	pwd V_2O_5	0.262 67 ±0.000 06	(0.023)	B^{11}	11
	pwd V_2O_5	0.262 753 ±0.000 012	(0.005)	Sc^{45}	Present study
Mn^{55}	$LiMnO_4$	0.247 90 ±0.000 03	(0.012)	Na^{23}	13
	$Ca(MnO_4)_2$	0.247 86 ±0.000 12	(0.048)	Na^{23}	11
	$Ca(MnO_4)_2$	0.247 866 ±0.000 012	(0.005)	Sc^{45}	Present study
Cu^{63}	pwd Cu_2Cl_2	0.265 09 ±0.000 06	(0.023)	Na^{23}	14
	Cu_2Cl_2	0.265 056 ±0.000 050	(0.019)		5
	Cu_2Cl_2+cat	0.265 15 ±0.000 05	(0.019)		1
	pwd Cu_2Cl_2	0.265 107 ±0.000 015	(0.006)	Sc^{45}	Present study
Cu^{65}	pwd Cu_2Cl_2	0.283 95 ±0.000 06	(0.021)	Cu^{63}	14
	Cu_2Cl_2	0.283 91 ±0.000 06	(0.021)		5
	Cu_2Cl_2+cat	0.284 04 ±0.000 09	(0.032)		1
	pwd Cu_2Cl_2	0.284 120 ±0.000 015	(0.005)	Sc^{45}	Present study
Br^{79}	NaBr	0.250 57 ±0.000 08	(0.032)	Br^{81}	15
	NaBr	0.250 59 ±0.000 05	(0.020)		1
	NaBr	0.250 579 ±0.000 012	(0.005)	Sc^{45}	Present study
Br^{81}	NaBr	0.270 04 ±0.000 08	(0.030)	Na^{23}	15
	LiBr	0.270 03 ±0.000 08	(0.030)		5
	NaBr	0.270 14 ±0.000 05	(0.019)		1
	NaBr	0.270 063 ±0.000 015	(0.006)	Sc^{45}	Present study
Rb^{87}	RbCl	0.327 18 ±0.000 07	(0.022)		5
	Rb_2CO_3+cat	0.327 18 ±0.000 16	(0.049)		1
	Rb_2CO_3+cat	0.327 101 ±0.000 023	(0.007)	Al^{27}	Present study
Nb^{93}	Nb_2O_5+HF	0.244 43 ±0.000 13	(0.053)	B^{11}	16
	Nb_2O_5+HF	0.244 428 ±0.000 012	(0.005)	Sc^{45}	Present study
I^{127}	pwd NaI	0.200 14 ±0.000 06	(0.030)	Na^{23}	10
	KI	0.200 03 ±0.000 07	(0.035)		1
	KI	0.200 044 ±0.000 010	(0.005)	D^2	Present study
Cs^{133}	CsCl	0.131 13 ±0.000 04	(0.031)	Li^7	5
	CsCl+cat	0.130 93 ±0.000 14	(0.107)		2
	CsCl+cat	0.131 169 ±0.000 006	(0.005)	D^2	Present study
La^{139}	$LaCl_3$+cat	0.141 16 ±0.000 14	(0.100)		2
	$LaCl_3$	0.141 251 ±0.000 014	(0.010)		17
	$LaCl_3$+cat	0.141 264 ±0.000 009	(0.006)	D^2	Present study
Tl^{203}	$TlC_2H_3O_2$	0.571 4 ±0.000 1	(0.017)		18
	$TlC_2H_3O_2$	0.571 499 ±0.000 050	(0.009)		9
	$TlC_2H_3O_2$+cat	0.571 40 ±0.000 04	(0.007)	Tl^{205}	Present study
Tl^{205}	$TlC_2H_3O_2$	0.577 0 ±0.000 01	(0.017)		18
	$TlC_2H_3O_2$	0.577 135 ±0.000 050	(0.009)		9
	$TlC_2H_3O_2$+cat	0.577 02 ±0.000 03	(0.005)		Present study

* Equivalent value for HF, according to Dickinson (reference 7).

TABLE IV. Nuclear *g*-values and nuclear magnetic moments.

Nucleus	Diamagnetic correction	Nuclear *g*-value	Spin	Nuclear magnetic moment (nuclear magnetons)
H^{1}*	1.000 03	5.585 10±0.000 00	1/2	2.792 55±0.000 00
D^{2}*	1.000 03	0.857 37±0.000 00	1	0.857 37±0.000 14
Li^{7}*	1.000 08	2.170 64±0.000 10	3/2	3.255 96±0.000 14
Be^{9}	1.000 12	0.784 98±0.000 06	3/2	1.177 46±0.000 09
B^{11}	1.000 17	1.792 27±0.000 12	3/2	2.688 40±0.000 18
F^{19}	1.000 39	5.256 84±0.000 28	1/2	2.628 42±0.000 14
Na^{23}	1.000 54	1.478 09±0.000 08	3/2	2.217 14±0.000 12
Al^{27}	1.000 72	1.456 41±0.000 07	5/2	3.641 01±0.000 17
P^{31}	1.000 91	2.263 30±0.000 14	1/2	1.131 65±0.000 07
Sc^{45}*	1.001 51	1.358 89±0.000 02	7/2	4.756 11±0.000 06
V^{51}	1.001 71	1.470 01±0.000 07	7/2	5.145 03±0.000 23
Mn^{55}	1.001 92	1.387 01±0.000 07	5/2	3.467 53±0.000 17
Cu^{63}	1.002 39	1.484 19±0.000 08	3/2	2.226 28±0.000 13
Cu^{65}	1.002 39	1.590 63±0.000 08	3/2	2.385 94±0.000 13
Br^{79}	1.003 08	1.403 83±0.000 07	3/2	2.105 74±0.000 10
Br^{81}	1.003 08	1.512 98±0.000 08	3/2	2.269 47±0.000 13
Rb^{87}	1.003 33	1.832 91±0.000 13	3/2	2.749 37±0.000 19
Nb^{93}	1.003 83	1.370 38±0.000 07	9/2	6.166 70±0.000 30
I^{127}	1.005 45	1.123 35±0.000 05	5/2	2.808 38±0.000 13
Cs^{133}	1.005 73	0.736 79±0.000 03	7/2	2.578 77±0.000 12
La^{139}	1.006 02	0.793 72±0.000 05	7/2	2.778 02±0.000 18
Tl^{203}	1.009 83	3.222 72±0.000 22	1/2	1.611 36±0.000 11
Tl^{205}	1.009 83	3.254 66±0.000 17	1/2	1.627 33±0.000 08

* Value used as a standard.

B^{11}: Agreement with previous work[1,5,6] is excellent.

F^{19}: Dickinson[7] has found that the fluorine resonance in different chemical compounds occurs at slightly different frequencies. If a Dickinson correction is applied to the data of Siegbahn and Lindstrom[8] and the data of Zimmerman[1] in order to obtain a value for the resonance in HF, agreement of their values with the present result and with the result of Poss[9] is satisfactory.

Na^{23}: The results obtained in the present work seem to indicate that the Na^{23} resonance frequency is slightly higher in $\mathrm{Na_2B_2O_4}$ than in NaBr. However, both frequencies fall within the limits obtained by Bitter[5] and Zimmerman[1] in earlier studies.

Al^{27}: The present value is in excellent agreement with earlier results.[1,5]

P^{31}: Considerable difficulty was encountered in matching the phosphorus peak pattern with the Li^{7} pattern, but the final result falls within the limits established by earlier investigations.[2,5,10]

V^{51}: Although the vanadium resonance is quite weak, the resonance-frequency value obtained confirms the value given in our preliminary report[11] but disagrees with the result obtained by Knight and Cohen.[12]

Mn^{55}: Agreement with the nuclear-induction results of Proctor and Yu[13] is excellent.

Cu^{63} and Cu^{65}: The present value for Cu^{63} is in good agreement with earlier values.[1,5,14] A somewhat asymmetrical line shape was obtained for Cu^{65}, and the resulting value of the resonance frequency is somewhat higher than that obtained by other investigators.

Br^{79}, Br^{81}, Rb^{87}: Present values fall well within the limits established in earlier work.[1,5,15]

Nb^{93}: The present result confirms the preliminary value obtained in this laboratory.[16]

I^{127}: The value obtained is within the limits established by earlier work of Zimmerman[1] but is significantly lower than the value obtained by Pound.[10]

Cs^{133}: Unambiguous matching of the caesium and deuteron signals was difficult to achieve. The value given in the table is in agreement with Bitter's results,[5] but a different matching procedure might well have yielded a result in agreement with Chambers' value.[2] The complex resonance pattern given by the super-regenerative oscillator proved a serious hindrance in the case of Cs^{133}; further work on this resonance by another method might be desirable.

La^{139}: The present value falls within the limits established by Chambers[2] and Dickinson.[17]

Tl^{203} and Tl^{205}: The present values are in excellent agreement with those obtained by Proctor[18] but are lower than those reported by Poss.[9]

NUCLEAR *g*-FACTORS AND MAGNETIC MOMENTS

The values of nuclear *g*-factors cannot be determined by direct substitution of observed frequency ratios ν_x/ν_s in Eq. (2), since, owing to the diamagnetic effects of atomic electrons, the local fields at the nuclei being compared may be slightly different even though the externally applied fields may be the same. However, by applying the diamagnetic correction developed by Lamb,[19] one can obtain nuclear *g*-factors in terms of the *g*-factor for the proton; in cases for which nuclear spins are known, nuclear magnetic moments can also be calculated. In obtaining the *g*-factors and magnetic moments listed in Table IV, the frequency ratios obtained in the present study were used in connection with the recent Bureau of Standards value[3] for the proton moment,

$$\mu_{\text{proton}} = 2.79255 \pm 0.00010 \text{ nuclear magnetons,}$$

and the nuclear spins listed in Mack's survey paper.[20] The Lamb diamagnetic corrections in the second column of Table IV are the factors applied to the observed frequency ratios in obtaining the listed values of the *g*-factors and nuclear moments.

The authors take pleasure in expressing their appre-

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ciation to Dr. W. H. Chambers and Mr. Yu Ting for their assistance in certain phases of the experimental work. Grateful acknowledgment is also made to the Graduate School, Research Foundation, and University Development Fund of Ohio State University for research grants and to the Atomic Energy Commission for a research fellowship granted (to R.E.S.) for this work.

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The $\mathrm{Mn}^{55}(p,n)\mathrm{Fe}^{55}$ Neutron Spectrum*

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A thin (20-kev) target of manganese on a tantalum backing was bombarded by monoenergetic protons of 2.97, 3.42, and 3.77 Mev from the Rockefeller electrostatic generator. Nuclear emulsion plates (Eastman NTB, 200 microns thickness) were mounted 15 cm from the target at 0° and 90° with respect to the incident proton beam. The resulting neutron spectra, obtained from the analysis of 2400 proton recoil tracks, show well-defined groups which correspond to excited states in Fe^{55} at 0.42, 0.94, 1.36, and 2.08 Mev. The group corresponding to the level at 1.36 Mev has an unusually large width indicating that this level is complex. The Q-value for the ground-state reaction was measured to be -1.05 ± 0.05 Mev, giving the threshold for neutron production as 1.07 ± 0.05 Mev. Levels in Fe^{55} at 0.935 and 1.41 Mev have been found by Deutsch and Hedgran from a study of the decay scheme of Co^{55}. These levels correspond closely to two of the levels reported here.

I. INTRODUCTION

THE investigation of the Co^{55} decay scheme by Deutsch and Hedgran[1] indicates the existence of excited states in the Fe^{55} nucleus at 0.935 and 1.41 Mev. From a study of the neutron spectrum produced by the $\mathrm{Mn}^{55}(p,n)\mathrm{Fe}^{55}$ reaction at proton-bombarding energies well above the threshold (1.18 Mev;[2] 1.02 Mev[3]), information can be obtained concerning the positions of excited levels in the residual nucleus, Fe^{55}, and the relative transition probabilities from the compound nucleus to these levels. Since the selection rules for $\beta-\gamma$ decay are more stringent than those for the (p,n) process, one would expect the (p,n) investigation to confirm the levels obtained from the $\beta-\gamma$ decay and to disclose, possibly, the existence of additional levels not excited in the $\beta-\gamma$ decay. We have performed an experiment in which the neutron spectra produced by bombarding a thin manganese target with monoenergetic protons from the Rockefeller electrostatic generator were measured by means of proton recoils in photographic emulsions.

II. EXPERIMENTAL METHOD

A 20-kev manganese metal[3a] target on a tantalum backing was bombarded by 2.97-, 3.42-, and 3.77-Mev protons. Proton energies were measured by a generating voltmeter calibrated by the $\mathrm{Li}^7(p,n)$ threshold at 1.882 Mev. Eastman NTB plates of 200 microns thickness were placed a mean distance of 15 cm from the target at 0° and 90° with respect to the incident proton beam. The processed emulsions were systematically scanned at 950× magnification (oil immersion) and proton recoil tracks within 10 degrees of the neutron direction were accepted for measurement. The range-energy relation used to convert proton recoil track lengths to neutron energy E_n was obtained by measuring the $\mathrm{Li}^7(p,n)$ spectrum at several bombarding energies and the d–d spectrum at a single deuteron-bombarding energy.

Three corrections were applied to the data to obtain plots of relative neutron intensity *vs* neutron energy: (1) the correction for the variation of the (n,p) collision cross section with energy, (2) the correction for the different probability of leaving the emulsion for tracks of different length, and (3) the correction for the variation with neutron energy of the spacing of the experimental points. The second correction is quite small for the present investigation. The third correction was applied to make the area under a given peak represent the relative intensity of the peak.

III. DISCUSSION

The corrected data, based on about 2400 measured tracks, are given in Figs. 1 and 2 as plots of relative neutron intensity *vs* neutron energy. Figure 1 shows the neutron spectrum at 0° and 90° with respect to the incident proton beam when a bombarding energy of 3.42 Mev was employed. Figure 2 shows the spectrum at 0° with proton-bombarding energies of 2.97 and 3.77 Mev. An indication of the statistical accuracy of the data is given by the conventional symbols placed

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[1] M. Deutsch and A. Hedgran, Phys. Rev. **75**, 1443 (1949).

[2] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

[3] J. J. G. McCue and W. M. Preston, private communication.

[3a] The manganese metal with a purity of 99.5 percent was obtained from the Fairmount Chemical Company.