Reaction Energies and Energy Levels from Proton and Deuteron Bombardment of the Iron Isotopes*

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(Received 10 October 1963)

Thin targets of natural iron and of iron oxide enriched in Fe^{54}, Fe^{57}, and Fe^{58} have been bombarded with protons and deuterons at several energies between 6.5 and 8.5 MeV. Reaction protons and alpha particles from the (p,p'), (p,α), and (d,p) reactions were analyzed with a broad-range magnetic spectrograph at a number of angles between 30 and 130 deg with respect to the incident beam. The (p,p') and (d,p) reactions gave information on the excited states of Fe^{54}, Fe^{55}, Fe^{56}, Fe^{57}, Fe^{58}, and Fe^{59}. For these isotopes, the regions of excitation studied extended from their ground states to 4.07, 7.47, 4.74, 5.80, 8.18, and 4.87 MeV, respectively, and the numbers of levels whose energies were measured in these regions were 11, 136, 25, 109, 133, and 64, respectively. Alpha-particle groups were observed which were associated with excited states in Mn^{53} at 0.380 MeV; in Mn^{54} at 0.057, 0.162, and 0.402 MeV; and in Mn^{55} at 0.128 MeV (all ± 0.012 MeV). Also, from (p,p') scattering from wolfram present in the targets, proton groups were identified whose energies corresponded to levels in W^{182}, W^{184}, and W^{186} at 0.100, 0.111, and 0.122 MeV, respectively (all ± 0.004 MeV). The ground-state Q values of the reactions studied were found to be:

$Fe^{54}(d,p)Fe^{55}$	$Q_0=7.084\pm0.008$ MeV,
$Fe^{56}(d,p)Fe^{57}$	$Q_0=5.425\pm0.008$ MeV,
$Fe^{57}(d,p)Fe^{58}$	$Q_0=7.815\pm0.008$ MeV,
$Fe^{58}(d,p)Fe^{59}$	$Q_0=4.357\pm0.008$ MeV,
$Fe^{56}(p,\alpha)Mn^{53}$	$Q_0=-1.060\pm0.009$ MeV,
$Fe^{57}(p,\alpha)Mn^{54}$	$Q_0=0.237\pm0.009$ MeV,
$Fe^{58}(p,\alpha)Mn^{55}$	$Q_0=0.402\pm0.009$ MeV.

I. INTRODUCTION

As part of a continuing program to measure the energy levels of nuclei by means of magnetic analysis of charged particles from nuclear reactions, investigations in the intermediate- and medium-weight nuclei were initiated in this laboratory several years ago. In 1955, a survey of the iron isotopes was started. Since that time, some preliminary results have been reported,[1] and more recently tabulations of the energy-level positions from these experiments have appeared in nuclear data compilations.[2] In this paper a more detailed report is presented.

The stable iron isotopes have mass numbers 54, 56, 57, and 58, and the abundances found in nature are 5.82, 91.66, 2.19, and 0.33%, respectively.

In this work, particular effort was directed toward investigating the (p,p') and (d,p) reactions of these isotopes. Some alpha particles resulting from proton bombardment were also observed and are reported here, but no special effort was made at a thorough search. Likewise, inelastic deuterons and alpha particles from deuteron bombardment were not investigated thoroughly. This was because of the use of an aluminum absorber placed next to the nuclear emulsion for the purpose of reducing the background of low-energy deuterons scattered by the defining slit system.

II. EXPERIMENTAL PROCEDURES

The MIT-ONR electrostatic generator and the 50-cm broad-range, single-gap spectrograph used in these experiments have been previously described.[3]

Preliminary investigation of the iron isotopes was begun with the bombardment of thin targets of naturally occurring iron. Metallic iron sponge was evaporated in vacuum from a tantalum boat onto thin films of Formvar supported by a wire frame. At a later stage, the separated isotopes of Fe^{54}, Fe^{57}, and Fe^{58} were obtained from the Stable Isotopes Division of the Oak Ridge National Laboratory in the form of Fe_2O_3. These oxides were also evaporated easily to form thin targets on Formvar backings. The boat reservoirs for the oxides were made of wolfram strips. The target thicknesses were later determined to be of the order of 10 keV or less for 7-MeV protons, or approximately 8.0×10^{17} atoms/cm^2.

The isotopic composition of natural iron,[4] along with the composition of the enriched isotopes[5] used in these experiments, is shown in Table I.

The first series of bombardments of the natural iron targets, using both protons and deuterons, was carried

* This work has been supported in part through an AEC contract, with funds provided by the U. S. Atomic Energy Commission, by the U. S. Navy Office of Naval Research, and by the U. S. Air Force Office of Scientific Research.

[1] W. W. Buechner and A. Sperduto, Bull. Am. Phys. Soc. **1**, 39 (1956); A. Sperduto and W. W. Buechner, *ibid.* **1**, 212 (1956); Laboratory for Nuclear Science Progress Reports, May 1956, p. 112; May 1957, p. 152; and May 1958, p. 127 (unpublished reports).

[2] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office National Academy of Science–National Research Council, Washington 25, D. C.).

[3] W. W. Buechner, A. Sperduto, C. P. Browne, and C. K. Bockelman, Phys. Rev. **91**, 1502 (1953); and C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).

[4] J. R. White and A. E. Cameron, Phys. Rev. **74**, 991 (1948); also, R. F. Hibbs, AECU Document No. 556 (unpublished).

[5] Prepared by the Stable Isotopes Division at Oak Ridge National Laboratory.

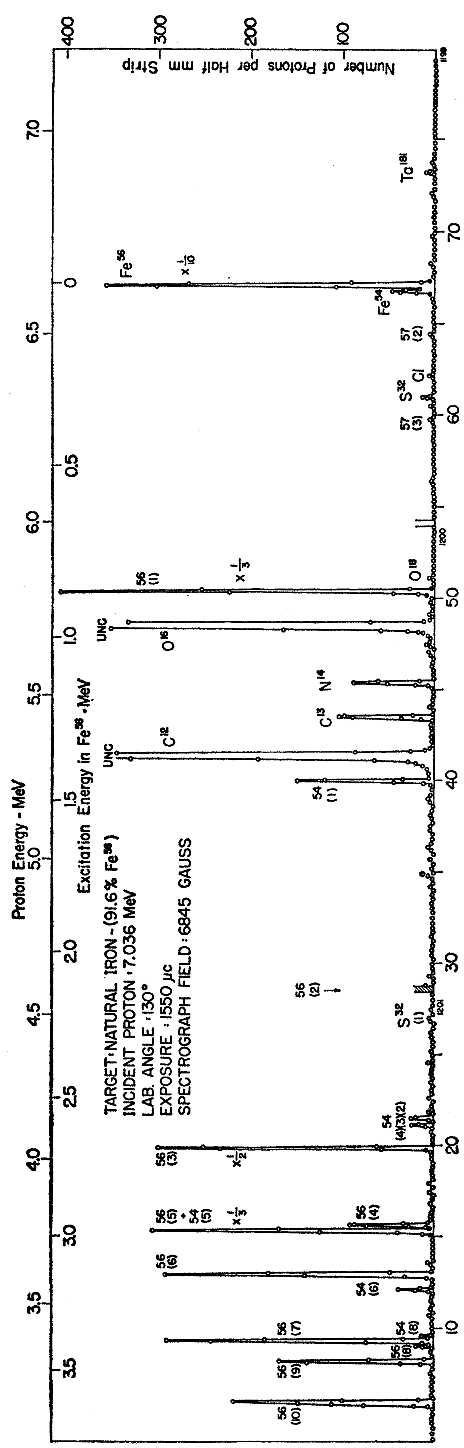

FIG. 1. Spectrum of protons scattered from natural iron (91.66% Fe56) target.

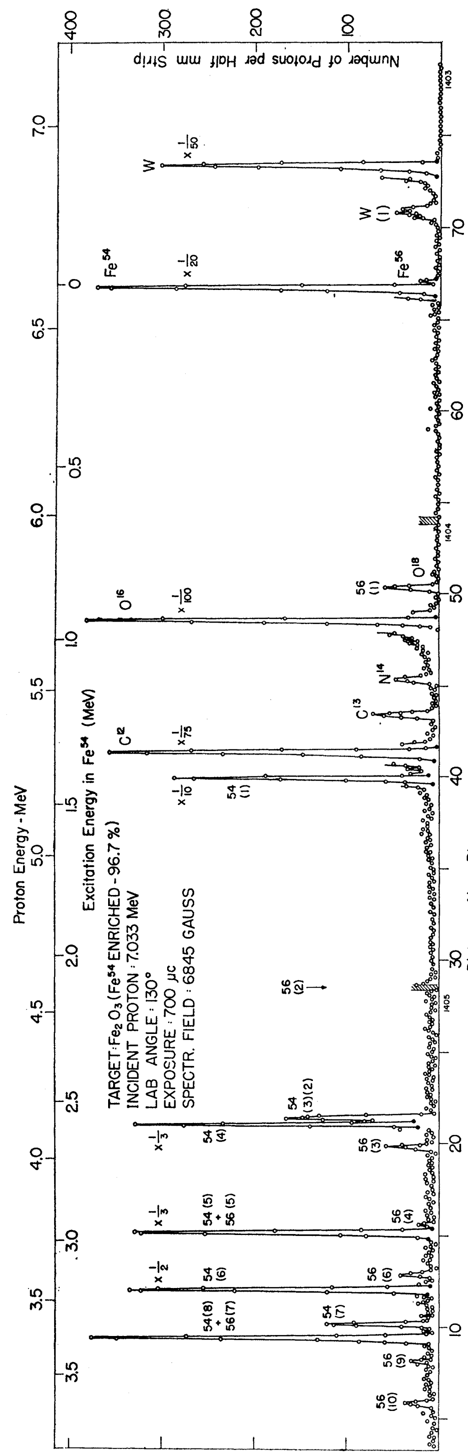

FIG. 2. Spectrum of protons scattered from enriched Fe54 (96.66%) target.

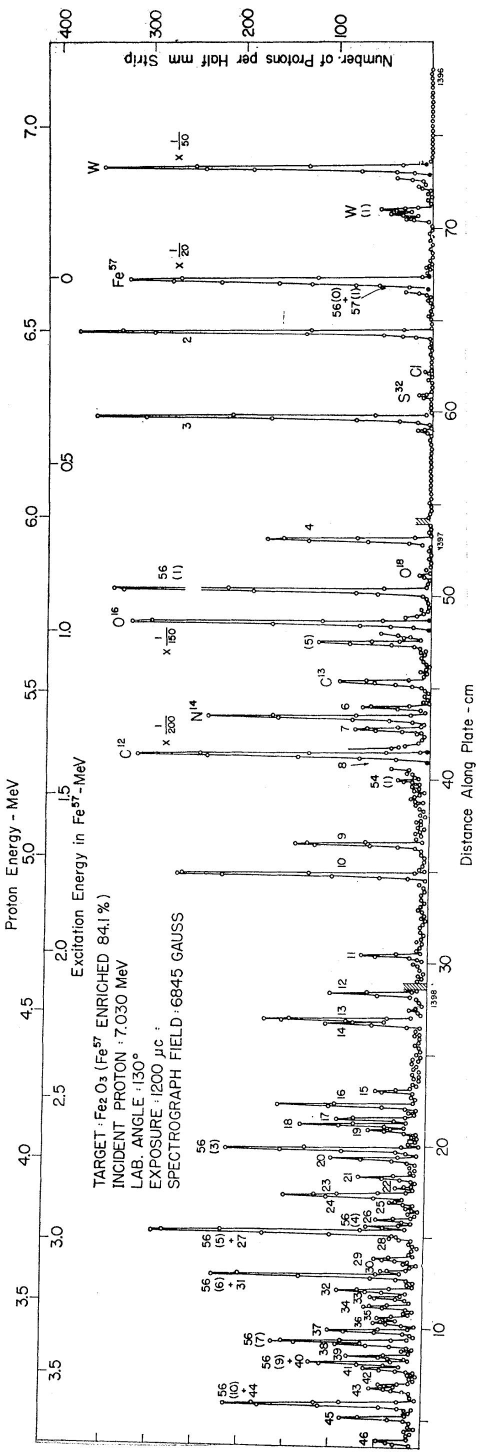

FIG. 3. Spectrum of protons scattered from enriched Fe^{57} (84.1%) target.

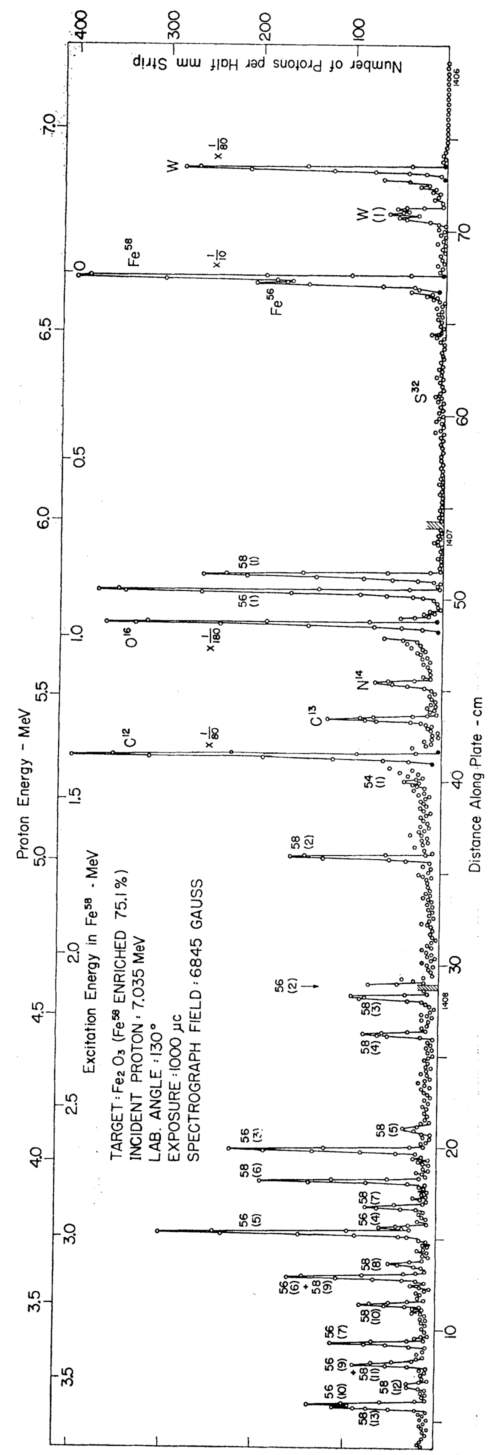

FIG. 4. Spectrum of protons scattered from enriched Fe^{58} (75.1%) target.

out to survey the usual problems of target thickness, reaction cross section, exposure requirements, spectrograph field settings, mass analysis of the target constituents, and degree of contamination by these constituents.

In addition, because of the isotopic impurity of natural iron, extra difficulties arising from the contributions of particle groups from the less prevalent isotopes were anticipated. The identification and assignment of these groups would be most difficult, if not impossible, without the high-resolution feature of the broad-range spectrograph. Initially, proton bombardments were made with both 6.54- and 7.01-MeV incident protons. Two runs at 6.54 MeV were made at 90 and 130 deg with respect to the incident beam. While testing different targets and surveying different excitation regions, other spectra of the reaction products were recorded at 30, 45, 90, and 130 deg with respect to the 7.01-MeV incident protons. More recently an exposure at 90 deg was recorded while bombarding a natural iron target with 8.5-MeV protons. This extended the excitation region in Fe^{56} by about 1.00 to 4.7 MeV.

For the deuteron-induced reactions, various natural iron targets were bombarded with 6.0-, 6.5-, and 7.0-MeV deuterons. A single 6.0-MeV run was made with the spectrograph set at 10 deg to the incident beam.

TABLE I. Isotopic analysis of iron targets.

Target sample	Fe^{54}	Fe^{56}	Fe^{57}	Fe^{58}
Enriched $Fe_2{}^{54}O_3$	96.66	2.34	0.77	0.23
Natural iron	5.82	91.66	2.19	0.33
Enriched $Fe_2{}^{57}O_3$	0.2	15.6	84.1	0.1
Enriched $Fe_2{}^{58}O_3$	0.6	22.1	2.2	75.1

At 6.5 MeV, three exposures were made at angles of 30, 45, and 90 deg, while at 7.0 MeV, the angles of observation were 10, 90, and 130 deg.

Later, when the enriched targets became available and for purposes of making direct comparison of group structure and intensity, the bombardment conditions used with the natural iron at 130 deg and 7.01-MeV incident protons were repeated on each of the three enriched targets. The proton spectra observed from each of these targets along with the natural iron target are shown in Figs. 1 through 4. The excitation region shown extends to about 3.8 MeV in each case.

For additional clarification of some dubious groups, two other bombardments with 7.01-MeV protons were made on the enriched Fe^{54}, Fe^{57}, and Fe^{58} targets. In each case the proton spectra were recorded at 90 deg to the incident beam and with a lower spectrograph field setting than that used at 130 deg. This permitted

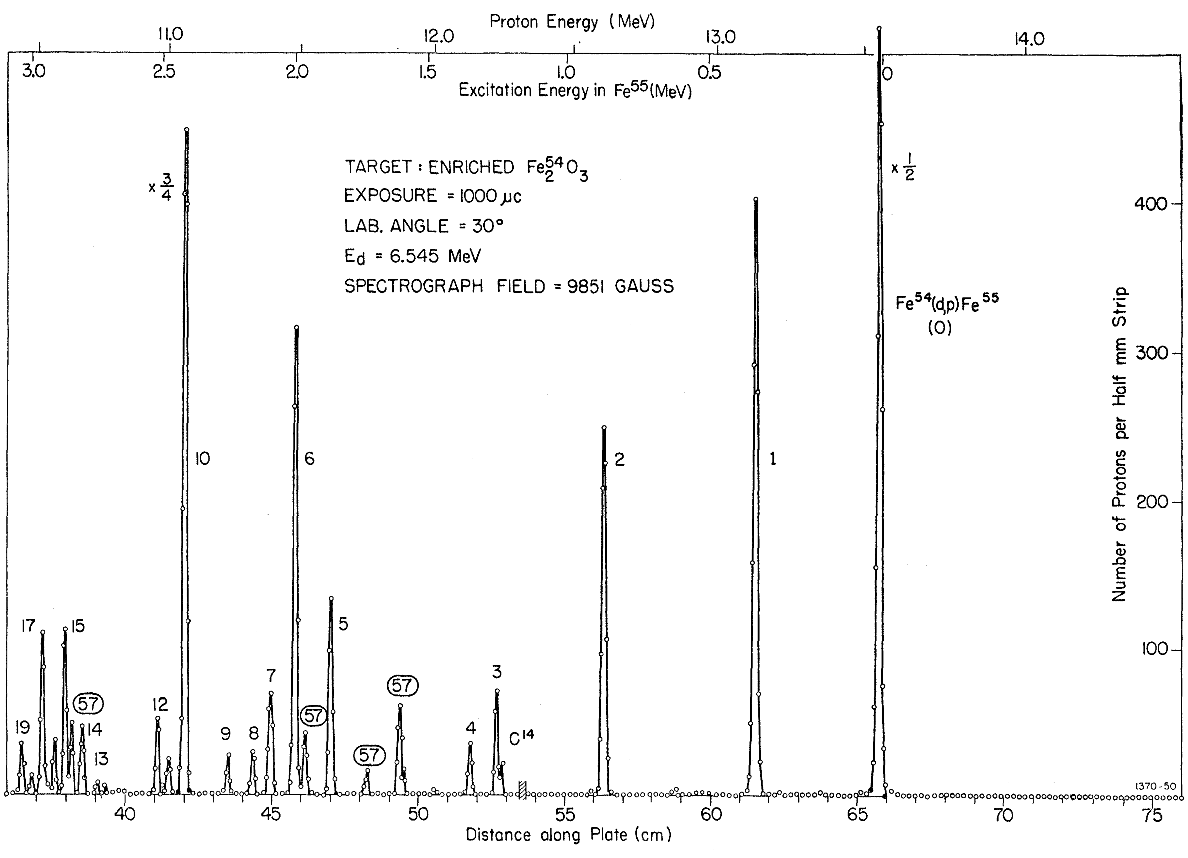

FIG. 5. Spectrum of protons from deuteron bombardment of a thin iron target enriched in Fe^{54} (96.66%).

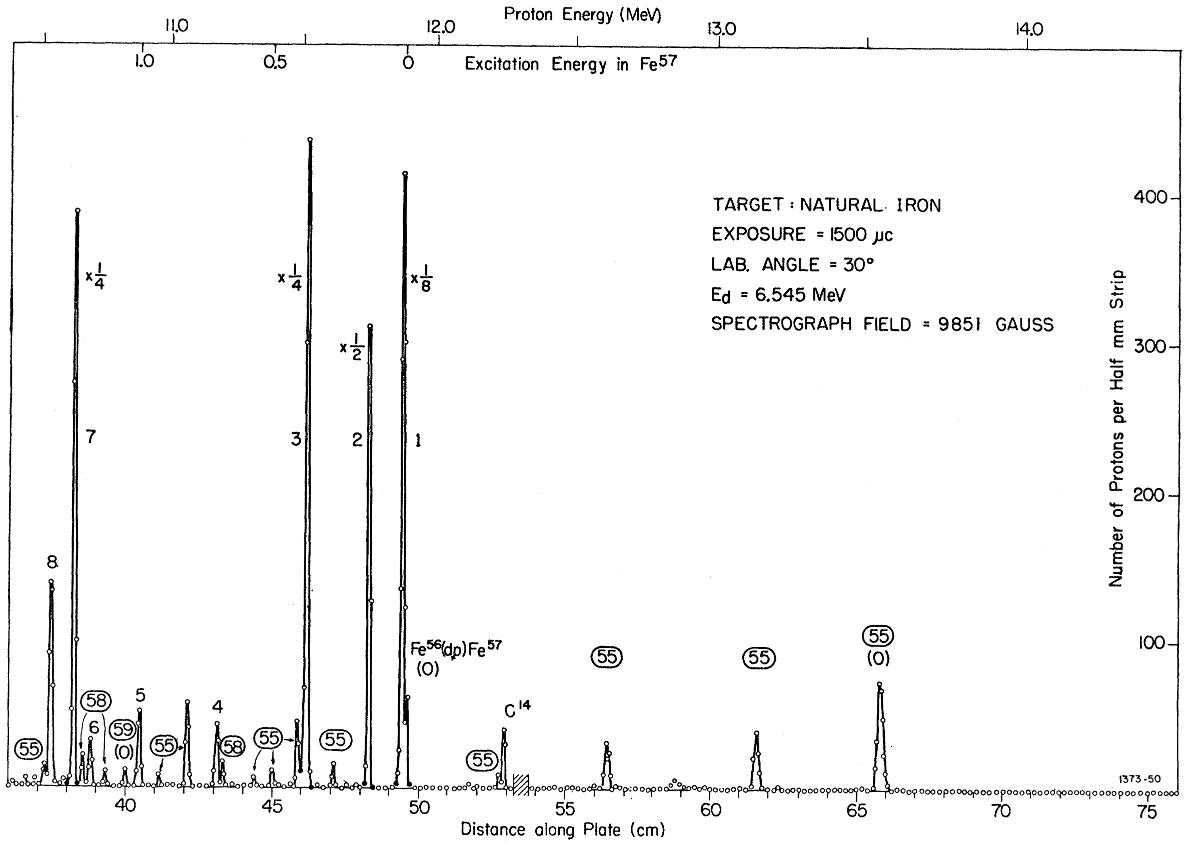

FIG. 6. Spectrum of protons from deuteron bombardment of a thin natural iron target (91.66% Fe^{56}).

the shifting of elastically scattered contaminant groups with respect to inelastic iron groups, and these latter at the same time moved toward the higher region on the nuclear-track plates where the spectrograph resolution is greater.

The deuteron bombardment of the three enriched target samples was made with both 6.5- and 7.0-MeV deuterons with analyzer and spectrograph field settings similar to those used with the natural iron targets, as noted above. However, with 6.5-MeV deuterons, the enriched targets were exposed at only 30 and 45 deg, and, in the case of the 7.0-MeV deuterons, only at 10 deg. The spectra observed for the 30-deg runs are reproduced in Figs. 5 through 12.

All of the plates exposed both to proton and deuteron bombardments were scanned, the data analyzed, and the relative intensities of the individual groups determined. Energy measurements were carried out only for those runs where the incident energies were precisely known and where the individual particle groups were sufficiently resolved. All measurements were made in accordance with standard procedures followed in this laboratory and reported in previous publications.[6]

[6] W. W. Buechner, E. N. Strait, A. Sperduto, and R. Malm, Phys. Rev. **76**, 1543 (1949); and E. N. Strait, D. M. Van Patter, W. W. Buechner, and A. Sperduto, *ibid.* **81**, 747 (1951).

In previously published measurements from this laboratory, the energy standard was based on a $B\rho$ value for the alpha particles from polonium equal to 331.59 kG-cm, corresponding to an energy of 5.299 $\pm$0.005 MeV. As a result of recent reviews of older measurements[7] of the alpha particles from radioactive materials and reports of more precise measurements[8] of the energies of the alpha particles from Po^{210}, there has been a growing tendency among experimenters to adopt a higher value for this energy. The value of 5.3042$\pm$0.0016 MeV, corresponding to a $B\rho=331.75$ kG-cm proposed by Nijgh *et al.*[9] was accepted[10] in 1960

[7] G. C. Hanna, *Experimental Nuclear Physics*, edited by E. Sayre (John Wiley & Sons, Inc., New York, 1959), Vol. III; A. H. Wapstra, Physica **21**, 367 (1955); and G. H. Briggs, Rev. Mod. Phys. **26**, 1, 472 (1954).

[8] E. R. Collins, C. D. McKenzie, and C. A. Ramm, Proc. Roy. Soc. (London) **216A**, 219 (1953); F. A. White, F. M. Rourke, J. C. Sheffield, R. P. Schuman, and J. R. Huizenga, Phys. Rev. **109**, 437 (1958); C. P. Browne, J. A. Galey, J. R. Erskine, and K. L. Warsh, *ibid.* **160**, 905 (1960); and E. H. Beckner, R. L. Bramblett, C. G. Phillips, and T. A. Eastwood, *ibid.* **123**, 2100 (1961).

[9] G. J. Nijgh, A. H. Wapstra, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

[10] W. W. Buechner, *Proceedings of International Conference on Nuclidic Masses*, edited by H. E. Duckworth (University of Toronto Press, Ontario, 1960), p. 267.

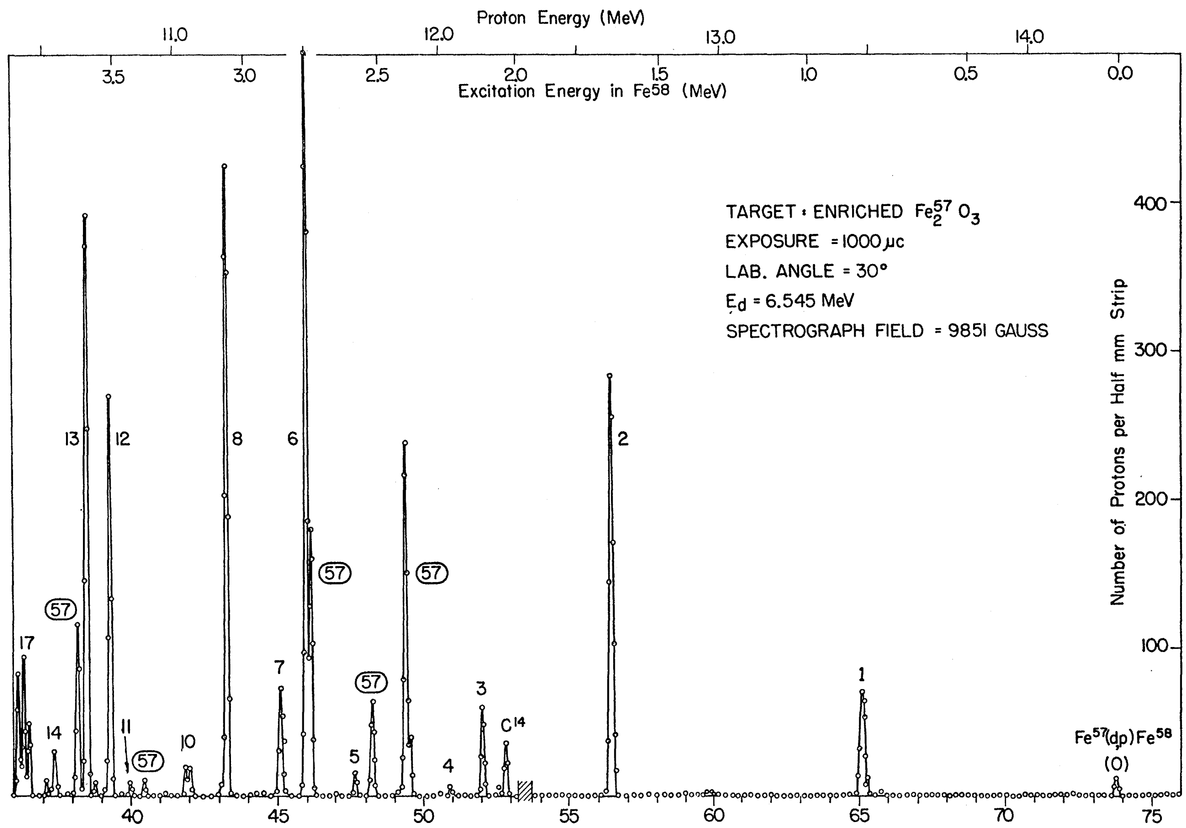

FIG. 7. Spectrum of protons from deuteron bombardment of a thin iron target enriched in Fe^{57} (84.1%).

in this laboratory as our new energy standard for calibrating our magnetic spectrographs. Still more recent measurements[11] of these alpha particles show less than 1-keV deviation from this value of 5.3042 MeV.

With a few exceptions, each Q value reported here, together with the excitation energy, is the arithmetic average of at least two and, in many cases, several, measurements made under different conditions of bombardment, such as change in bombarding energy, angle of observation, target sample, spectrograph field settings, and so on. The exceptions will be mentioned.

The energy spread from two or more determinations for a given particle group was generally of the order of one-half the quoted probable error. Because of the great number of measurements involved, part of the computations was performed with the aid of an IBM-650 computer.

III. RESULTS

A. $Fe^{56}(p,p')Fe^{56}$ Reaction

The data from bombardments of the natural iron targets are being discussed first because reaction products from these targets were first to be investigated and some of the level assignments to the less prevalent isotopes were initially made on the basis of these early experiments.

A typical spectrum of protons scattered elastically from a natural iron target (91.6% Fe^{56}) is shown in Fig. 1. The energy range covered in this spectrum extends from about 3 to 7 MeV. The peaks that are due to protons elastically scattered from the target constituents are indicated by the chemical symbol of the scattering nuclei. Except for the expected intense iron, carbon, and oxygen groups, it is noted that the presence of contaminants is not appreciable. The nitrogen and sulfur contents are present in the Formvar backings. The small peak at a distance of 73.5 cm is due to tantalum which was the material used as the boat reservoir in the evaporation process. The single inelastic group from a contaminant constituent, sulfur, is marked $S^{32}(1)$ and appears at a distance of 27 cm. This group arises from the first excited state in S^{32} at 2.234 MeV.[12] The remaining groups have been attributed to one of the iron isotopes, the responsible nucleus being indicated by the mass number followed by a number in parentheses indicating the level position. For example, the group marked 56-(3) arises from inelastic scattering

[11] *Proceedings of Second International Conference on Nuclidic Masses*, edited by W. H. Johnson, Jr. (Springer-Verlag, Berlin, 1963).

[12] P. M. Endt, W. W. Buechner, C. M. Braams, C. H. Paris, and A. Sperduto, Phys. Rev. **105**, 1002 (1957).

from Fe^{56} and corresponds to the third excited state. The spectrum of Fig. 1 displays altogether the positions of nineteen inelastic groups assigned to iron; seven to Fe^{54}, ten to Fe^{56}, and two to Fe^{57}. At a distance of about 67 cm, the two main components of the protons elastically scattered from iron (5.9% Fe^{54} and 91.6% Fe^{56}) are well resolved. The spacing here for the 130-deg angle of observation is 3.2 mm (17.2 keV) for the mass difference of two units, as expected. The component marked Fe^{56} was not resolved from the elastic contribution expected from the 2.2% Fe^{57} present in the target. Furthermore, as later observed (see the section on the $Fe^{56}(d,p)Fe^{57}$ reaction), the first state in Fe^{57} is at only 14-keV excitation, and thus any possible contribution expected from this state in the region between the Fe^{54} and Fe^{56} elastics was not detected.

With respect to the nineteen inelastic peaks observed here from the natural iron target, it can be seen from comparison of this spectrum (Fig. 1) with those observed from the enriched samples (Figs. 2, 3, 4) that assignment to the responsible iron isotope can be made on the basis of intensity considerations. The groups shown in Fig. 1 arising from the less abundant isotopes were observed with considerably greater intensities in the respective enriched runs. More accurate determinations of the intensities of individual peaks at corresponding distances were made and compared with the intensity of the elastically scattered peak from the associated iron isotope. The elastic intensity attributed to each isotope from a given run was proportioned according to the isotopic abundances shown in Table I, the assumption being made that all four isotopes have similar elastic scattering cross sections. In some instances, the assignment of a particular group was also aided by comparing its intensity with that of a well-established and isolated group from one of the iron isotopes, such as the groups corresponding to the 0.845-MeV level in Fe^{56} and the 1.409-MeV level in Fe^{54}.

Apart from making group assignments based on intensity ratios, it was observed from the early runs on the natural iron targets that independent isotopic assignment of a given group was also possible from measurements of the characteristic energy change observed with an angle shift from 30 to 130 deg and with 7.0-MeV incident protons. Four determinations of the excitation energy for each inelastic group were made at both angles, each calculation being based on the assumption that the group in question was due to one of the four stable isotopes.

The expected difference in excitation per mass unit over the excitation region shown in Fig. 1 was 4 to 8 keV per mass unit. Generally, our measurements were

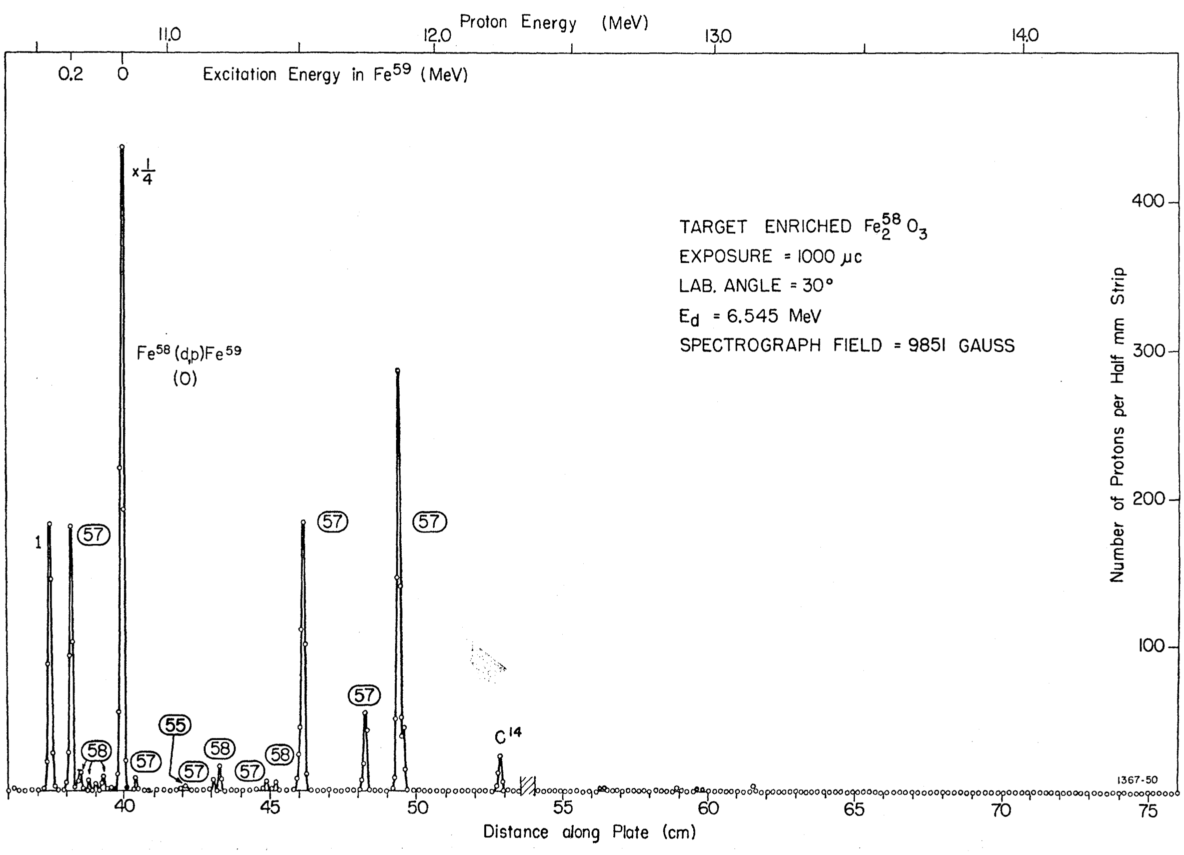

FIG. 8. Spectrum of protons from deuteron bombardment of a thin iron target enriched in Fe^{58} (75.1%).

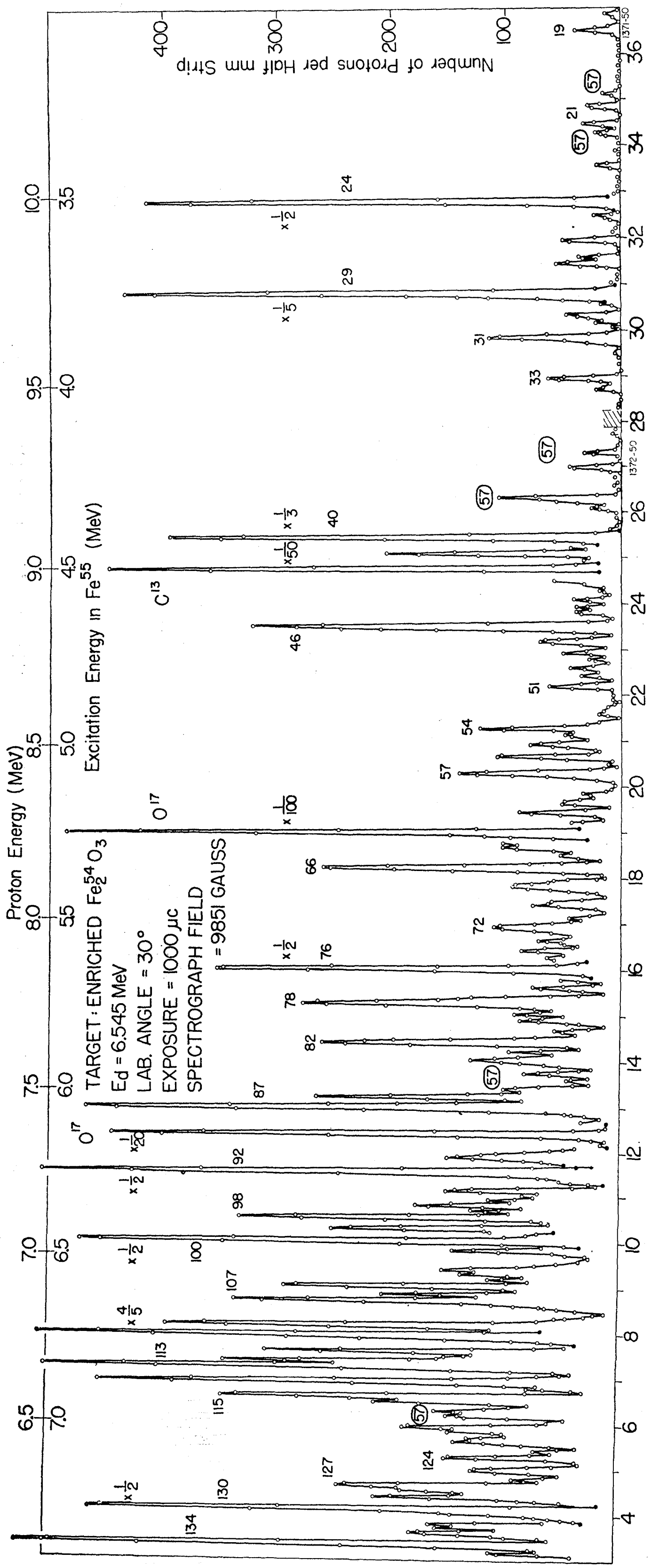

FIG. 9. Spectrum of protons from deuteron bombardment of a thin iron target enriched in Fe^{54} (96.66%).

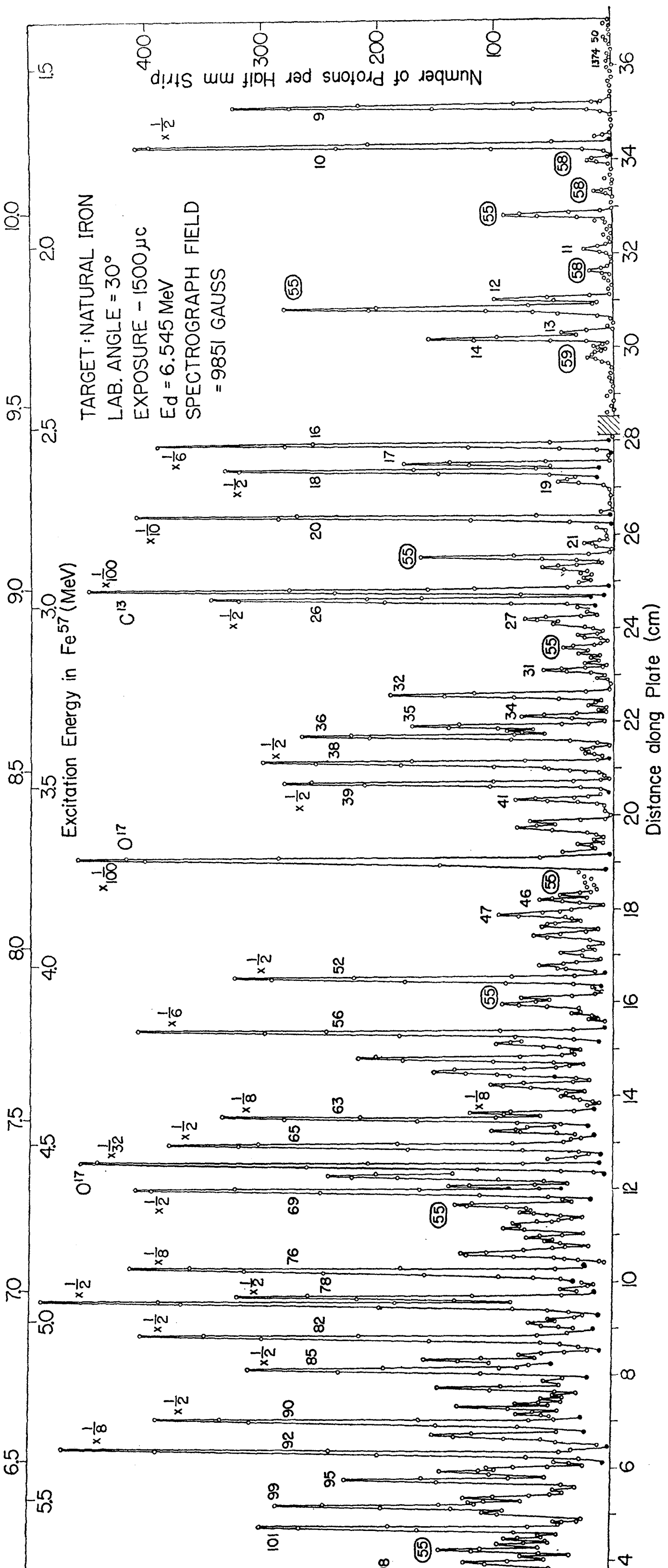

FIG. 10. Spectrum of protons from deuteron bombardment of a thin natural iron target (91.66% Fe^{56}).

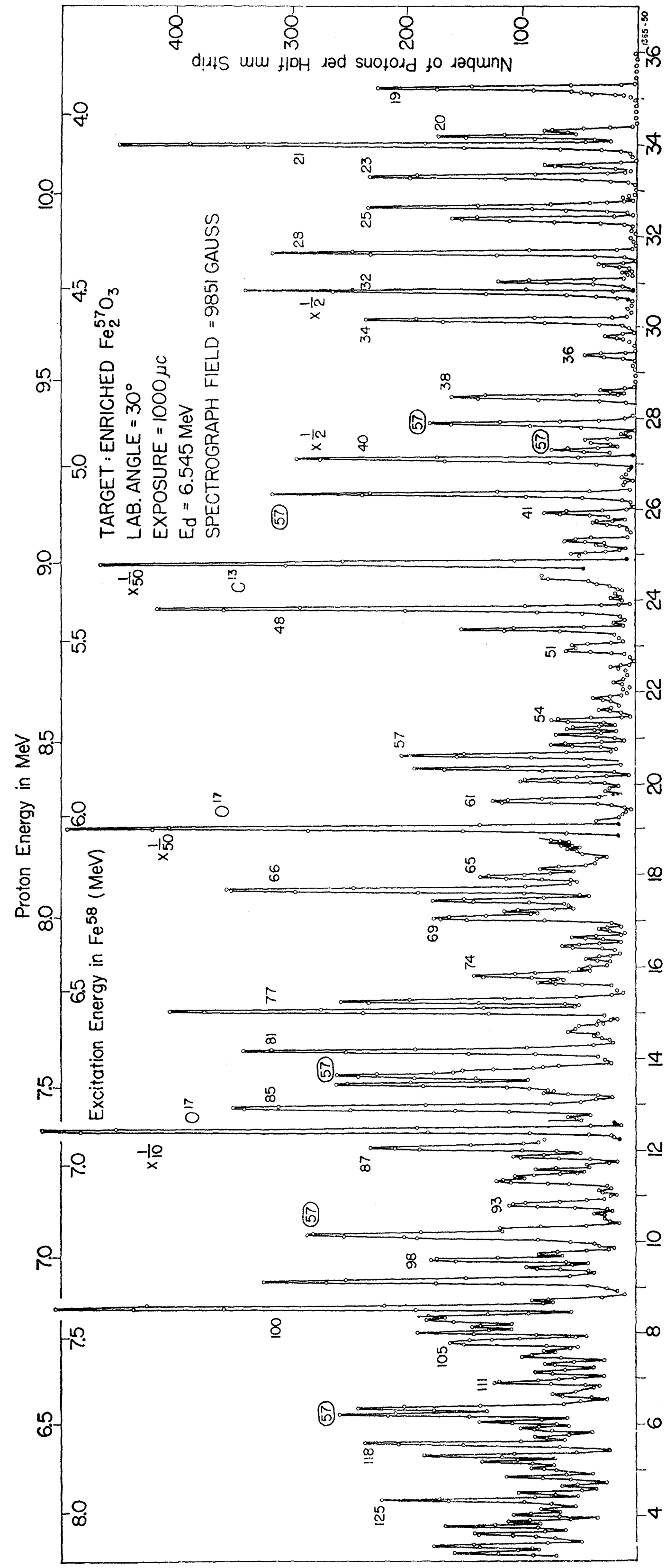

FIG. 11. Spectrum of protons from deuteron bombardment of a thin iron target enriched in Fe^{57} (84.1%).

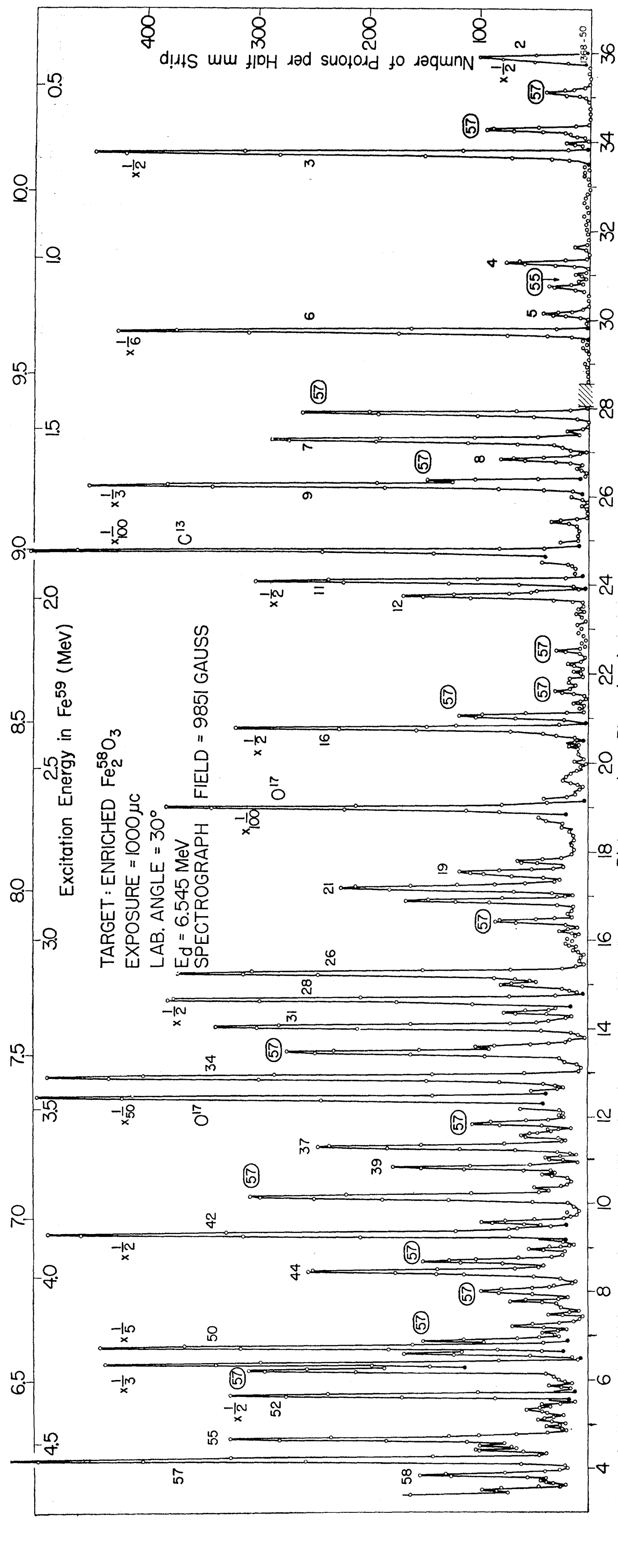

FIG. 12. Spectrum of protons from deuteron bombardment of a thin iron target enriched in Fe^{58} (75.1%).

TABLE II. Energy levels in Fe^{56}.

Level No.	E_x[a] (MeV)	$Fe^{56}(p,p')Fe^{56}$ reaction Group intensity[b] relative to Ground state	Level at 0.845 MeV	$Co^{59}(p,\alpha)Fe^{56}$ reaction[c] E_x (MeV)
0	0	100	456	0
1	0.845	21.9	100	0.844
2	2.085	...	...	2.085
3	2.658	7.3	33.5	2.661
4	2.940	1.3	6.1	...
5	2.958	11.1	50.6	2.964
6	3.119	4.0	18.3	3.127
7	3.369	3.2	13.9	3.379
8	3.388	0.2	1.0	...
9	3.445	2.4	10.8	
10	3.601	3.7	16.8	
11	3.830			
12	3.856			
13	4.042			
14	(4.094)			
15	(4.115)			
16	(4.295)			
17	(4.392)			
18	(4.453)			
19	(4.507)			
20	(4.535)			
21	(4.587)			
22	(4.606)			
23	(4.657)			
24	(4.680)			
25	(4.743)			

[a] All excitation energies $\leq \pm 0.005$ MeV.
[b] At 7.036 MeV and 130°.
[c] From Ref. 13.

consistent, and reproducible to within 2 to 3 keV (or approximately 0.05%) so that isotopic assignment was possible by this means.

The results of the energy measurements are tabulated in Table II, along with relative intensities observed from the 7.0-MeV exposure at 130 deg. The numbers in column 1 correspond with the labeling of the peaks in Fig. 1. The excitation energies, as measured from the $Fe^{56}(p,p')Fe^{56}$ reaction are listed in column 2. Column 5 lists the energies of these states in Fe^{56} as measured in this laboratory through the $Co^{59}(p,\alpha)Fe^{56}$ reaction.[13]

Columns 3 and 4 give the peak intensities relative to the elastic ground state and to the level at 0.845 MeV, respectively. The numbers in column 3 are based on assigning to the Fe^{56} elastic intensity 91.6% of the total of the two groups observed at a distance of 67 cm. A possible error is incorporated here because of the unknown contribution of the unresolved 0.014-MeV state [see section on $Fe^{56}(d,p)Fe^{57}$ reaction] arising from the 2.2% of Fe^{57} present in the natural iron target. For this reason, column 4 is included where this error appears only in the figure of 456 for the intensity of the elastic scattering relative to the 0.845-MeV level. The group corresponding to the 2.085-MeV level occurs in the region between plates at the 130-deg run so that no intensity measurements were possible. Groups Nos. 11 and 12 fall outside the range of the 130-deg run. These, together with group 2, were observed and measured from runs at other energies and angles. In the 130-deg run the group corresponding to level 5 in Fe^{56} is coincident with a group corresponding to the 2.959-MeV level in Fe^{54}. It is obvious from the intensity shown for the peak at a distance of about 15 cm in both Figs. 1 and 2 that both Fe^{54} and Fe^{56} isotopes have intense peaks at this energy. In each of the runs, the least of the two abundant isotopes contributed only about 5% of the intensity shown.

A similar situation of superposition of Fe^{54} and Fe^{56} peaks is observed at a distance of about 9.5 cm. Again the contribution of the least abundant isotope was small so that the accuracy of the energy measurements of the individual groups was not greatly affected by the isotopic impurity here. This was not generally the case, however, as will be seen later where intense groups from the isotopes of low concentration are observed in close proximity to weak groups from the more abundant isotope. The least intense of the first twelve groups attributed to Fe^{56} was that corresponding to the level of 3.388 MeV. At 7.0 MeV and 130 deg, this intensity was about 1% of that from the 0.845-MeV level. This approximate ratio was also noted from other exposures at 45 and 90 deg. The twelve groups numbered 13 through 25 were observed from a single run at 90 deg with 8.5-MeV incident protons.

An energy-level diagram for Fe^{56} is shown in Fig. 13, which also includes the energy-level diagrams of the other iron nuclei investigated from both the (p,p') and (d,p) reactions.

B. $Fe^{54}(p,p')Fe^{54}$ Reaction

Figure 2 shows the spectrum of scattered protons observed at 130 deg with 7.0-MeV incident protons from the bombardment of an iron oxide target enriched to 96.66% in Fe^{54}. An intense group, seen at a distance of 73.5 cm (also seen in Figs. 3 and 4), has been at-

TABLE III. Energy levels in Fe^{54}.

Level No.	E_x[a] (MeV)	$Fe^{54}(p,p')Fe^{54}$ reaction Group intensity[b] relative to Ground state	Level at 1.409 MeV
0	0	100	393
1	1.409	25.5	100
2	2.534 }	1.6	6.6
3	2.540 }		
4	2.564	6.7	26.0
5	2.959	7.8	30.6
6	3.164	5.4	21.2
7	3.296	0.8	3.1
8	3.345	2.9	11.5
9	(3.838)		
10	(4.048)		
11	(4.074)		

[a] All excitation energies $\leq \pm 0.005$ MeV.
[b] At 7.033 MeV and 130°.

[13] M. Mazari, A. Sperduto, and W. W. Buechner, Phys. Rev. **107**, 365 (1957).

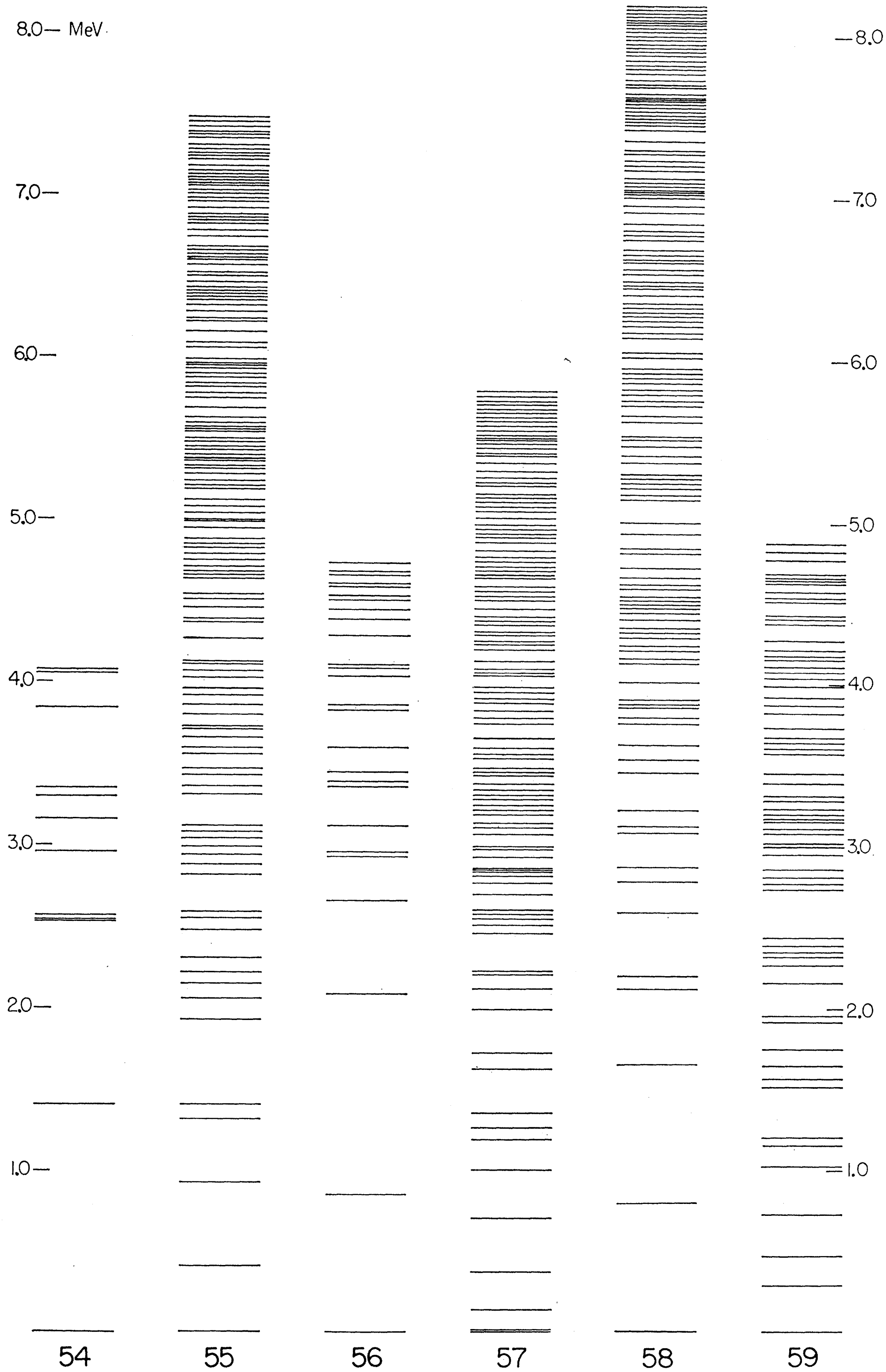

FIG. 13. Energy-level diagram for the iron isotopes.

tributed to elastic scattering from wolfram. The oxide targets were prepared by evaporation from a wolfram boat instead of the tantalum boat as was used for the natural metallic target. (Apparently, a good deal more of the boat material was evaporated along with the enriched isotopes.) The grouping at a distance of about 71 cm consists of three components which, if assumed to be due to inelastic scattering from wolfram, would be consistent with the assignment to the well-known Coulomb-excited states[14] in W^{182}, W^{184}, and W^{186} at 100.1, 111.1, and 122.5 keV, respectively. The average of the excitation energies measured here and from the Fe^{57} and Fe^{58} targets gives values of 100, 111, and 122 keV, all ± 4 keV.

Table III lists the excitation energies of eleven groups attributed to levels in Fe^{54} obtained from measurements made from both enriched and natural iron targets. The relative intensities, as in Table II, are those measured at 130 deg with 7.0-MeV incident protons. Note that the group corresponding to the first level in Fe^{54} at 1.409 MeV is the most intense and is comparable in intensity to the first level in Fe^{56} at 0.845 MeV. The energies for groups Nos. 9, 10, and 11 are enclosed in parentheses because they were derived from a single observation—from an enriched Fe^{54} target at 90 deg with 7.0-MeV incident protons. This excitation region was not covered in other runs. Six of the remaining eight groups were initially[1] assigned to Fe^{54} from the natural iron target runs on the basis of the differential energy change observed with a change in angle. Of the two groups not at first identified with Fe^{54}, one (No. 5) was coincident with and therefore obscured by the more intense group (also No. 5) arising from Fe^{56} at 2.958 MeV. The other was in fact reported as a single group from Fe^{54}, but later with more intensity from the enriched Fe^{54} targets it was found to consist of two components (Nos. 2 and 3) with only 6-keV spacing. This pair of levels was not completely resolved, but the evidence for assigning two groups comes from a comparison of the peak shape with that of group No. 4 in each of three runs.

In addition to the eight groups from Fe^{54} shown in Fig. 2, it is noted that seven of the ten groups from Fe^{56} in this region are also observed clearly from the 2.9% Fe^{56} present in the Fe^{54} enriched targets. Of those not observed, 56-(8) at 3.388 MeV is the least intense of all the Fe^{56} groups and 56-(5) and 56-(7) are masked by more prominent groups from Fe^{54}.

C. $Fe^{57}(p,p')Fe^{57}$ Reaction

The spectrum of scattered protons at 130 deg with 7.0-MeV incident protons on an iron oxide target enriched to 84.1% in Fe^{57} is shown in Fig. 3. In the energy range shown, forty-six groups have been identified with inelastic scattering from Fe^{57}. The prefix number 57, identifying the Fe^{57} peaks, has been left out in Fig. 3 to avoid confusion in numbering, particularly where the density of levels increases at high excitation. Thus, the level numbers without parentheses identify the groups from Fe^{57}. The notation on groups from Fe^{54} and Fe^{56} is the same as in Figs. 1 and 2. Of the forty-six groups observed, two were also observed from bombardment of the 2.2% Fe^{57} present in the natural iron targets. These are the groups numbered 2 and 3 and correspond to levels in Fe^{57} at 0.135 and 0.365 MeV. The presence of 15.6% Fe^{56} in the enriched Fe^{57} target gave assurance that all nine Fe^{56} groups shown in Fig. 1 contributed to the spectrum in Fig. 3. From comparison of the yields of the group giving rise to the level in Fe^{56} at 0.845 MeV in Figs. 1

TABLE IV. Energy levels in Fe^{57}.

Level No.	$Fe^{56}(d,p)Fe^{57}$ reaction[a] E_x[b] (MeV)	$Fe^{57}(p,p')Fe^{57}$ reaction E_x[c] (MeV)	Group intensity[d] relative to Ground state	Group intensity[d] relative to Level at 0.135 MeV	Adopted[e] E_x (MeV)
0	0	0	100	18000	0
1	0.014	...	1.6[f]	31[f]	0.014
2	0.136	0.135	5	100	0.135
3	0.366	0.365	4.3	86	0.365
4	0.707	0.705	2.2	44.5	0.706
5	1.010	1.006	1.2	24.8	1.008
6	1.119	1.196	0.7	14.0	1.198
7	1.266	1.263	0.9	18.0	1.264
8	1.359	(1.357)	...	...	1.358
9	1.630	1.627	1.3	26.7	1.629
10	1.728	1.725	2.4	48.0	1.727
11	1.995	1.991	0.5	10.3	1.994
12	2.124	2.120	1.0	20.6	2.122
13	2.212	2.209	1.2	23.8	2.210
14	2.227	2.219	0.7	13.6	2.225
15	2.461	2.456	0.3	5.5	2.460
16	2.511	2.507	1.1	21.2	2.509
17	2.557	2.554	0.7	13.9	2.556
18	2.580	2.574	0.9	18.5	2.576
19	2.603	2.597	...	...	2.600
20	2.702	2.698	0.6	11.8	2.700
21	2.769	2.767	0.4	8.7	2.768
22	...	(2.803)	0.1	1.9	2.803
23	2.830	2.829	1.4	27.2	2.830
24	2.841	2.836	...	...	2.840
25	...	(2.855)	0.2	3.8	2.855
26	2.928	2.920	0.3	6.0	2.925
27	2.976	2.974	...	...	2.975
28	2.990	2.990	0.2	4.0	2.990
29	3.067	3.065	0.6	12.0	3.067
30	3.115	3.110	0.3	5.7	3.115
31	3.135	3.127	0.9	18.0	3.135
32	3.188	3.180	0.6	12.4	3.184
33	3.216	3.207	0.4	7.4	3.214
34	3.246	3.239	0.4	8.2	3.243
35	3.290	3.284	0.3	6.4	3.290
36	3.303	3.298	0.4	7.5	3.303
37	3.336	3.333	0.6	12.4	3.334
38	3.375	(3.369)	0.4	9.1	3.375
39	3.433	3.428	0.4	8.7	3.431
40	...	3.452	0.4	8.7	3.452
41	3.474	3.472	0.4	8.5	3.473
42	3.539	3.535	0.3	5.0	3.539
43	3.553	3.548	0.4	7.4	3.551
44	3.599	3.608	0.6	11.1	3.601
45	(3.66)	3.661	0.4	9.1	3.661
46	3.752	3.752	0.3	5.7	3.752

[14] E. L. Crump, A. F. Clark, J. W. M. DuMond, F. J. Gordon, and H. M. Mark, Phys. Rev. **107**, 745 (1957).

TABLE IV (*continued*).

(d,p) reaction continued					
Level No.	E_x (MeV)	Level No.	E_x (MeV)	Level No.	E_x (MeV)
47	3.784	68	4.573	89	5.241
48	3.827	69	4.594	90	5.271
49	3.881	70	4.652	91	5.306
50	3.903	71	(4.68)	92	5.364
51	3.943	72	4.693	93	5.404
52	3.982	73	4.719	94	5.422
53	4.049	74	4.753	95	5.445
54	4.081	75	4.771	96	5.472
55	4.093	76	4.824	97	5.500
56	4.139	77	4.873	98	5.512
57	4.208	78	4.902	99	5.525
58	4.239	79	4.922	100	5.564
59	4.255	80	4.954	101	5.590
60	4.294	81	4.976	102	5.623
61	4.316	82	5.019	103	5.641
62	4.363	83	5.064	104	5.675
63	4.381	84	5.085	105	5.688
64	4.412	85	5.115	106	5.721
65	4.458	86	5.140	107	5.737
66	4.506	87	5.166	108	5.769
67	4.544	88	5.224	109	5.802

[a] Ground-state Q value $=5.425\pm0.008$ MeV.
[b] All excitation energies $\leq\pm0.010$ MeV.
[c] All excitation energies $\leq\pm0.005$ MeV.
[d] At 7.030 MeV and 130°.
[e] Weighted average where measurements from both reactions were made.
[f] Estimated from known isotopic abundances of targets bombarded (Table I), from observed yields of elastic peaks, and from measured ratios of inelastic to elastic intensities (groups 56–1 to 56–0).

and 3, it was determined that 44% of the Fe^{56} spectrum shown in Fig. 1 is superimposed on the spectrum of Fe^{57} levels in Fig. 3. The contribution from the Fe^{54} content (0.2%) in the enriched Fe^{54} target was negligible; only the group corresponding to the 1.409-MeV level was observed.

In Table IV are listed the excitation energies and, where possible, the relative intensities of the forty-six peaks shown in Fig. 3. Again, those energy values enclosed within parentheses were obtained from single observations. In one of the two runs made, the peak in question may have been too low in intensity and therefore was not resolved from an adjacent peak, or it may have been completely masked by a contaminant peak. The intensities indicated for the Fe^{57} peaks occurring in the vicinity of the Fe^{56} peaks are the results of subtracting 44% of the Fe^{56} intensity in the run shown in Fig. 1 from the total intensity observed at the corresponding distance in Fig. 3. Thus, it was determined that no superposition of peaks in Fig. 3 was involved from Fe^{56} in the region of peaks 56-(1), (2), (3), and (4); whereas, in the regions of peaks 56-(5) through 56-(10), the intensity measurements indicated the presence of contributions from Fe^{57} groups.

The first excited state at 0.014 MeV in Fe^{57} was not observed from the (p,p') reaction because of the proximity of the intense elastically scattered protons from Fe^{56} and Fe^{57}. It was, however, clearly resolved in the measurements of the $Fe^{56}(d,p)Fe^{57}$ reaction (Sec. III-E). The increase in the density of the levels observed above about 2.5-MeV excitation in Fe^{57} makes the process of sorting out and identifying all the individual groups very difficult. Particle groups with level spacings

TABLE V. Energy levels in Fe^{58}.

Level No.	$Fe^{57}(d,p)Fe^{58}$ reaction[a] E_x[b] (MeV)	$Fe^{58}(p,p')Fe^{58}$ reaction E_x[c] (MeV)	Group intensity[d] relative to Ground state	Level at 0.799 MeV	Adopted[e] E_x (MeV)
0	0	0	100	2000	0
1	0.800	0.799	5.0	100	0.800
2	1.664	1.663	2.1	42.5	1.664
3	2.124	2.123	1.6	31.5	2.124
4	(2.20)	2.251	0.7	14.9	2.251
5	2.593	2.586	0.5	9.4	2.590
6	2.775	2.773	1.8	35.8	2.774
7	2.870	2.864	1.1	21.6	2.867
8	3.077	3.072	0.8	15.0	3.075
9	...	3.123	1.0	19.5	3.123
10	3.224[f]	3.222[f]	0.9	18.4	3.223
11	3.454	3.453	0.5	9.8	3.454
12	3.532	3.532	0.5	10.1	3.532
13	3.623	3.613	0.9	18.0	3.620

(d,p) reaction continued					
Level No.	E_x (MeV)	Level No.	E_x (MeV)	Level No.	E_x (MeV)
14	3.748	54	5.723	94	7.166
15	3.787	55	5.746	95	7.199
16	3.855	56	5.792	96	7.230
17	3.875	57	5.822	97	7.272
18	3.896	58	5.859	98	7.289
19	4.009	59	5.892	99	7.351
20	4.133	60	(5.92)	100	7.430
21	4.156	61	5.953	101	7.457
22	4.209	62	(6.02)	102	7.473
23	4.238	63	(6.05)	103	7.492
24	4.290	64	6.146	104	7.507
25	4.316	65	6.168	105	7.534
26	4.348	66	6.208	106	7.567
27	4.399	67	6.239	107	7.578
28	4.437	68	6.270	108	7.585
29	4.470	69	6.288	109	7.605
30	4.490	70	6.322	110	7.628
31	4.513	71	6.348	111	7.653
32	4.543	72	6.405	112	(7.68)
33	4.587	73	6.438	113	(7.69)
34	4.622	74	6.457	114	7.734
35	4.662	75	6.476	115	7.775
36	4.716	76	6.529	116	7.797
37	4.810	77	6.557	117	7.824
38	4.829	78	6.605	118	7.846
39	4.928	79	6.622	119	7.883
40	4.998	80	6.636	120	7.901
41	5.144	81	6.675	121	7.918
42	5.170	82	6.744	122	7.946
43	5.217	83	6.772	123	7.974
44	5.236	84	6.789	124	7.997
45	(5.27)	85	6.842	125	8.018
46	(5.29)	86	6.909	126	8.045
47	5.383	87	6.953	127	8.065
48	5.414	88	7.023	128	8.084
49	5.471	89	7.028	129	8.100
50	5.513	90	7.048	130	8.121
51	5.525	91	7.060	131	8.137
52	5.620	92	7.094	132	8.157
53	5.660	93	7.124	133	8.182

[a] Ground-state Q value $=7.815\pm0.008$ MeV.
[b] All excitation energies $\leq\pm0.010$ MeV.
[c] All excitation energies $\leq\pm0.005$ MeV.
[d] At 130° and 7.035 MeV.
[e] Weighted average where measurements were made from both reactions.
[f] Probable double peak.

of the order of a few kilovolts have been observed from both the (p,p') and (d,p) results, and these spacings would require a magnetic spectrograph with higher resolution to obtain convincing measurements of both energy and intensities. This is particularly true where peak intensities are low and close to other more intense members. Thus, should there exist any peaks with intensities of about half that shown for Nos. 22, 25, 26, 28, and 30, they could very well have been missed.

In a comparison of the proton spectrum of Fig. 3 with that of Figs. 6 and 10 from the $Fe^{56}(d,p)Fe^{57}$ reaction, it can be seen that, within the range in excitation energy covered by the (p,p') experiments, three levels, Nos. 22, 25, and 40, were not observed in the (d,p) studies. These are very weakly excited in the (p,p') experiments and perhaps even less by (d,p) excitation.

D. $Fe^{58}(p,p')Fe^{58}$ Reaction

The spectrum of scattered protons from an enriched Fe^{58} (75.1%) target is shown in Fig. 4, and the excitation energies and intensities of groups identified with levels in Fe^{58} are given in Table V. Following the procedure used in the analysis of Fe^{54} and Fe^{57} particle groups, we find the yield of each group from Fe^{56} (in the proportion shown for the 0.845-MeV level in the spectra of Figs. 1 and 4, here approximately 50%) was first subtracted from the total yield at the corresponding distance in Fig. 4. Except for the contributions arising from the 0.6% Fe^{54} and the 2.2% Fe^{57} [only groups 54-(1) and 57-(2) and (3) have been identified in Fig. 4] present in the enriched Fe^{58} target, the remaining spectrum was attributed to Fe^{58}.

Superimposed, or nearly superimposed, Fe^{56} and Fe^{58} peaks are found in the region of groups Nos. 6, 9, and 10 from Fe^{56} and to the extent of about 50% of the intensity shown. The Fe^{58} peaks involved are Nos. 9, 11, and 13 at 3.123, 3.453, and 3.613 MeV, respectively. No group corresponding to the level at 3.123 MeV has been observed in the (d,p) work (Sec. III-G). However, some groups, such as No. 12 (Fig. 4) at 3.532 MeV, in each of the three (d,p) runs were extremely weak, and any other group with only half the intensity of group 12 could certainly have been missed.

E. The $Fe^{56}(d,p)Fe^{57}$ Reaction

Again, as in the case of the (p,p') investigations, a survey of the deuteron-induced reactions was initiated with the bombardment of natural iron targets. An attempt was made to resolve the pair of levels formed by the group leading to the ground-state transition of the $Fe^{56}(d,p)Fe^{57}$ reaction and to the group corresponding to the level at 0.014 MeV in Fe^{57}. Precise measurements of the ground-state Q value for this reaction, as well as those for the other isotopes, were also a primary objective.

Using incident deuterons of 6.5 MeV, the emitted protons from iron recorded in these experiments ranged from about 6.5 to 14.5 MeV. The corresponding limits in the excitation energies observed were 7.5 MeV for Fe^{55}, 5.9 MeV for Fe^{57}, 8.2 MeV for Fe^{58}, and 4.8 MeV for Fe^{59}.

The preliminary analyses of the proton spectra from natural iron revealed a surprisingly large yield for the (d,p) interaction and a rapidly increasing level density with increasing excitation energy. In the present investigation an attempt was made to sort out and identify every peak that was sufficiently resolved. The spectra of seven different runs from natural iron targets were analyzed, and identification was made of 106 particle groups ascribed to the $Fe^{56}(d,p)Fe^{57}$ reaction alone. Many other groups arising from the less prevalent isotopes in natural iron along with the usual contaminant carbon and oxygen groups were also identified and measurements made. In the combined spectra shown in Figs. 6 and 10 recorded from a single exposure, over 150 particle groups were resolved, including four oxygen and carbon contaminant groups, at least twenty-five arising from the 5.9% Fe^{54}, nine coming from the 2.2% Fe^{57}, and two being attributed to the 0.33% Fe^{58} present in the natural iron targets.

Additional measurements were also made of several of the more intense $Fe^{56}(d,p)Fe^{57}$ reaction groups observed from the bombardment of the targets enriched in Fe^{54}, Fe^{57}, and Fe^{58} (Figs. 5 and 9, 7 and 11, and 8 and 12, respectively), in which the Fe^{56} content was 2.3%, 15.6%, and 22.1%, respectively.

The proton spectra shown in Figs. 5 to 12 are from the bombardment of each of the four targets under identical conditions of incident energy, observation angle, and spectrograph field setting. In Figs. 5 through 8, the proton groups observed in the energy range between about 10.5 and 14.5 MeV are shown. The continuation of each of these spectra down to energies of about 6.0 MeV are shown in Figs. 9 through 12. The distance, and therefore the energy, scale in the latter set was expanded to twice that of Figs. 5 through 8 in order to display better the increasing number of groups at the higher excitation region. Isotopic assignment of the many particle groups was made mainly on the basis of intensity comparisons of the individual peaks at corresponding distances from the set of runs shown in Figs. 5 through 12 in the manner described earlier.

Similar intensity comparisons were also made from sets of identical runs on the four targets with 6.5-MeV deuterons and a 45-deg angle of observation and also with 7.0-MeV deuterons at a 10-deg angle. In the case of the (d,p) reactions for the iron isotopes, the change in excitation energy per mass unit $(\Delta E_x/\Delta M)$ for a given particle group with energy within the range of about 6 to 15 MeV, as observed in these experiments, varies from 10 to 15 keV at 130 deg and approximately 0.5 to 1 keV at 30 deg. Although this differential change in energy is ordinarily adequate for making proper isotopic assignment of individual groups, the high density of levels (spacings of the order of 10 to 20 keV) encountered in the higher excitation region, accompanied by the contributions of peaks from the less prevalent isotopes, made it difficult to identify the responsible isotope with certainty.

The results of the (d,p) measurements from Fe^{56} are tabulated in Table IV. Each energy value listed is the result of at least two measurements, except those in parentheses, in which case only one measurement was made. The level numbers in Table IV and in Figs. 6 and 10 are the same as those used for the corresponding levels from the $Fe^{57}(p,p')Fe^{57}$ reaction (Fig. 3). Thus, a given level in Fe^{57} is identified in this paper with the same number in both the (p,p') and (d,p) results in the excitation region where the two experiments overlap. Because of space limitation in Figs. 9 through 12, in the spectrum region where the level density is high, some group numbers have been omitted. The groups that have been numbered can at best serve as a guide in associating a specific group with the corresponding energy level in Table IV. Some of the more intense groups arising from the less prevalent isotopes are indicated by the residual mass number only, which in Figs. 5 through 12 are circled for greater clarity. The level number for a prominent group from one of the less abundant isotopes may be noted on the peak at the corresponding distance from the enriched target run.

Of the forty-six levels found from the $Fe^{57}(p,p')Fe^{57}$ reaction, all but three (Nos. 22, 25, and 40) are identified in the $Fe^{56}(d,p)Fe^{57}$ reaction. In the case of Nos. 22 and 25, the presence of contaminant groups or coincident contributions from strongly excited groups from the $Fe^{54}(d,p)Fe^{55}$ reaction can very easily obscure weakly excited groups from the $Fe^{56}(d,p)Fe^{57}$ reaction (see spectrum at distances of 25.1 and 25.6 cm in Fig. 10). In the case of No. 40, again a low-intensity group here could well be buried in the low-energy tail of group No. 39. Groups with intensities comparable to Nos. 6, 11, and 21 might also have been missed had they occurred near more prominent groups. The possibility of missing more of such groups at excitations above about 3.5 MeV is clearly evident from a study of the spectrum of Fig. 10. The listed levels in Table IV are thus only those that were sufficiently resolved and measurable, were observed in more than one run, and were not coincident with more intense groups from the other isotopes. We are convinced there exist more levels in this excitation region than are listed in Table IV.

The ground-state Q value for the $Fe^{56}(d,p)Fe^{57}$ reaction has been determined from a number of measurements to be 5.425 ± 0.008 MeV. The group corresponding to the first excited state at 0.014 MeV in Fe^{57} can be seen just resolved from the ground-state group in each of the Figs. 5 through 8 at a distance of 49.5 cm. In the portion of the spectrum displayed in Fig. 6 can be seen seven more groups from the $Fe^{56}(d,p)Fe^{57}$ reaction. It is noted that all of these except one are seen in the spectrum of the enriched Fe^{58} target (Fig. 8). The exception, No. 8, is coincident with group No. 1 from Fe^{59}. Also in the spectrum of the enriched targets Fe^{54} and Fe^{57} (Figs. 5 and 7), the intensities of these groups are seen to be reduced in proportion to their prevalence in the target sample. In Fig. 5, only Nos. 0, 1, 2, 3, and 7 are prominent, while in Fig. 7 all are seen except groups Nos. 4 and 8, which, although weak, are apparently obscured by groups Nos. 8 and 14 from the $Fe^{57}(d,p)Fe^{58}$ reaction. Apart from the nine groups attributed to levels in Fe^{57} in Fig. 6 and the one from C^{14}, there are fifteen other groups assigned to one of the other three iron isotopes. Each is labeled with the appropriate mass number of the residual nucleus, and the enhanced intensity of each can be seen in the figure showing the corresponding enriched isotope. An example of a situation occurring many times as the density of levels increases is noted at a distance of about 37.3 cm. A proton group at this distance is observed on each of the four spectra (Figs. 5–8). In each case, the predominant contribution comes from the enriched isotope. Thus, at this distance, the group corresponds to a level in Fe^{57} at 1.359 MeV in Fig. 6 (group No. 8), a level in Fe^{55} at 3.035 MeV in Fig. 5 (group No. 7), a level in Fe^{59} at 0.287 MeV in Fig. 8 (group No. 1), and a level in Fe^{58} at 3.748 MeV in Fig. 7 (group No. 14). The assignment of such coincident groups has been made only after a measure of the intensity of the groups in question from each run was compared with the yield from a standard isolated group from each isotope. In column 6 of Table IV are listed our adopted values of the excitation levels in Fe^{57} obtained from a weighted average of the results from the (p,p') and (d,p) measurements. The level scheme for Fe^{57} is incorporated into Fig. 13.

F. The $Fe^{54}(d,p)Fe^{55}$ Reaction

The sample of Fe^{54} used in making the targets for these experiments was the most highly enriched (96.4%) of the four iron targets. There were no traces of peaks detected from the 0.77% Fe^{57} and the 0.23% Fe^{58} present in these Fe^{54} targets. This was partly due to the fact that there were no intense levels in Fe^{58} and Fe^{59} in the region of the spectra shown in Figs. 7 and 8 where contributions from these small abundances would be best resolved and detected. In the case of the 2.3% Fe^{56} present in the enriched Fe^{54} target, it is seen from comparing the intensities of a prominent and isolated Fe^{56} group, say, the ground-state doublet, in Figs. 5 and 6 that about 3% of the $Fe^{56}(d,p)Fe^{57}$ spectrum shown in Figs. 6 and 10 should then be superimposed on the $Fe^{54}(d,p)Fe^{55}$ spectrum of Figs. 5 and 9. Except for the $Fe^{56}(d,p)Fe^{57}$ peak Nos. 0, 1, 2, 3, 7, 9, 10, 18, 20, 63, and 92, the remaining contributions from Fe^{56} are mostly masked by Fe^{55} peaks.

The Q value for the ground-state transition of the $Fe^{54}(d,p)Fe^{55}$ reaction has been determined as 7.084 ±0.008 MeV. In the region of excitation investigated here up to 7.5 MeV, 136 peaks have been assigned to levels of Fe^{55}. These energy levels are tabulated in Table VI. Again, the number in column 1 denotes the level position and corresponds to numbering of the peaks in Figs. 5 and 9. The energy-level diagram for Fe^{55} is also shown in Fig. 13.

G. The $Fe^{57}(d,p)Fe^{58}$ Reaction

The iron samples bombarded for the study of reactions from Fe^{57} had very low isotopic impurity in the form of Fe^{54} and Fe^{58} (only 0.2 and 0.1%, respectively). No contribution from these isotopes was observed. However, the large percentage of Fe^{56} (15.6%) contributed heavily to the spectrum shown in Figs. 7 and 11. About 10% of the yield of the $Fe^{56}(d,p)Fe^{57}$ peaks shown in Figs. 6 and 10 are superimposed on the $Fe^{57}(d,p)$ spectrum in Figs. 7 and 11. The prominent Fe^{57} peaks in these latter figures are all labeled with the encircled number (57), and the level position can be seen by referring to the corresponding distances in Figs. 6 and 10. The group corresponding to the ground-state transition for the $Fe^{57}(d,p)Fe^{58}$ reaction is seen relatively weakly at a distance of 74 cm in Fig. 7. The Q value has been determined to be 7.815±0.008 MeV.

TABLE VI. Energy levels from the $Fe^{54}(d,p)Fe^{55}$ reaction[a]

$Q_0=7.084\pm0.008$ MeV.

Level No.	E_x (MeV)	Level No.	E_x (MeV)	Level No.	E_x (MeV)	Level No.	E_x (MeV)
1	0.413	35	4.110	69	5.480	103	6.596
2	0.933	36	4.123	70	5.497	104	6.610
3	1.322	37	4.273	71	5.542	105	6.628
4	1.413	38	4.372	72	5.556	106	6.654
5	1.925	39	4.387	73	5.564	107	6.670
6	2.058	40	4.463	74	5.599	108	6.745
7	2.151	41	4.507	75	5.634	109	6.776
8	2.218	42	4.538	76	5.687	110	6.826
9	2.307	43	4.636	77	5.745	111	6.846
10	2.478	44	4.658	78	5.775	112	6.857
11	2.546	45	4.673	79	5.817	113	6.874
12	2.585	46	4.707	80	5.839	114	6.916
13	2.818	47	4.751	81	5.872	115	6.962
14	2.880	48	4.790	82	5.900	116	6.980
15	2.940	49	4.824	83	5.933	117	7.008
16	2.987	50	4.849	84	5.947	118	7.030
17	3.035	51	4.877	85	5.955	119	7.054
18	3.076	52	4.948	86	5.989	120	7.070
19	3.119	53	4.990	87	6.059	121	7.092
20	3.311	54	4.999	88	6.090	122	7.105
21	3.362	55	5.041	89	(6.16)	123	7.126
22	3.431	56	5.078	90	6.229	124	7.149
23	3.469	57	5.124	91	6.237	125	7.178
24	3.559	58	5.185	92	6.282	126	7.215
25	3.599	59	5.208	93	6.319	127	7.235
26	3.661	60	5.237	94	6.348	128	7.252
27	3.709	61	5.286	95	6.374	129	7.270
28	3.722	62	5.306	96	6.387	130	7.310
29	3.800[b]	63	5.326	97	6.410	131	7.360
30	3.860	64	5.363	98	6.425	132	7.369
31	3.916	65	(5.37)	99	6.456	133	7.382
32	(3.96)	66	5.394	100	6.495	134	7.419
33	4.028	67	5.435	101	6.524	135	(7.45)
34	4.057	68	5.445	102	6.579	136	(7.47)

[a] All excitation energies $\leq \pm0.010$ MeV.
[b] Probable double peak.

TABLE VII. Energy levels from the $Fe^{58}(d,p)Fe^{59}$ reaction,[a] $Q_0=4.357\pm0.008$ MeV.

Level No.	E_x (MeV)	Level No.	E_x (MeV)	Level No.	E_x (MeV)	Level No.	E_x (MeV)
1	0.287	17	2.390	33	3.311	49	4.181
2	0.473	18	2.442	34	3.388	50	4.224
3	0.728	19	2.735	35	3.452	51	4.277
4	1.026	20	2.768	36	3.565	52	4.377
5	1.162	21	2.812	37	3.600	53	4.409
6	1.214	22	2.856	38	3.639	54	4.423
7	1.517	23	2.947	39	3.668	55	4.516
8	1.572	24	(2.99)	40	3.734	56	4.541
9	1.648	25	(3.02)	41	3.824	57	4.580
10	1.749	26	3.076	42	3.872	58	4.629
11	1.921	27	3.110	43	3.921	59	4.650
12	1.962	28	3.155	44	3.989	60	4.660
13	2.158	29	3.169	45	4.045	61	4.686
14	2.273	30	3.194	46	4.083	62	(4.77)
15	2.321	31	3.235	47	4.124	63	(4.83)
16	2.345	32	3.280	48	4.159	64	(4.87)

[a] All excitation energies $\leq \pm0.010$ MeV.

On the whole, intensities of the Fe^{58} peaks appear generally low as compared with the Fe^{55} and Fe^{57} levels. This seems to be so also in the case of peaks from the $Fe^{58}(p,p')$ reaction (see Sec. III-D). In the excitation region up to about 3.6 MeV, overlapped by both reactions, group No. 9 at 3.123 MeV was not observed in the (d,p) work. Peaks No. 10 showed signs of double structure in the (p,p') work. At a distance of 42 cm in Fig. 7, the two peaks are seen just resolved. A total of 133 groups have been identified with this reaction. A list of the excitation energies is shown in Table V, where the level numbers are those corresponding to the peak numbers seen in Figs. 7 and 11. In column 6 are listed the weighted averages of the excitation energies obtained from the (p,p') results of column 3 and (d,p) results from column 2.

H. The $Fe^{58}(d,p)Fe^{59}$ Reaction

The content of Fe^{58} in the natural iron target and those targets enriched in Fe^{54} and Fe^{57} was 0.33, 0.23, and 0.1% (see Table I), respectively. No particle groups resulting from the $Fe^{58}(d,p)Fe^{59}$ reaction were identified in the spectra obtained from the bombardment of the enriched Fe^{54} and Fe^{57} targets. Only in the case of the spectrum from the natural iron bombardment was there evidence of the presence of Fe^{58}. The ground-state group at a distance of 40 cm in Fig. 6 and peak No. 6 at a distance of 29.7 cm in Fig. 10 are the only contributions observed from Fe^{58}. Other expected contributions at higher excitations were negligible or undetected because of the preponderance of peaks from the dominant isotope. In the spectrum from the enriched Fe^{58} target, the presence of 0.6% Fe^{54} gave rise to only two barely detectable peaks at a distance of 42 cm in Fig. 8 and at a distance of 30.8 cm in Fig. 12. The 2.2% of Fe^{57} gave rise to about ten well-defined peaks, five of which are labeled with the number 58 in Fig. 8.

Contributions at higher excitation were also observed and accounted for but are not easily discerned in the compressed-energy scales of the figures. The major impurity in the spectra of Figs. 8 and 12, of course, is Fe^{56}. Approximately 13% of the $Fe^{56}(d,p)Fe^{57}$ spectrum in Figs. 6 and 10 is here superimposed on the spectrum of $Fe^{58}(d,p)Fe^{59}$ reactions. The Q value measured for the ground-state transition is 4.357 ± 0.008 MeV. Excitation energies are listed in Table VII, and the level diagram for Fe^{59} appears in Fig. 13.

I. (p,α) Reactions from the Iron Isotopes

In the process of scanning the nuclear emulsions primarily exposed in these experiments for investigating the (p,p') reactions, a number of alpha-particle groups were observed. All of these groups were identified with one of the iron isotopes. In the case of proton bombardment of the Fe^{54} enriched isotope, no alpha groups were found. The ground-state Q value for the $Fe^{54}(p,\alpha)Mn^{51}$ reaction is calculated from the masses to be about -3.13 MeV. With 7.0-MeV incident protons, the energy of the reaction alpha particles is about 3 MeV, and this energy region fell outside the range of the spectrograph field settings used in the present experiment. In the following three (p,α) reactions from the iron isotopes, the Q values for the ground-state transitions had not been previously measured.

$Fe^{56}(p,\alpha)Mn^{53}$

From the bombardment of natural iron, two alpha-particle groups were observed on each of several runs. In the case of three runs, in particular (at 45 and 90 deg with incident 7.0-MeV protons and at 90 deg with 8.5-MeV incident protons), sufficient intensities were observed to permit accurate energy measurements of these groups. The average Q values from the three measurements were -1.060 ± 0.009 MeV and -1.440 ± 0.009 MeV, with the first group being assigned to the ground-state transition of the $Fe^{56}(p,\alpha)Mn^{53}$ reaction and the second group to excitation of the first state in Mn^{53} at 0.380 MeV. This latter value is in good agreement with previously reported measurements made both from the neutron and gamma spectra observed from the $Cr^{53}(p,n'\gamma)Mn^{53}$ reaction[15] and from the gamma rays following positron decay of Fe^{53}.[16]

$Fe^{57}(p,\alpha)Mn^{54}$

From the proton bombardment of enriched Fe^{57} four groups of alpha particles were observed on each of two runs, at 130 and 90 deg with incident energies of 7.0 and 7.5 MeV, respectively. The average Q values determined from these runs are 0.237 ± 0.009 MeV for the ground-state transition and 0.180 ± 0.009 MeV, 0.075 ± 0.009 MeV, and -0.165 ± 0.009 MeV for the lower energy groups corresponding to excited levels in Mn^{54} at 0.057, 0.162, and 0.402 MeV, respectively. None of these levels have previously been reported.

$Fe^{58}(p,\alpha)Mn^{55}$

From the proton bombardment of the enriched Fe^{58} targets, two groups of alpha particles were observed on each of two runs at 90 and 130 deg, both with an incident energy of 7.0 MeV. The average Q value for the higher energy group attributed to the ground-state transition of the $Fe^{58}(p,\alpha)Mn^{55}$ reaction was determined to be 0.402 ± 0.009 MeV. The lower energy group with measured Q value of 0.275 ± 0.007 MeV results from excitation of the first level in Mn^{55} at 0.127 MeV. This is in excellent agreement with the value of 0.128 MeV determined in this laboratory from the $Mn^{55}(p,p')Mn^{55}$ reaction[17] and numerous other measurements from (n,n') and $(n,n'\gamma)$ reactions.[2]

IV. DISCUSSION

A. Levels in Fe^{54}

At the start of this work previous knowledge of the level structure of Fe^{54} had been limited to the level at 1.409 MeV. The existence of a level in Fe^{54} at about 1.5 MeV was predicted from considerations based on shell-model theory.[18] Measurements of a gamma ray with energy of about 1.4 MeV following inelastic scattering of neutrons from both natural and enriched Fe^{54} led to the tentative assignment of this gamma ray to a level at 1.4 MeV in Fe^{54}.[19] Magnetic analysis of inelastically scattered protons from natural and enriched Fe^{54} targets confirmed the existence of this level. Windham *et al.*[20] obtained a value of 1.413 ± 0.005 MeV, in good agreement with our present measurement.

Shapiro and Higgs[21] reported a number of gamma rays observed from inelastic scattering of neutrons from natural iron targets and targets enriched in Fe^{54} and Fe^{57}. In addition to the 1.41-MeV gamma ray from the Fe^{54} bombardments, they observed four other gamma rays with energies of 0.57, 0.77, 1.95, and 2.17 MeV. These they associated with the levels in Fe^{54} at 1.39, 1.95, and 2.17 MeV. No evidence for levels at these energies has been found in our experiments.

Most recently, Aspinall *et al.*,[22] using 11.97-MeV incident protons have extended the measurement of

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inelastic proton groups from enriched Fe^{54} targets and observed 79 groups up to an excitation energy of 6.836 MeV. Except for the doublet (Nos. 2 and 3) not resolved by Aspinall *et al.*, there is excellent agreement in the excitation region covered by both experiments.

B. Levels in Fe^{55}

Knowledge of the level structure for Fe^{55} has also until recently been limited to the lower excitation region. Earlier measurements of ground-state Q values for the $Fe^{54}(d,p)Fe^{55}$ (7.11 ± 0.05 MeV [23]; 7.18 ± 0.07 MeV [24]) reaction are in good agreement with the value reported here. The Q value deduced from the measurement of the highest energy gamma ray observed (9.298 ± 0.007 MeV[25]; 9.295 ± 0.015 MeV[26]) from thermal neutron capture in Fe^{54} is in excellent agreement with the present measurement. Both authors also report a second gamma ray (8.872 MeV[25] and 8.86 MeV[26]) which they attribute to capture in Fe^{54} and which is consistent with de-excitation directly to the level at 0.413 MeV in Fe^{55}.

From an early study of the positron decay of Co^{55}, Deutsch and Hedgran[27] proposed the existence of levels in Fe^{55} at 0.935 and 1.41 MeV. From $\beta^+-\gamma$ coincidence measurements, Caird and Mitchell[28] suggested additional levels in Fe^{55} at 1.84 and 2.17 MeV. In the latest study of the Co^{55} decay scheme Mukerji *et al.*[29] find no evidence for the assignment of energy levels at 1.84 and 2.17 MeV. Instead, they find a new positron group, which is consistent with a level at 1.657 MeV. From experiments utilizing scintillation-counter techniques to measure the de-excitation gamma rays following the proton bombardment of Mn^{55}, Lobkowicz *et al.*[30] propose a level scheme involving levels in Fe^{55} at 0.410, 0.930, 1.320, 1.405, 2.07, and 2.52 MeV. Because of selection rules forbidding certain β and γ transitions, a level scheme deduced from these data must usually be confirmed and augmented by other types of experiments. Apart from the present investigation of Fe^{55}, the only previous or concurrent direct nuclear-reaction experiments involve the measurement at the energies of neutron groups from the $Mn^{55}(p,n)Fe^{55}$ reaction. Stelson and Preston,[31] utilizing nuclear emulsions, and measuring the ranges of proton recoils, reported groups corresponding to levels in Fe^{55} at 0.42, 0.94, 1.36, and 2.08 MeV. Elwyn *et al.*,[32] using time-of-flight techniques to measure the neutron energies, report levels at 0.399, 0.901, 1.270, and 1.358 MeV. The detection of slow neutron thresholds by means of the "counter ratio" method has been used successfully in making precise assignment of energy levels from (p,n) reactions.

With this technique, Chapman and Slattery[33] have investigated the excitation region above 900 keV and reported levels at 0.924, 1.327, 2.17, 2.554, 2.92, and 3.76 MeV. Gossett and Butler[34] made measurements in the energy range below 1 MeV and report levels at 0.414 ± 0.003 and 0.931 ± 0.002 MeV. Lee and Mooring[35] have employed a counter-ratio technique for the detection of neutrons of a specific energy scattered from a resonant scatterer. Using lithium (resonant energy of 257 keV) as the scatterer, they made precise determination of the proton energies at which 257-keV neutrons were detected. Their measurements indicate levels in Fe^{55} at 0.437 ± 0.020, 0.936 ± 0.008, 1.315 ± 0.010, and 1.414 ± 0.006 MeV.

All of the above measurements are generally in agreement with the results from the (d,p) reaction studied in this laboratory. The energy level at 1.504 MeV, previously reported in an LNS Progress Report,[36] was discovered to be in error. Most recently, Kim,[37] using an improved resolution time-of-flight technique observed two weakly excited neutron groups from the $Mn^{55}(p,n)Fe^{55}$ reaction and attributed to levels in Fe^{55} at 0.510 ± 0.010 and 0.680 ± 0.010 MeV. A close re-examination of the (d,p) spectra obtained in the present work showed no evidence for these levels. A lower limit in the intensity for the detection of these levels via the (d,p) process is estimated at about 1% of the ground-state transition.

A preliminary study of the angular distribution of proton groups from the $Fe^{54}(d,p)Fe^{55}$ reaction has been reported[38] from this laboratory, and the results will soon be published.

C. Levels in Fe^{56}

Early knowledge of the level scheme for Fe^{56} was chiefly obtained from gamma-ray measurements following the radioactive decay of both Mn^{56} and Co^{56}.[39] From such studies, Elliott and Deutsch[40] first estab-

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lished the existence of four excited states in Fe^{56} at 0.845±0.015, 2.11±0.040, 2.66±0.050, and 2.98±0.060 MeV. A few measurements had also been made of the energies of gamma rays following inelastic scattering of neutrons.[41] Direct information from nuclear reactions had been limited to these same levels in the case of neutron inelastic scattering measurements[42] and to the first excited state alone in (p,p') inelastic scattering.[43]

During the course of this work a large number of experiments have been undertaken with the primary purpose of measuring the spin and parity of those levels in Fe^{56} that were initially reported from this laboratory in 1956 and 1957. From experiments using scintillation spectroscopy and coincidence techniques, measurements of the energies and intensities of the decay products from Mn^{56} and Co^{56}, and measurements of the energies, intensities, and angular distribution of the de-excitation gamma rays from Fe^{56} have led to assignments of the spins and parity of several of the levels in Fe^{56} (see Ref. 2).

In a concurrent study in this laboratory on the $Co^{59}(p,\alpha)Fe^{56}$ reaction,[13] the excitation region covered extended to about 3.4 MeV. Alpha-particle groups corresponding to six of the eight levels in this region were found in good agreement with the (p,p') results. The two groups not observed from the (p,α) reaction correspond to levels at 2.940 and 3.388 MeV, the least intense groups in the (p,p') experiments (see Table II).

On the basis of nuclear models proposed by Scharff-Goldhaber and Weneser[44] and Wilets and Jean,[45] Levine *et al.*[46] made a study of the similarities of the level schemes of Fe^{56}, Fe^{58}, and Ni^{60}. From their analysis, they predict the existence of a 2^+ level in Fe^{56} at about 1.7-MeV excitation that should correspond to the 2^+ level at 1.66 MeV in Fe^{58} and the 2^+ level at 2.16 MeV in Ni^{60}. From their own search employing $\gamma-\gamma$ and $\beta-\gamma$ coincidence measurements in the $Mn^{56}-Fe^{56}$ decay, their evidence for the existence of this level is admittedly inconclusive.

Although a small peak is seen in Fig. 2 at about 1.7-MeV excitation, its origin here has not been associated with Fe^{56}. Its intensity is approximately 1% of the group corresponding to the 0.845-MeV level at 130 deg from 7.0-MeV incident protons, but assignment to Fe^{56} has been ruled out because of lack of further substantiating evidence from several additional bombardments.

Recent measurements from (p,p') experiments using higher energy proton beams have extended the excitation region investigated in Fe^{56}. Aspinall *et al.*[21] report thirty-three levels up to an excitation energy of 5.191 MeV, while Matsuda[47] has identified eighteen levels in Fe^{56} up to 5.02 MeV. In the region up to 4.743 MeV, there is good agreement with our results.

D. Levels in Fe^{57}

Previous knowledge of the level structure in Fe^{57} has also been limited to the lower excitation region.[2] Information has been obtained mainly from studies of the decay of Co^{57} and Mn^{57}, from measurements of gamma rays following inelastic scattering of neutrons, protons, and alpha particles, from gamma rays emitted after neutron capture in iron, and from (d,p) reactions from natural iron. From the study of beta decay of Mn^{57}, Cohen *et al.*[48] observed de-excitation gamma rays with energies of 117, 134, 220, 350, and 690 keV, all of which can be identified with transitions to the levels at 0.135, 0.365, and 0.706 MeV in Fe^{57}. The decay of Co^{57} by K capture to the 135-keV level has been studied by observing the gamma rays[49] and internal conversion electrons.[50] Precise measurements of three gamma rays with energies of 14.4, 122.0, and 136.3 keV have been made by several workers[2] with the results indicating a level in Fe^{57} at 14.4 keV. This has been confirmed by the (d,p) results in the present work.

The spacing of the two proton groups corresponding to the ground-state transition and the first excited state in Fe^{57} was of the order of 1.3 mm on the nuclear emulsion, and the major error in the determination of the energy level was the precision with which this spacing could be measured. From four measurements, an average value of 13.6±2.0 keV has been calculated.

Measurements of proton groups from the $Fe^{56}(d,p)Fe^{57}$ reaction have been made by Harvey[23] and McFarland *et al.*[24] Using incident deuterons of 10 MeV and absorber techniques, Harvey reported a Q value of 5.42±0.10 MeV for the ground-state transition. With 14-MeV deuterons and the same energy-measuring techniques, McFarland observed the ground-state group with a Q value of 5.49±0.06 MeV and six other groups corresponding to levels in Fe^{57} at 1.24, 1.65, 2.46, 3.23, and 4.11 MeV.

From neutron-capture experiments in natural iron, Kinsey and Bartholomew[25] and Adyasevich *et al.*[26] both report a large number of gamma rays whose exact position in the level scheme could not be determined with certainty. Neither group of authors could ascertain whether the highest energy gamma ray they attributed to capture in Fe^{56} (7.639±0.004 MeV[25] and

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7.636±0.010 MeV[26]) represented the direct transition to the ground state or the transition to the 14-keV level.

Combining the value for the binding energy of the deuteron (2.225±0.001 MeV) with the ground-state Q value for the $Fe^{56}(d,p)Fe^{57}$ reaction measured in the present experiment (5.425±0.008 MeV), we deduce a value of 7.650±0.008 MeV for the energy of the gamma ray making direct transition to the ground state of Fe^{57}. Thus, it appears most likely that the highest energy neutron-capture gamma rays reported above correspond to transitions to the 14-keV level.

A preliminary study of the angular distribution of the proton groups from the $Fe^{56}(d,p)Fe^{57}$ reaction has been reported,[51] and the results will soon be published.

E. Levels in Fe^{58}

The ground-state Q value for the $Fe^{57}(d,p)Fe^{58}$ reaction has previously been reported as 7.89±0.07 MeV, along with energy levels in Fe^{58} at 0.79, 1.62, 2.67, and 4.21 MeV.[24] Kinsey and Bartholomew[25] have observed a weak gamma ray from neutron capture in natural iron and assigned it to the direct transition from the capturing state to the ground state of Fe^{58}. The reported energy of 10.16±0.04 MeV is not in serious disagreement with our ground-state Q value (7.815±0.008 MeV) measurement of the $Fe^{57}(d,p)Fe^{58}$ reaction when combined with the deuteron binding energy.

Other experimental work[2] on the energy levels in Fe^{58} involves only the levels at 0.800 and 1.664 MeV.

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F. Levels in Fe^{59}

There are no reported previous measurements on the energy levels for Fe^{59}. The ground-state Q value (4.357±0.008 MeV) measured here for the $Fe^{58}(d,p)Fe^{59}$ reaction is not in good agreement with the value deduced from mass-spectroscopic measurements. Combining the results from the mass-doublet measurements[52] of Fe^{58} and Co^{59} with the beta-decay energy (1.561±0.006)[53] for Fe^{59} gives a calculated Q value of 4.407±0.009 MeV. The discrepancy of 50 keV is approximately three times that obtained from similar comparisons with the ground-state (d,p) Q values for the other iron isotopes.

ACKNOWLEDGMENTS

The authors would like to thank those members of the High Voltage Laboratory ONR-Generator group who helped in various phases of this work. We especially appreciate the efforts of various members of the scanning group, and particularly those of Wilton Tripp who performed the major part of the scanning in these experiments. We also wish to acknowledge the assistance of E. Loh and Miss Sylvia Darrow in aiding with the task of measuring and cataloging the energies and intensities of the several hundred particle groups observed in these runs. Finally, we are indebted to Mrs. Mary White for her suggestions in improving the manuscript.

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