the shortened half-life because of interaction with the ionization continuum.

So far we can only say the lines coming from preionized levels are very much weakened at low pressures. The quantitative relationship between their intensity and the electron density remains to be determined.

A few words should be said about the completeness of our present knowledge of the Kr I and Xe I spectra. All types of predicted levels have now been found. The new p' and f' levels cannot be expected to combine with the ground state because of the parity selection rule and this explains their absence in the absorption spectrum. As was mentioned before, the s' and d' levels observed in the far ultraviolet absorption are probably so broad that transitions from them will only contribute to the continuous emission spectrum. The p' levels in xenon have not yet been found definitely. The levels to be expected, p_{11}', p_{01}', p_{12}', p_{00}' in the order of increasing energies, are probably sufficiently separated to locate them individually. Unfortunately, the levels are so broad and the measurements so inaccurate that at the present time nothing can be said about the individual levels.

TABLE III. Agreement between calculated and observed f' levels.

	Krypton levels (cm^{-1}) calc	Krypton levels (cm^{-1}) obs	Xenon levels (cm^{-1}) calc	Xenon levels (cm^{-1}) obs nf'	Xenon levels (cm^{-1}) obs nf_{22}'
$4f'$	111 378.6	111 380.2[a]	101 426.3	101 425.3	101 429.8
$5f'$	113 867.3	113 868	103 929.7	103 928.7	103 931.9
$6f'$	115 219.2	115 220	105 290.3	105 288.7	
$7f'$	116 033.8	116 037	106 110.1	106 108.3	
			106 641.7	106 639.6	

[a] Average of the four separated nonpreionized levels. See *Atomic Energy Levels*, edited by C. E. Moore, National Bureau of Standards Circular No. 467 (U. S. Government Printing Office, Washington, D. C., 1952), Vol. II.

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Excitation Function for $Fe^{56}(n,p)Mn^{56}$ †

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The relative cross section for $Fe^{56}(n,p)Mn^{56}$ has been measured by an activation method for neutron energies of 3.4 to 8.2 and 12.4 to 17.9 Mev, and normalized to the previously known value of 110±10 mb at 14.3 Mev. The cross section rises above the minimum detectable value of 0.2 mb at about 4.5 Mev, reaches a maximum of 116 mb at 13.5 Mev, and decreases to 62 mb at 17.9 Mev. The experimental results are compared with the predictions of statistical theory; the fit, although good in the vicinity of maximum yield, is poor at lower energies, the predicted yield being considerably too small. Cross sections for $Fe^{54}(n,2n)Fe^{53}$ were also roughly determined at 16.9 and 17.9 Mev.

INTRODUCTION

THE excitation function of the reaction $Fe^{56}(n,p)$ Mn^{56} is of interest from the various standpoints of fast neutron detection, reactor design, and nuclear theory. This reaction, with an energetic threshold of 2.9 Mev,[1] results in beta activity with a convenient half-life of 2.576 hours.[2] This paper reports activation measurements of the relative yield of the reaction at various neutron energies in the range from 3.4 to 17.9 Mev. The yield may be put on an absolute basis by normalization to the value 110±10 mb at 14.3 Mev, an average[3] of the results reported by Forbes[4] and by Paul and Clarke.[5]

EXPERIMENTAL PROCEDURE

The excitation function was determined by placing as many as 15 iron samples at various angles around d-D or d-T neutron sources, irradiating them simultaneously for about 2 hours, and measuring the induced Mn^{56} activities. Since the neutrons produced by these sources have energies varying rapidly with angle, a wide energy range can be covered by a few irradiations. In order to obtain relative cross sections for the energy range covered by a single source, the relative angular distribution of neutrons from the source must be known. The sets of data obtained with several different sources can then be internormalized if the integrated neutron flux is known at one angle for each irradiation.

Three different neutron sources were used in this work: d-D sources at average deuteron energies of 2.00 and 4.98 Mev and a d-T source at 1.74 Mev deuteron energy. Both the 2.5 Mev and large Los Alamos electrostatic accelerators were used. For two of these sources (2.00 Mev d-D and 1.74 Mev d-T) the neutron flux was continuously monitored with a counter tele-

† Work performed under the auspices of the U. S. Atomic Energy Commission. A preliminary report was given by J. Terrell and D. M. Holm, Phys. Rev. 95, 650(A) (1954).

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TABLE I. Cross sections for $Fe^{56}(n,p)Mn^{56}$.

Neutron source	θ_{lab} from neutron source	Relative angular distribution of source	Neutron energy (Mev)[a]	$Fe^{56}(n,p)Mn^{56}$ cross section (mb)[b]
d-T (E_d=1.74 Mev)[c]	0°	1.000	17.89±0.08	62 ±2
	45°	0.861	16.89±0.32	74 ±2
	60°	0.793	16.23±0.41	84 ±2
	75°	0.730	15.48±0.44	96 ±2
	90°	0.671	14.71±0.44	105 ±2
	105°	0.618	13.99±0.39	114 ±2
	120°	0.570	13.35±0.29	116 ±3
	150°	0.510	12.43±0.11	111 ±3
d-D (E_d=4.98 Mev)[d]	0°	1.000	8.21±0.02	39 ±5
	30°	0.125	7.41±0.23	34 ±4
	45°	0.075	6.54±0.31	20 ±2
	60°	0.10	5.55±0.34	5.6 ±0.8
	75°	0.09	4.56±0.33	0.4 ±0.6
d-D (E_d=2.00 Mev)[e]	0°	1.000	5.24±0.05	2.6 ±0.2
	30°	0.360	4.86±0.16	1.2 ±0.1
	45°	0.180	4.44±0.24	0.08±0.12
	60°	0.148	3.94±0.28	−0.07±0.14
	75°	0.145	3.43±0.29	0.02±0.13

[a] The over-all spread in neutron energy is given for each point.
[b] Standard deviations are relative, including all uncertainties except the normalization to 110±10 mb at 14.3 Mev (reference 3).
[c] Angular distribution data from Bame and Perry (reference 8).
[d] Angular distribution data from Smith and Perry (reference 9). The measured differential cross section at 0° was 78.9±5.5 mb/sterad.
[e] Angular distribution data from Bame (reference 7).

scope[6] at 30°. Recoil protons from a polyethylene radiator in this neutron spectrometer passed through two proportional counters and were stopped in a CsI scintillation crystal. The scintillator pulses, if in coincidence with pulses from the other two counters, were displayed on an 18-channel pulse-height analyzer. Analysis of this spectrum and calculation of the counter sensitivity gave the absolute value of integrated primary flux for each irradiation. The relative angular distributions for the two neutron sources mentioned above have been measured by Bame,[7] and by Bame and Perry,[8] using counter telescopes. Since the flux monitoring of the 4.98-Mev *d*-D work was not on an absolute basis, the neutron flux at each angle was calculated from measured *d*-D cross section, target length, deuterium gas pressure, and integrated deuteron current. The 4.98-Mev differential cross sections have been measured with a neutron counter telescope by Smith and Perry.[9]

The samples irradiated were strips of chemically pure, outgassed, arc-melted iron (approximately 99.99% Fe), about 10 inches long, $\frac{1}{2}$ inch wide, and 0.005 inch thick. For irradiation, these were coiled into tight cylinders; for counting, they were uncoiled, wound and taped into single-layer spirals around a cylindrical mandrel of $\frac{13}{16}$ inch diameter, and placed around a $\frac{3}{4}$-inch diameter thin-walled Geiger-Mueller counter. The activities were followed for several half-lives, using two internormalized counters. Since the samples varied by a few percent in weight, all counting data were normalized to equal sample weight.

During irradiation the samples were held in well-defined positions, at 10.1 cm radius, inside an aluminum sample-holding ring which was carefully aligned about the target. In order to reduce the effect of errors in sample placement, two samples were placed at each angle used (except 0°), on opposite sides of the gas target of the electrostatic accelerator. No significant difference was observed between the activities of any two samples placed at the same angle. For all three neutron sources the same samples, counters, and geometries were used.

A background measurement which was performed for each neutron source used in this work was the determination of Mn^{56} activity induced in the samples by fast neutrons which did not originate in the target gas. These measurements consisted of irradiating and counting iron samples under the same conditions and at the same angles as previously described, except that the targets were flushed and filled with helium or hydrogen. Appreciable yield of Mn^{56}, amounting to a correction of as much as 2 mb, was found in such blank runs for all three neutron sources used. Slow neutrons could have contributed to this yield through the reaction $Mn^{55}(n,\gamma)Mn^{56}$. However, spectroscopic analysis of the iron samples indicated a Mn content of less than 0.03%, and earlier work with samples of 1010 steel, containing 0.2% Mn^{55}, gave the same uncorrected yield as pure iron at all neutron energies. Since the entire yield of Mn^{56} was due to the blank effect at energies below 4.5 Mev, it is clear that there was no noticeable yield from Mn capture, and that fast neutrons were responsible for the blank yield of Mn^{56}. Such fast neutrons could have originated from the Al(*d*,*n*) reaction at the two lower deuteron energies used, since the target window was 1.47 mg/cm² aluminum. At 4.98-Mev deuteron energy, the fast background may have been due to deuterium embedded in the target assembly (the foil used was 1.1 mg/cm² nickel). Deuteron breakup,[10] either in the entrance foil or gas target, could not have been a problem in this experiment because of the low energy of the resultant neutrons, below the 2.9-Mev threshold for $Fe^{56}(n,p)Mn^{56}$.

RESULTS

Two or three irradiations were performed for each of the neutron sources described, with essentially the same results each time. The results of the irradiations performed under the best conditions are given in Table I. The $Fe^{56}(n,p)Mn^{56}$ cross sections have been

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normalized to the value 110±10 mb at 14.3 Mev,[3] which is an average of the results reported by Forbes[4] (124±12 mb at 14.1 Mev), and Paul and Clarke[5] (96.7±12 mb at 14.5 Mev). Their results have been plotted in Fig. 1 along with the results of this experiment. There is an appreciable slope to the cross-section plot in this energy region, which partially accounts for the difference between the two reported absolute cross sections. Between 8.2 and 12.4 Mev no measurements were made because of the lack of suitable neutron sources.

In Table I the neutron energy spread is indicated for each neutron energy; this spread arises primarily from the angular spread caused by target length and sample diameter. Also tabulated are the relative angular distributions[7–9] used at each deuteron energy. They are consistent with most other work on the *d*-D and *d*-T reactions.[11–13] The angular distributions of the neutrons are estimated to be uncertain to 2% or 3% for the 1.74 Mev *d*-T source (for normalization at about 100°), about 3% for the 2.00 Mev *d*-D source (relative to the monitor position of 30°), and 7% or more for the 4.98-Mev *d*-D source (on an absolute basis). Normalizations of the 2.00- and 4.98-Mev *d*-D data to the *d*-T data have been assigned additional uncertainties of 5% and 7%, respectively, to allow for errors in neutron flux measurement.

Small corrections have been applied to all data for finite target length, decay during irradiation, counter background, varying effects of finite angular resolution on yield (generally about 1%) and activity produced by the helium or hydrogen target background irradiations. No corrections were considered necessary for counting losses, absorption of neutron flux in the iron samples, or back-scattering from the sample-holding ring. Counting statistics and the uncertainties in angular distributions, absolute flux determinations, corrections, and geometry have all been taken into account in assigning relative standard deviations to the $Fe^{56}(n,p)Mn^{56}$ cross sections.

No long half-lives were observed in the course of this work. None of the other known activities produced by neutrons on iron have half-lives which would interfere with the measurement of Mn^{56} activity.[14] All decay corrections to the Mn^{56} counting rates were made on the basis of 2.576 hours half-life,[2] which was quite consistent with all data taken. Although no attempt was made to do absolute beta-counting of the irradiated iron samples, the estimated over-all efficiency of the counting arrangement checks with the 20.1% figure calculated from measured neutron fluxes and the known $Fe^{56}(n,p)Mn^{56}$ cross section at 14.3 Mev.

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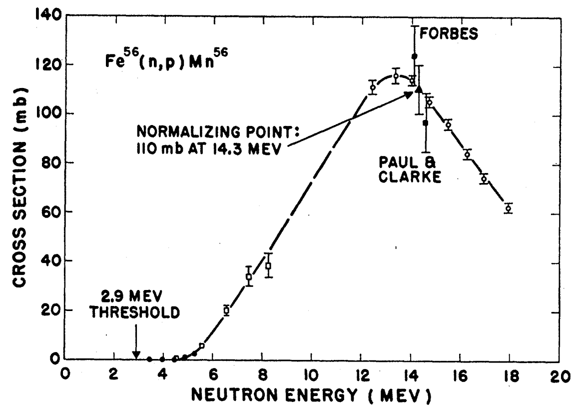

FIG. 1. Cross section for $Fe^{56}(n,p)Mn^{56}$ as a function of incident neutron energy. Results from different neutron sources are indicated by different symbols. The standard deviations include all uncertainties except the normalization to 110±10 mb at 14.3 Mev.[3] Also shown are the absolute cross sections determined by Forbes[4] and by Paul and Clarke.[5]

An incidental result of this experiment was the observation of a 9±2 minute activity at the highest neutron energies used. This was attributed to the 8.9-minute Fe^{53} positron activity from the reaction $Fe^{54}(n,2n)Fe^{53}$. On this basis, estimating that the Fe^{53} positrons are counted with about 1.4 times the efficiency with which the three Mn^{56} beta groups and their associated gamma rays are counted, one obtains rough cross sections for this reaction of 120 mb at 16.9 Mev and 170 mb at 17.9 Mev. These cross sections are uncertain by at least 30%. The threshold for the $Fe^{54}(n,2n)Fe^{53}$ reaction is at 14.1±0.2 Mev neutron energy, according to most determinations of the $Fe^{54}(\gamma,n)Fe^{53}$ threshold.[15–18]

DISCUSSION

Absolute excitation functions for (n,p) reactions have been reported[3,19–25] in the neutron energy range up to 8 Mev for He^3, N^{14}, F^{19}, Na^{23}, Al^{27}, P^{31}, and S^{32}. For the

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energy range 12–18 Mev, (n,p) yields have been reported[25–27] as functions of energy for O^{16}, Mg^{24}, Si^{28}, S^{32}, Cl^{37}, and Sr^{88}. In no other case, apparently, except[25] for S^{32}, has the (n,p) yield been determined over as wide a range of energy as is reported here for Fe^{56}.

Although the energetic threshold of the $Fe^{56}(n,p)Mn^{56}$ reaction is 2.9 Mev,[1] the Coulomb barrier prevents any appreciable yield until considerably higher energies are used. The observed cross section rises above the 0.2 mb minimum observable level in the vicinity of 4.5 Mev, continues to increase until the peak cross section of 116 mb is reached at about 13.5 Mev, and then decreases above this energy. The compound nucleus Fe^{57}, formed during this reaction, can yield a number of different end products; the more probable reactions, with their Q values,[1] are as follows:

(1) $Fe^{56}(n,n')Fe^{56*}(\gamma)Fe^{56}$,

(2) $Fe^{56}(n,2n)Fe^{55}$, $Q=-11.2$ Mev,

(3) $Fe^{56}(n,p)Mn^{56}$, $Q=-2.9$ Mev,

(4) $Fe^{56}(n,pn)Mn^{55}$, $Q=-10.2$ Mev,

(5) $Fe^{56}(n,\alpha)Cr^{53}$, $Q=0.3$ Mev,

(6) $Fe^{56}(n,d)Mn^{55}$, $Q=-7.9$ Mev.

The most probable reactions in the neutron energy range 3 to 18 Mev are inelastic scattering (1) or the closely related $(n,2n)$ reaction (2). The decrease in cross section for reaction (3) above 14 Mev may be due to an increase in the competitive effect of (1) and (2), or more probably to the (n,pn) reaction (4) which directly reduces the yield of (3). Reaction (4) has an energetic threshold at 10.4 Mev, but its yield should be low for several Mev above the threshold because of the Coulomb barrier. The probability that a residual Mn^{56} nucleus will be left in a state of excitation above the dissociation energy, leading to reaction (4), should increase rapidly with incident neutron energy in the same energy range in which the (n,p) cross section is observed to decrease. Reactions (5) and (6) would be expected to have lower yields than (3) and would therefore have little effect on the excitation function for (3).

Although there is ample evidence from angular distributions and energy spectra of emitted protons that (n,p) reactions in general, and $Fe^{56}(n,p)$ in particular, proceed partially by direct interaction,[28–30] most of the yield in the case of $Fe^{56}(n,p)$ probably comes from compound-nucleus processes.[29,31] For this reason, a comparison of the observed yield of protons with that predicted by the statistical model, or evaporation model, of nuclear reactions is of some interest. In the formulation of this theory given by Blatt and Weisskopf,[32] the cross section for the (n,p) reaction may be expressed by

$$\sigma(n,p)=\sigma_{cn}(E_n)F_p/(F_p+F_{pn}+F_n).$$

In this equation, $\sigma_{cn}(E_n)$ is the cross section for formation of a compound nucleus by an incident neutron of energy E_n, and F_p, F_{pn}, and F_n are proportional to the respective probabilities for emission of a proton alone, a proton followed by a neutron, and a neutron (whether or not a subsequent particle is emitted). For simplicity other less probable reactions, such as (n,α), have been neglected. The emission probabilities are given by

$$F_p=\int_{\epsilon_{pm}}^{E_n+Q}\epsilon_p\sigma_{cp}(\epsilon_p)\omega_{\mathrm{Mn}}(E_n+Q-\epsilon_p)d\epsilon_p,$$

$$F_{pn}=\int_0^{\epsilon_{pm}}\epsilon_p\sigma_{cp}(\epsilon_p)\omega_{\mathrm{Mn}}(E_n+Q-\epsilon_p)d\epsilon_p,$$

$$F_n=\int_0^{E_n}\epsilon_n\sigma_{cn}(\epsilon_n)\omega_{\mathrm{Fe}}(E_n-\epsilon_n)d\epsilon_n,$$

in which $Q=-2.9$ Mev is the energy release of the (n,p) reaction, ϵ_p and ϵ_n are the energies of emitted protons and neutrons, $\sigma_{cp}(\epsilon_p)$ is the cross section for the formation of a compound nucleus by an incident proton of energy ϵ_p, and ω_{Mn} and ω_{Fe} are the level densities of the residual nuclei Mn^{56} and Fe^{56} as functions of excitation energy. The energy ϵ_{pm} is the minimum energy with which a proton may be emitted without permitting an additional particle (presumed to be a neutron) to be emitted. It is given by $\epsilon_{pm}=0$ for $E_n\leqq E_t$, and $\epsilon_{pm}=E_n-E_t$ for $E_n\geqq E_t$, in which $E_t=10.4$ Mev is the threshold energy for the (n,pn) reaction.

For the calculations performed, σ_{cn} and σ_{cp} were interpolated from tables given by Blatt and Weisskopf,[32] based on a black square-well model for the nucleus, for the radius constant $r_0=r/A^{\frac{1}{3}}=1.46\times10^{-13}$ cm. This value of r_0 is known[33–35] to give approximately correct values for the elastic and nonelastic neutron cross sections of Fe^{56}. The level densities used are based on a Fermi degenerate gas model and are given by

$$\omega(E)=C\exp(2a^{\frac{1}{2}}E^{\frac{1}{2}}),$$

in which E is the excitation energy and a and C are constants. It was assumed that a is the same for both residual nuclei Fe^{56} and Mn^{56}, but that $C_{\mathrm{Mn}}=bC_{\mathrm{Fe}}$, so that b is the ratio of level densities between odd-odd and even-even nuclei for equal excitations. The calculations were carried out on this basis for the neutron

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energy range 4 to 18 Mev, for various values of a, and with b chosen to give the observed maximum (n,p) cross section of 116 mb. The necessary values of b were 2.38, 5.54, and 18.2, for $a=1$, 2, and 4, respectively; the expected value[36] of b is in the neighborhood of 4.

The results of the statistical model calculation are given in Fig. 2, along with the experimental data for the yield of $Fe^{56}(n,p)Mn^{56}$. Since the shape of the yield curve is greatly affected by competition with the $Fe^{56}(n,pn)Mn^{55}$ reaction, the calculated yield of the latter is also shown in Fig. 2. It should be kept in mind that this yield of Mn^{55} includes only those cases in which the proton is emitted before the neutron. Because of the normalization used, the calculated (n,p) yield is not very sensitive to the value of a, particularly for $E_n<14$ Mev. The normalized results are also not very dependent on the choice of r_0; a calculation performed for $r_0=1.3\times10^{-13}$ cm and $a=2$ gave results almost indistinguishable from those for $r_0=1.46\times10^{-13}$ cm and $a=2$, shown in Fig. 2. The experimental results for $E_n>12$ Mev are fairly well represented by $a=2$ to 4. The value of the parameter a for $A=56$ is estimated to be about 2 by Blatt and Weisskopf[32]; Fong[37] estimates $a=2.8$ from fast-neutron capture cross sections; excitation functions[38–40] of most medium-weight nuclides give similar values of a.

The results of statistical theory fit the experimental data rather poorly for $E_n<12$ Mev; for any combination of the parameters a and r_0 used in these calculations, the theoretical yield is considerably too small. This might be an indication that direct interaction, less inhibited by the Coulomb barrier, is the dominant process in this energy range for the (n,p) reaction. However, other factors, such as the theoretical values of σ_{cp} and σ_{cn}, may be responsible for the poor fit.*

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* *Note added in proof.*—The computations described here have been repeated using optical model cross sections σ_{cp} and σ_{cn} furnished by C. E. Porter and based on an IBM 704 code prepared by R. M. Thaler and G. Igo. There was no essential difference in the results; the best values of a are in the range 1 to 2, with 1.59 and 3.28 the corresponding values of b.

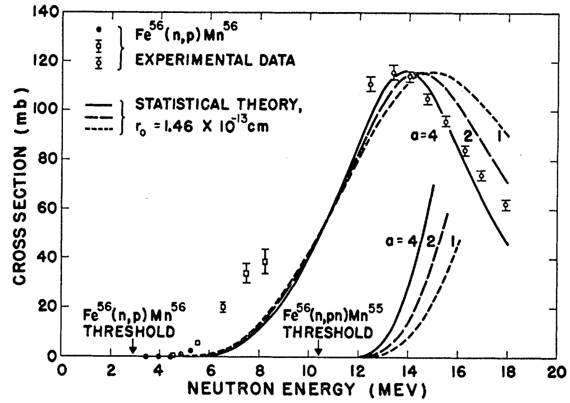

FIG. 2. Comparison of experimental and theoretical results for the cross section of $Fe^{56}(n,p)Mn^{56}$. The calculated yields are normalized to the experimental maximum value of 116 mb by the choice of the ratio of level densities between Fe^{56} and Mn^{56}. Also shown is the calculated yield of $Fe^{56}(n,pn)Mn^{55}$; note that this does not include the yield of $Fe^{56}(n,np)Mn^{55}$. The values of a are in units of $(\text{Mev})^{-1}$.

Wilhelmi[41] has also calculated the yield from $Fe^{56}(n,p)Mn^{56}$ on the basis of statistical theory. The excitation function which he calculated is at variance with those calculated in the present paper, but the reason for the difference is not known.

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