

Nuclear Reactions of Iron with 340-Mev Protons*

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Natural iron has been bombarded with the full energy proton beam of the Berkeley 184-inch synchro-cyclotron, and a number of radioactive spallation products have been isolated and identified and their formation cross sections measured against that of the reaction $\text{Al}^{27}(p, 3pn)\text{Na}^{24}$. A simple mechanism has been postulated to account for the observed product yields. A new isotope of chromium, assigned to mass 48, has been observed and partially characterized.

I. INTRODUCTION

A SERIES of bombardments of iron with 340-Mev protons has been carried out in the circulating beam of the Berkeley 184-inch cyclotron with the purpose of studying the cross section for formation of the various spallation or fission products. It has been found possible to isolate a number of radioactive product nuclides by standard radiochemical techniques using inert carriers and to identify the nuclides so obtained by observing their half-lives and radiation characteristics. Both absorption measurements and low resolution magnetic beta-spectrometer measurements were used where appropriate to differentiate between isotopes of the same element with similar half-lives.

A mechanism of spallation has been postulated which contains the basic assumption that the probability of emitting a proton from a highly excited nucleus of low atomic number (i.e., less than 30) is approximately equal to the probability of emitting a neutron from the same nucleus under the same conditions. From the postulated mechanism it can be deduced that the spallation products for a given nuclide can be divided into groups *a priori*, the yields of the products in any given group falling on a smooth curve when plotted against mass number. Five such groups were predicted for the spallation products of iron, considering only the abundant isotope Fe^{56} . Experimental results show satisfactory agreement with the hypothesis.

II. EXPERIMENTAL TECHNIQUES

A. Target Makeup

Two types of targets were used which may be referred to for convenience as "thin" and "thick." Each thin target consisted of a single iron foil approximately ten one-thousandths of an inch in thickness through which the beam passed perpendicular to the plane of the foil. On either side of the target foil were "guard foils" of 0.001-inch thick aluminum, and outside and parallel to these were foils of 0.0005-inch thick aluminum (see Fig. 1) used to monitor the total beam through the

target by use of the $\text{Al}^{27}(p, 3pn)\text{Na}^{24}$ reaction as described by Stevenson and Folger.¹ Energy degradation of a 340-Mev proton beam in passing through such a foil is negligible.

Each thick target consisted of a stack of from four to six 0.01-inch iron foils, the dimensions of the stack being about $1\frac{3}{4} \times \frac{1}{2}$ inches, the beam passing through the stack parallel to the $\frac{1}{2}$ -inch dimension. The energy degradation undergone by a 340-Mev proton beam in $\frac{1}{2}$ inch of iron is calculated to be about 20 Mev.² The beam in this case was monitored by observing the yield of Fe^{52} , previously calibrated against the $\text{Al}^{27}(p, 3pn)\text{Na}^{24}$ reaction in thin target bombardments.

The iron used was of high purity. A spectrographic analysis performed by Conway and Moore of this laboratory showed very slight amounts of a small number of impurities. These impurities are tabulated in Table I.

Seven bombardments were made. Table II lists the data pertinent to each bombardment.

B. Chemical Separations

Usually 10 mg of each element to be isolated was added as carrier to the dissolving medium prior to addition of the target. The chemical methods used in the bombardments consisted of specific or group precipitations or solvent extractions for each element sought, combined with precipitations of unwanted elements (added as carriers) by reagents not precipitating the desired elements (so-called "scavenge" precipitations). The precise combinations of extractions, specific precipitations, and scavenges used varied depending on which combinations of elements were to be isolated. However, the more important steps in the isolation and purification of the different elements are given below. The percentage recovery of the activities formed was determined gravimetrically by weighing the recovered carrier, complete exchange being assumed. The target was dissolved in approximately 12 N HCl (bombardments *FeP1* to *FeP5*) or in approximately 3 N HNO_3 (bombardments *FeP6* and *FeP7*).

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¹ P. C. Stevenson and R. L. Folger (unpublished work).

² Aron, Hoffman, and Williams, AEC Unclassified Document No. 663 (May 28, 1951).

1. Cobalt

Cobalt was precipitated from ammoniacal solution with hydrogen sulfide gas. The sulfide was dissolved in hydrochloric acid containing potassium chlorate, and cobalt was then precipitated by the use of potassium hydroxide. This precipitate was dissolved in acetic acid, and potassium nitrite was added to precipitate $K_3Co(NO_2)_6 \cdot H_2O$. This precipitate was washed, dried at 110°C on an aluminum dish, and weighed. In bombardments *FeP1* and *FeP2* an extraction of cobalt-thiocyanate complex into ethyl acetate was used as an additional purification step.

2. Iron

The principal step in the iron isolation was the extraction of ferric chloride from 7.5 N HCl into isopropyl ether. The extraction is specific for iron in this region of the periodic table. The ether layer was washed three times with 7.5 N HCl, then iron was re-extracted into water and ferric hydroxide precipitated by the addition of ammonium hydroxide. This precipitate was dissolved in 7.5 N HCl and the cycle repeated. The final ferric hydroxide precipitate was washed, dried, and ignited on a platinum dish to Fe_2O_3 and weighed. In bombard-

TABLE I. Spectrographic analysis of target iron.

Impurity	Amount, parts per million by weight
As	Not detected (<100)
Co	60
Mn	Not detected (<100)
Ni	150
Cu	<50

ment *FeP2* ferric-thiocyanate complex was also extracted into ethyl acetate and re-extracted into aqueous ammonia. In bombardments *FeP1* and *FeP2* iron was precipitated as ferric phosphate from dilute hydrochloric acid, washed, dried, and weighed as $FePO_4 \cdot H_2O$.

3. Manganese

Manganese was precipitated as manganese dioxide by potassium chlorate from a fuming nitric acid solution. The precipitate was dissolved in hydrochloric acid containing hydrogen peroxide. Tartaric acid and small amounts of chromium, titanium, and vanadium were added and manganous sulfide was then precipitated from alkaline solution. The sulfide was dissolved in concentrated nitric acid and manganese dioxide was brought down from fuming nitric acid solution as before. The whole cycle was repeated once. The MnO_2 precipitate was then dried at 110°C and weighed.

4. Chromium

In bombardment *FeP3* chromium was separated as the iodate from 1 N HCl (after removing titanium and iron). The iodate was destroyed by reduction with sulfur dioxide, and chromium was precipitated as the

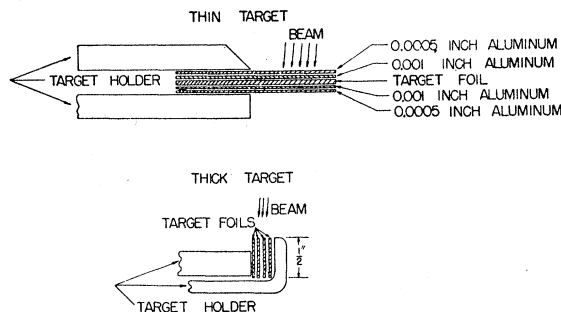


FIG. 1. Assembly of the two types of targets used.

hydroxide. The hydroxide was oxidized to chromate with basic peroxide solution, and the chromium was extracted as perchromic acid from dilute perchloric acid into amyl acetate. The amyl acetate layer was washed and chromium was re-extracted into aqueous ammonia. The perchromic acid extraction was repeated. Finally, chromium was precipitated from acetic acid solution as $BaCrO_4$, washed, dried at 110°C, and weighed.

In bombardment *FeP5* chromium was first brought down as barium chromate, then extracted into amyl acetate from a perchloric acid solution containing hydrogen peroxide. In bombardment *FeP2* chromium was oxidized with potassium bromate in perchloric acid and then extracted into ether after cooling and addition of hydrogen peroxide.

5. Vanadium

Vanadium was separated as sulfide from ammoniacal solution. The sulfide was dissolved in concentrated nitric acid, scavenged with manganese dioxide, precipitated with potassium chlorate and fuming nitric acid and then with yttrium hydroxide in ammoniacal solution. Vanadium sulfide was again precipitated. The sulfide was dissolved and the solution was buffered with sodium acetate-acetic acid. Chromium was then added to act as holdback and vanadium was oxidized by hydrogen peroxide. Lead vanadate was precipitated. The precipitate was dissolved in 2 N HNO_3 , and lead was removed as the sulfide. The solution was then buffered with sodium acetate-acetic acid and oxidized and $Pb(VO_3)_2$ was again brought down. This was washed, dried at 100°C, and weighed.

TABLE II. Summary of bombardments.

Bombardment No.	Duration of bombardment (min)	Type of target	Elements isolated
<i>FeP1</i>	20	Thin	Fe, Co
<i>FeP2</i>	46	Thin	Fe, Co, Cr
<i>FeP3</i>	46	Thin	Fe, Co, Cr, Mn, V
<i>FeP4</i>	17	Thick	Fe, Mn, Ca, Ti, Sc
<i>FeP5</i>	109	Thick	Fe, Co, Cr, Mn, Na, S, P, Ca
<i>FeP6</i>	65	Thin	Fe, V, Sc, K, Si, Cl
<i>FeP7</i>	55	Thin	Fe, Ti, K, Cl, Si, Cr

6. Titanium

For the separation of titanium the precipitation of titanium iodate from 6 *N* HNO₃ was used. The precipitate was dissolved in hydrochloric acid containing sodium sulfite. Titanium was then precipitated as hydroxide with ammonia. The hydroxide was dissolved in 0.5 *N* HNO₃ and scavenged with yttrium oxalate. Tartaric acid was added and the solution made ammoniacal to be scavenged with iron and manganese sulfides. The supernatant from the last scavenge was made 1 *N* in hydrochloric acid, and titanium was precipitated with cupferron. The precipitate was then metathesized to TiO₂·H₂O with ammonium hydroxide. The hydrous oxide was dissolved in hydrochloric acid and the iodate precipitated. The iodate was dissolved in hydrochloric acid and sodium sulfite. Finally, titanium was precipitated as hydroxide with ammonia, washed, ignited to TiO₂, and weighed.

7. Scandium

Scandium was separated by precipitation with oxalic acid from 0.5 *N* HNO₃. The precipitate was dissolved in concentrated nitric acid; manganese carrier and fuming nitric acid were then added. Potassium chlorate was added to precipitate manganese dioxide and to destroy the oxalate. Scandium was precipitated as the hydroxide by adding ammonia gas to the supernatant. After two more oxalate-hydroxide cycles the scandium hydroxide was washed, ignited to Sc₂O₃ on a platinum dish, and weighed.

8. Calcium

Calcium was precipitated as calcium oxalate with oxalic acid (bombardment *FeP4*) or as calcium carbonate from alkaline solution. The calcium precipitates were dissolved in nitric acid (plus potassium chlorate in bombardment *FeP4*). The solution was made alkaline with ammonium hydroxide and scavenged with yttrium and titanium hydroxides, then with manganese dioxide (precipitated by hydrogen peroxide), and finally with cobalt sulfide. The supernatant was acidified with acetic acid, and calcium was precipitated with oxalic acid. The cycle was repeated twice. Finally, the calcium oxalate precipitate was washed, dried at 110°C, and weighed as CaC₂O₄·H₂O.

9. Potassium

After the precipitation of most elements with ammonium hydroxide, potassium was left in solution. This supernatant was made about 0.1 *N* in acid, phosphate ion added, and then ferric ion in excess to bring down ferric phosphate. The solution was then made alkaline with ammonium hydroxide and scavenged twice with iron and titanium hydroxides, then twice with chromium sulfide and with calcium carbonate or calcium oxalate. The solution was then acidified with hydrochloric acid and evaporated to dryness in a

porcelain casserole. The ammonium salts were removed by fuming over a Meker burner. The residue was dissolved in water. Perchloric acid was added, the solution was heated to fuming, then cooled in an icebath, and absolute alcohol was added to precipitate potassium perchlorate. This was carefully washed with absolute alcohol to remove ammonium perchlorate and recrystallized twice from perchloric acid. The precipitate was washed with alcohol, dried at 110°C, and weighed as KClO₄.

10. Chlorine

When chlorine was to be isolated, the carrier was added as solid, freshly prepared silver chloride, and the target was dissolved in dilute (~3 *N*) nitric acid. The exchange between chloride ion in the silver chloride precipitate and the radioactive chloride ion in the solution is supposed to be rapid and complete.³ After the target had completely dissolved, the silver chloride precipitate was separated. Silver chloride was then dissolved in 5 *N* NH₄OH and scavenged with ferric hydroxide. Potassium iodide was then added to precipitate silver iodide, and after centrifuging, an excess of silver nitrate was added to remove iodide. The supernatant was acidified with nitric acid to precipitate silver chloride and the precipitate was washed, dried at 110°C, and weighed.

11. Sulfur

The sulfur carrier was added in the form of SO₄²⁻, and the target was dissolved in concentrated hydrochloric and nitric acids. Barium sulfate was precipitated from 1 *N* HCl. This was converted to barium carbonate by boiling with 50 percent aqueous potassium carbonate solution for about 1 hour. The precipitate was discarded, and the supernatant was made 1 *N* in hydrochloric acid. Barium sulfate was precipitated by the addition of barium chloride solution. The procedure was repeated twice. Finally, the barium sulfate precipitate was washed, dried at 110°C, and weighed as BaSO₄.

12. Phosphorus

Phosphorus was added as PO₄³⁻, and the target was dissolved in hydrochloric and nitric acids. Phosphorus was then isolated by precipitation as ammonium phosphomolybdate from 1 *N* HNO₃. The precipitate was dissolved in ammonium hydroxide, vanadium holdback agent was added, and magnesium ammonium phosphate was precipitated by the addition of magnesia mixture. The precipitate was dissolved in 1 *N* HNO₃ and the cycle was repeated. Finally, phosphorus was precipitated as magnesium ammonium phosphate. This was washed, ignited on a platinum dish, and weighed as Mg₂P₂O₇.

³ A. S. Newton, thesis, University of Michigan, Ann Arbor, Michigan (June, 1941), University Microfilm Service.

13. Silicon

Silicon carrier was added as $(\text{NH}_4)_2\text{SiF}_6$. After the target had dissolved, silica was brought down by the addition of boric acid and digestion with hot concentrated sulfuric acid. The silica was carefully washed with warm diluted sulfuric acid, then it was dissolved in potassium hydroxide. The solution was scavenged with titanium hydroxide. Holdback agents of iron, cobalt, chromium, vanadium, and yttrium were added, and the mixture was acidified with hydrochloric acid. Silica was precipitated by digestion. The cycle was repeated. The precipitate was then washed, ignited on a platinum dish, and weighed as SiO_2 .

14. Sodium

In the procedure sodium was left in ammoniacal solution. This solution was scavenged twice with iron and titanium hydroxides, with cobalt sulfide, and with calcium oxalate. The supernatant was acidified with hydrochloric acid and evaporated to dryness in a porcelain casserole. Ammonium salts were removed by fuming over a Meker burner. The residue was taken up in water, filtered, and zinc uranyl acetate was added to the cooled supernatant. The sodium zinc uranyl acetate precipitate was dissolved in alcohol saturated with hydrogen chloride gas and cooled. Sodium chloride precipitated. The precipitate was dissolved in a small amount of water, potassium holdback agent was added, and sodium zinc uranyl acetate was reprecipitated. The cycle was repeated once more. Finally, sodium chloride was washed with alcohol-hydrochloric acid, dried at 110°C , and weighed.

C. Counting Techniques

The purified counting samples were transferred to weighed aluminum or platinum dishes and spread as uniformly as possible over the total area of the dish ($\sim 5\text{ cm}^2$). After suitable drying, the dishes were weighed again and the sample weight obtained by difference. The samples were then fixed in position on the dishes by evaporating dilute solutions of collodion or zapon on them, and the dishes were fastened to cardboard holders with Scotch tape, as shown in the diagram (Fig. 2). These holders were designed to fit in any one of five standard positions beneath the window of a chlorine-quenched Amperex Geiger-Müller tube. The position selected for counting a given sample was as far from the counter window as convenient, the criterion being the desirability of securing a sufficiently large number of counts in a short counting time to give good statistical reliability to the calculated counting rate. Absorption curves were taken with the absorber as close as possible to the counter window and the sample as far away as possible in order to minimize scattering of radiation into the counter by the absorber.⁴

⁴ R. C. Gibbs, Chairman, Division of Mathematical and Physical Sciences, National Research Council, Nuclear Science Series, Preliminary Report No. 8, "Conference on Absolute β -Counting," Papers 1 and 3 (October, 1950).

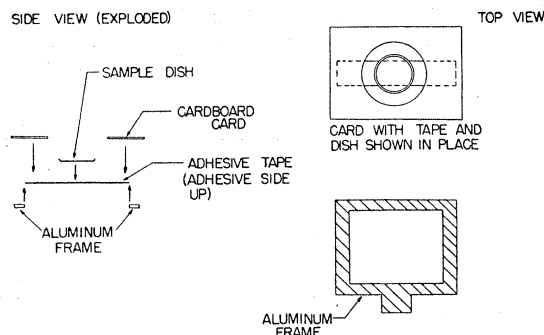


Fig. 2. Method used for mounting samples for counting.

The observed counting rates were subjected to the following corrections:

1. A correction for counts lost due to dead time of the counter tube (so-called coincidence correction).
2. A correction for background activity.
3. A geometric correction to the position in which the monitor sample was counted. This was determined empirically in each case.
4. A correction for air and window absorption, determined by back-extrapolation of the observed aluminum absorption curve.
5. A correction for backscattering from the sample dish. The figures used for beta-energies greater than 0.6 Mev were 1/1.22 for aluminum dishes and 1/1.75 for platinum dishes, calculated from the saturation backscattering data of Burt.⁵ For beta-energies less than 0.6 Mev the backscattering was calculated from the data of Yaffe and Justus.⁶
6. A factor for self-scattering and absorption by the sample material itself, estimated from the work of Malatesta.⁷
7. A factor for relative counting efficiency in the case of x-ray or gamma-activities. "Counting efficiency" is defined as the number of counts registered by the counter per particle (or photon) passing through the tube window.
8. A factor to correct for the decay of the sample from the time of the end of the bombardment to the time of initial measurement of the activity.

III. RESULTS

A. New Chromium Isotope

In the chromium decay curves a new activity was found after subtraction of the activity due to 26.5-day Cr^{51} . This half-life was found to be 19 hours, 24 hours, and 23 hours in bombardments FeP2 , FeP3 , and FeP5 . Owing to a very poor chemical yield in bombardment FeP2 , however, the last two figures should be more accurate. Since the electrons from Cr^{51} can easily be blocked by a thin aluminum absorber ($\sim 30\text{ mg/cm}^2$), the growth and the decay of an isotope of a half-life of 16 days could be observed. In bombardment FeP5 two sets of absorption measurements were made, one after about 15 hours and the other several days after the bombardment. These measurements showed the growth of an activity with beta-radiation of about 0.7 Mev maximum energy. Furthermore, part of the purified chromium fraction from bombardment FeP5

⁵ B. P. Burt, *Nucleonics* 5, 32 (1949).

⁶ L. Yaffe and K. M. Justus, *J. Chem. Soc. (London)* S341 (1949), Part V.

⁷ L. Malatesta, private communication.

TABLE III. Yield of cobalt isotopes.

Reported in literature ^a			Experimental results		
Mass No.	$T_{\frac{1}{2}}$	Radiation	Bomb. No.	$T_{\frac{1}{2}}$	Yield, mb (1 mb = 10^{-27} cm ²)
55	18.2 hr	β^+ , γ	<i>FeP1</i>	18.3 hr	0.42
			<i>FeP2</i>	18.1 hr	0.14
			<i>FeP3</i>	17.6 hr	0.53
			<i>FeP5</i>	17.6 hr	0.53
56	72 days	β^+ , γ , <i>EC</i>	<i>FeP3</i>	78 days	0.21
			<i>FeP5</i>	72 days	0.26

^a Any previously reported data on half-lives or radiation characteristics is taken from G. T. Seaborg and I. Perlman, *Revs. Modern Phys.* **20**, 585 (1948).

was left to decay for two weeks in the presence of inactive vanadium carrier. The vanadium was then separated chemically. This vanadium sample showed an activity with a half-life of 16.2 days and an energy of 0.78 Mev (determined from aluminum absorption measurements). The chromium isotope can from these experiments be assigned the mass number 48. Furthermore, the counting efficiency of the isotope was determined from the counting rate of its daughter to be

TABLE IV. Yield of iron isotopes.

Reported in literature			Experimental results		
Mass No.	$T_{\frac{1}{2}}$	Radiation	Bomb. No.	$T_{\frac{1}{2}}$	Yield, mb
52	7.8 hr	β^+	<i>FeP1</i>	8.1 hr	0.55
			<i>FeP2</i>	8.3 hr	0.56
			<i>FeP3</i>	8.3 hr	0.66
			<i>FeP4</i>	8.4 hr	...
			<i>FeP5</i>	8.3 hr	...
			<i>FeP6</i>	8.3 hr	0.71
			<i>FeP7</i>	8.6 hr	0.67

about 4 percent which indicates that it decays mainly by electron capture.

B. Spallation Yields

1. Cobalt

It was assumed in determining the yield of Co⁵⁶ that all long-lived activity was to be attributed to Co⁵⁶ (see Table III). Co⁵⁸ can only be formed from Fe⁵⁷ and Fe⁵⁸, and these isotopes are in low abundance in natural iron (together 2.5 percent). This yield of Co⁵⁶ is not corrected for any branching decay by electron capture.

TABLE V. Yield of manganese isotopes.

Reported in literature			Experimental results		
Mass No.	$T_{\frac{1}{2}}$	Radiation	Bomb. No.	$T_{\frac{1}{2}}$	Yield, mb
51	46 min	β^+	<i>FeP3</i>	46.8 min	4.09
			<i>FeP4</i>	42.7 min	3.95
52	5.8 days	$\beta^+(35\%)$, <i>EC</i> , γ	<i>FeP3</i>	5.8 days	14.5
			<i>FeP4</i>	5.8 days	11.0
			<i>FeP5</i>	5.7 days	13.1
54	310 days	β^+ , <i>EC</i> , γ	<i>FeP3</i>		12.1
			<i>FeP4</i>		11.8
56	2.59 hr	β^- , γ	<i>FeP4</i>	2.72 hr	0.56
			<i>FeP4</i>	2.43 hr	0.61

2. Iron

In bombardments *FeP4* and *FeP5*, Fe⁵² was used as a monitor (see Table IV). The counting efficiency of the isotope was determined by observation of the growth of Mn⁵² and by chemical separation of Mn⁵². The counting efficiency was thus determined to be 1.72 for the equilibrium mixture. For Fe⁵² only, it is 0.70 which indicates that the parent isotope decays to the extent of about 30 percent by orbital electron capture.

TABLE VI. Yield of chromium isotopes.

Reported in literature			Experimental results		
Mass No.	$T_{\frac{1}{2}}$	Radiation	Bomb. No.	$T_{\frac{1}{2}}$	Yield, mb
48	(Previously unreported)		<i>FeP2</i>	19 hr	0.73
			<i>FeP3</i>	24 hr	0.91
			<i>FeP5</i>	23 hr	0.75
49	41.9 min	β^+ , γ	<i>FeP2</i>	41 min	4.9
			<i>FeP3</i>	40 min	6.1
			<i>FeP7</i>	43 min	3.5
51	26.5 days	<i>EC</i> , γ , e^-	<i>FeP2</i>	(21 days)	53
			<i>FeP3</i>	27 days	38
			<i>FeP5</i>	28 days	33

3. Manganese

In the determination of the yield of Mn⁵⁴ it was assumed that all the activity in the manganese fractions after the decay of Mn⁵² consisted of Mn⁵⁴ (see Table V). The samples were observed for too short a time for a determination of the half-life. The figures for the yield are therefore uncertain. The counting efficiency of Mn⁵⁴ was assumed to be 10 percent (from Miller's data).⁸

4. Chromium

For Cr⁵¹ a counting efficiency of 3 percent has been assumed (see Table VI). This figure is very uncertain, and the yield may be in error by a factor of two.

TABLE VII. Yield of vanadium isotopes.

Reported in literature			Experimental results		
Mass No.	$T_{\frac{1}{2}}$	Radiation	Bomb. No.	$T_{\frac{1}{2}}$	Yield, mb
47	33 min	β^+	<i>FeP3</i>	35 min	2.42
48	16 days	$\beta^+(58\%)$, <i>EC</i> , γ	<i>FeP3</i>	16.0 days	9.6
			<i>FeP6</i>	16.1 days	11.0
49	600 days	<i>EC</i> , γ	<i>FeP3</i>	...	31

5. Vanadium

The yield for V⁴⁹ is only approximate since it was assumed that all activity after subtraction of 16-day V⁴⁸ consisted of V⁴⁹ (see Table VII). The counting efficiency for V⁴⁹ is assumed to be 1 percent. (Decays solely by orbital electron capture.)

6. Titanium

No long-lived titanium isotope was found (see Table VIII).

⁸ D. R. Miller, AEC Declassified Document No. 2193 (August 6, 1948).

7. Scandium

The yield of Sc^{44m} was determined by counting through 222 mg/cm² aluminum absorber to block the radiations from Sc⁴⁷ and Sc⁴⁸ (see Table IX). It was assumed that the decay by orbital electron capture of Sc⁴⁴ is negligible. The yield of Sc⁴⁶ is not corrected for possible decay by orbital electron capture. Sc⁴³ and Sc⁴⁴ could not be separated in either bombardment nor could Sc⁴⁷ and Sc⁴⁸ in bombardment *FeP6*. Owing to the difficulty in separating Sc⁴⁷ and Sc⁴⁸ in bombard-

TABLE VIII. Yield of titanium isotopes.

Reported in literature			Experimental results		
Mass No.	T _½	Radiation	Bomb. No.	T _½	Yield, mb
45	3.08 hr	β ⁺ , γ	<i>FeP4</i> <i>FeP7</i>	3.13 hr 3.07 hr	3.31 4.05

ment *FeP4* the figures for the yields are uncertain. Sc⁴⁹ could not be detected.

8. Calcium

In *FeP4* the decay of the calcium sample was observed for three months (see Table X). The decay follows a 152-day line fairly well. The absorption measurements made about two and one-half months after the bombardment (*FeP5*) indicated a β⁻ energy of 0.3 Mev and no gamma-radiation.

9. Potassium

The reason for the large difference in the yield determinations in the two bombardments may be due to occlusion of perchloric acid by the precipitate in bom-

TABLE IX. Yield of scandium isotopes.

Reported in literature			Experimental results		
Mass No.	T _½	Radiation	Bomb. No.	T _½	Yield, mb
43 and 44	both 3.92 hr	β ⁺ , γ, (EC)	<i>FeP4</i> <i>FeP6</i>	4.1 hr 4.0 hr	4.43 4.14
44	2.44 days	e ⁻ , γ	<i>FeP4</i> <i>FeP6</i>	2.61 days 2.48 days	2.61 2.59
46	85 days	β ⁻ , γ, EC	<i>FeP4</i> <i>FeP6</i>	84 days	3.27 3.14
47	3.4 days	β ⁻	<i>FeP4</i>	3.5 days	0.84
48	44 hr	β ⁻	<i>FeP4</i>	44 hr	0.45

bombardment *FeP6* (see Table XI). The higher figures for yield are therefore believed to be the more reliable.

10. Chlorine

The Cl³⁴ and Cl³⁸ activities were resolved by the use of a recording magnetic beta-spectrometer (see Table XII). The half-lives are obtained by the analysis of the data from this instrument, and they are not very accurate.

TABLE X. Yield of calcium isotopes.

Reported in literature			Experimental results		
Mass No.	T _½	Radiation	Bomb. No.	T _½	Yield, mb
45	152 days	β ⁻	<i>FeP4</i> <i>FeP5</i>	(152 days) (152 days)	0.54 0.58
47	5.8 days	β ⁻ , γ	<i>FeP4</i> <i>FeP5</i>	5.6 days 5.5 days	0.007 0.006

11. Sulfur

The sulfur decay was observed for about two months and showed a half-life fairly close to the reported one (see Table XIII). Aluminum absorption measurements showed a β⁻ energy of 0.15 Mev.

TABLE XI. Yield of potassium isotopes.

Reported in literature			Experimental results		
Mass No.	T _½	Radiation	Bomb. No.	T _½	Yield, mb
42	12.4 hr	β ⁻ , γ	<i>FeP6</i> <i>FeP7</i>	12 hr 12 hr	0.26 1.15
43	22.4 hr	β ⁻ , γ	<i>FeP6</i> <i>FeP7</i>	22 hr 21 hr	0.12 0.72

TABLE XII. Yield of chlorine isotopes.

Reported in literature			Experimental results		
Mass No.	T _½	Radiation	Bomb. No.	T _½	Yield, mb
34	33 min	β ⁺ , γ	<i>FeP6</i> <i>FeP7</i>	36 min 27 min	0.08 0.14
38	38 min	β ⁻ , γ	<i>FeP6</i> <i>FeP7</i>	45 min 37 min	0.13 0.20
39	55 min	β ⁻	<i>FeP6</i> <i>FeP7</i>	55 min 58 min	0.05 0.04

TABLE XIII. Yield of sulfur isotopes.

Reported in literature			Experimental results		
Mass No.	T _½	Radiation	Bomb. No.	T _½	Yield, mb
35	87 days	β ⁻	<i>FeP5</i>	80 days	0.23

12. Phosphorus

TABLE XIV. Yield of phosphorus isotopes.

Reported in literature			Experimental results		
Mass No.	T _½	Radiation	Bomb. No.	T _½	Yield, mb
32	14.3 days	β ⁻	<i>FeP5</i>	15.0 days	0.044

13. Silicon

The half-life reported in literature seems to be too long. Both silicon samples were followed for a period of eight to ten half-lives, and both showed single com-

ponent decay with a half-life of 157 minutes (see Table XV).

14. Sodium

The yield of Na^{22} is uncertain because the decay was not followed long enough to establish the identity of the isotope with certainty (see Table XVI).

IV. DISCUSSION

A cursory examination of the data presented in Table XVII seems to show no obvious systematic trend in the yields except that, as would be expected from

TABLE XV. Yield of silicon isotopes.

Reported in literature			Experimental results		
Mass No.	$T_{1/2}$	Radiation	Bomb. No.	$T_{1/2}$	Yield, mb
31	170 min	β^-	<i>FeP6</i>	157 min	0.12
			<i>FeP7</i>	157 min	0.125

previous work,⁹⁻¹³ the nuclides formed in high yield are those which have atomic numbers only slightly below that of iron. The converse is not necessarily true, e.g., compare Cr^{48} , 0.80 mb, with Sc^{44m} , 2.60 mb. It is, however, possible to correlate the various yields somewhat more closely. To a first approximation natural iron can be considered to consist entirely of the isotope Fe^{56} (91.6 percent).¹⁴ At the bombarding energies under consideration the formation of a compound nucleus is believed to be unlikely. Transmission of excitation energy from the bombarding particle to the target nucleus is believed to take place by single nucleon-nucleon collisions within the nucleus,¹⁵ the more energetic of the nucleons involved escaping from the nucleus. This will leave either Fe^{56} or Co^{56} in a highly excited

TABLE XVI. Yield of sodium isotopes.

Reported in literature			Experimental results		
Mass No.	$T_{1/2}$	Radiation	Bomb. No.	$T_{1/2}$	Yield, mb
24	14.9 hr	β^-, γ	<i>FeP5</i>	15.1 hr	0.026
22	2.6 hr	β^+, γ	<i>FeP5</i>	...	0.021

state. Let us assume that these two species are formed in approximately equal abundance. Let us further assume either that protons and neutrons "boil off" with equal probability or that the most likely mode of dissipation of excitation energy is by emission of alpha-particles or deuterons with neutrons and protons boiling off with equal low probability. It can be seen that the most likely nuclide of a given mass to be formed by

⁹ R. E. Batzel, Phys. Rev. **79**, 528 (1950).

¹⁰ H. H. Hopkins, Phys. Rev. **77**, 717 (1950).

¹¹ M. Lindner and I. Perlman, Phys. Rev. **78**, 499 (1950).

¹² N. A. Bonner and W. C. Orr, Phys. Rev. **76**, 140 (1949).

¹³ Batzel, Miller, and Seaborg, Phys. Rev. **84**, 671 (1951).

¹⁴ J. R. White and A. E. Cameron, Phys. Rev. **74**, 991 (1948).

¹⁵ R. Serber, Phys. Rev. **72**, 1114 (1947).

TABLE XVII. Summary of the yields observed.

Isotope	Yield (mb)	Remarks
Co^{56}	0.49	
Co^{56}	0.24	No correction for orbital electron capture
Fe^{52}	0.68	
Mn^{51}	4.0	
Mn^{52}	12.9	
Mn^{54}	12	10 percent counting efficiency. ^a
Mn^{56}	0.59	
Cr^{48}	0.80	
Cr^{49}	4.8	
Cr^{51}	41	3 percent counting efficiency. ^b
V^{47}	2.4	
V^{48}	10.3	
V^{49}	31	1 percent counting efficiency assumed.
Ti^{46}	3.7	
Sc^{44m}	2.60	
Sc^{46}	3.20	No correction for orbital electron capture.
Sc^{47}	0.84	Uncertain.
Sc^{48}	0.45	
Ca^{46}	0.56	
Ca^{47}	0.007	
K^{42}	0.7	
K^{43}	0.4	
Cl^{34}	0.11	
Cl^{38}	0.17	
Cl^{39}	0.045	
S^{35}	0.23	
P^{32}	0.044	
Si^{31}	0.12	
Na^{24}	0.026	
Na^{22}	0.02	Approximate.

^a See reference 8.

^b R. E. Batzel (private communication).

such a process must lie on a line represented on a plot of Z versus $(A-Z)$ with a 45° (positive) slope passing through Co^{57} . Such nuclides are those such that $Z=27-X$, $A=57-2X$, where $X=0, 1, 2$, etc. This simple picture would, of course, have to be modified for heavier nuclides, where the neutrons outnumber the protons appreciably. Some effects due to nuclear shell structure might also be observed.

Figure 3 represents a portion of the "Chart of the Nuclides" in which the ordinate represents the atomic number (Z) and the abscissa, the number of neutrons ($A-Z$) of the nuclides shown. The nuclides predicted by this simple picture to be formed in high yield are then those lying along the diagonal line marked "I" in

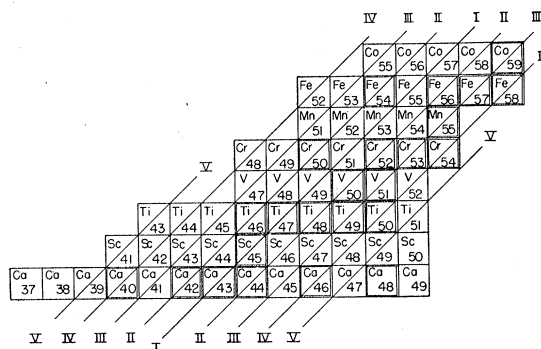


FIG. 3. Systematic grouping of nuclides formed by spallation of Fe^{56} .

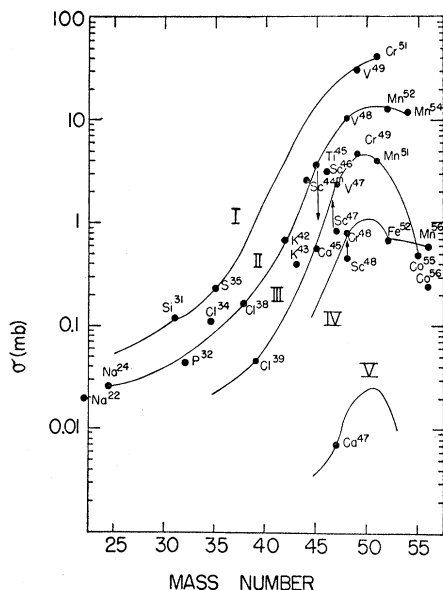


FIG. 4. Cross section for formation of various spallation products of natural iron as a function of mass number.

the figure; those next most probable by this model lie on the two lines marked "II," and so on. A tabulation of the expected nuclides is given in Table XVIII.

If one plots formation cross section *versus* mass number, it is apparent that all the nuclides of a given group (see Table XVII) fall on the same smooth curve with almost no exceptions and furthermore, that the curves so obtained are quite closely parallel on a semi-logarithmic plot, as shown in Fig. 4. Since the curves are parallel on a semilogarithmic plot, the ratio of expected yields for two isobars on different curves is approximately constant. This fact enables us to draw from Fig. 4 an approximate distribution curve (Fig. 5) for the yields of various isobars of any given mass.

A few isotopes do not fall on their proper curves, e.g., for curve II, Sc⁴⁶ is a little low. However, the counting efficiency of this isotope was not corrected for electron capture. Such a correction should indicate a higher value for the yield. Sc⁴⁷ belonging to curve III is also low. This yield is very uncertain, however.

The yield of Ti⁴⁶ belonging to curve III is very high. This can be partially accounted for by considering that Fe⁵⁴ is in a rather high abundance (5.9 percent) in natural iron. With help of the distribution curve from Fig. 5 the contribution to the yields from Fe⁵⁴ has been estimated. It comes out to be 45 percent of the total yield for the isotopes Mn⁵¹, Cr⁴⁹, V⁴⁷, Ti⁴⁶ but only 6 percent for Mn⁵², V⁴⁸, Sc^{44m}. If the yields are corrected for this and also for the estimated contribution from Fe⁵⁷ and Fe⁵⁸, Ti⁴⁶ falls below curve II even if it still seems to be high.

The picture given above indicates why Fe⁵² is in

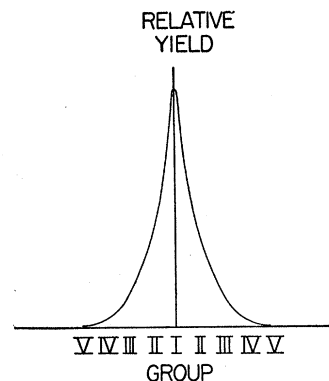


FIG. 5. The distribution of various nuclides of given mass according to the systematic method of grouping products.

such low yield. It also explains why Sc⁴⁹ (57 minute) could not be detected. It belongs to "curve" V and its yield is probably a factor of 100 lower than the yield of Sc⁴⁴ (3.9 hour). It will therefore be completely masked by the latter isotope. Ti⁵¹ also belongs to "curve" V. It could not be detected.

The yields of nuclides of mass 55 and above are not regular in this system. However, it is expected that these yields are low, since the nucleus is excited to a degree such that at least two or three nucleons may be expected to boil out. In this case the rarer, heavy isotopes of iron are expected to exert a disproportionately large effect of a magnitude which is difficult to estimate.

TABLE XVIII. A systematic grouping of measurable product nuclides.

Group	Probability	Nuclides
I	Highest	Co ⁵⁷ , Cr ⁵¹ , V ⁴⁹ , S ³⁵ , Si ³¹
II	Next highest	Co ⁵⁶ , Mn ⁵⁴ , Mn ⁵² , V ⁴⁸ , Sc ⁴⁶ , Sc ⁴⁴ , K ⁴² , Cl ³⁸ , P ³² , Na ²⁴
III	Third highest	Co ⁵⁵ , Mn ⁵¹ , Cr ⁴⁹ , V ⁴⁷ , Ti ⁴⁵ , Sc ⁴⁷ , Ca ⁴⁶
IV	Fourth highest	K ⁴³ , Cl ³⁹
V	Fifth highest	Mn ⁵⁶ , Fe ⁵² , Cr ⁴⁸ , Cl ³⁴ , Na ²²

From Fig. 4 the total reaction cross section of natural iron for high energy protons is estimated to be 340 mb.

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