Absolute (d,α)-Reaction Cross Sections of Zirconium, Molybdenum, Titanium, and Sulfur*

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Absolute cross sections for 7.8-Mev deuterons were measured for the following reactions: $Zr^{94}(d,\alpha)Y^{92*}$; $Zr^{92}(d,\alpha)Y^{90*}$; $Zr^{90}(d,\alpha)Y^{88*}$; $Mo^{97}(d,\alpha)Nb^{95*}$; $Mo^{97}(d,\alpha)Nb^{95m}$; $Mo^{98}(d,\alpha)Nb^{96}$; $Mo^{92}(d,\alpha)Nb^{90}$; $Ti^{46}(d,\alpha)Sc^{44}$; $Ti^{48}(d,\alpha)Sc^{46}$; and $S^{34}(d,\alpha)P^{32*}$. Excitation functions were also determined for the reactions indicated with an asterisk. Beam intensity was determined with a Faraday cage coupled to a current integrator able to measure the current with less than 1% error. The reaction products from the thin targets were chemically purified by carrier-free separations. The absolute disintegration rates were determined by 4π beta counting and coincidence gamma counting. Carrier-free tracer techniques were used to establish the yields of chemical purification steps.

I. INTRODUCTION

ALTHOUGH many cross section values are reported in the literature[1,2] few are good to better than 10–15% and many are much poorer. This is particularly true of values for certain low-yield charged particle reactions such as the (d,α). A recent publication[3] describes some of the techniques used in this laboratory for precise cross-section determinations of (d,α) reactions and reports some measurements. The purpose of the present work was to further refine the experimental approach to such measurements, to improve some of the older values, and to report on several new reactions.

II. EXPERIMENTAL[4]

A. Bombardment Arrangement

The deuterons for this study were obtained from the deflected external beam of the 42-inch fixed frequency cyclotron of the University of Michigan. The maximum deuteron energy available from this machine was 7.778±0.005 Mev.[5] This deflected beam is magnetically focused and collimated several times before striking the target which is placed just behind the focal plane. The transmitted beam is caught in a Faraday cup placed behind the target. Extreme care was taken to avoid the loss of secondary electrons from the Faraday cup during the bombardments. This was achieved by placing a suppressor ring charged to a potential of −1000 v between target and Faraday cup. The loss of recoiling reaction products was minimized by use of 0.001-inch thick Mylar target supports as recoil catchers.[6]

B. Beam Measurement

The deuteron beam current was measured with a current integrator connected by a low-capacity coaxial cable to the Faraday cup. The instrument was constructed according to a modified version of the circuit reported by Higinbotham and Rankowitz.[7] The integrator operating in the range 0–1 microampere was calibrated against standard currents produced by a stable high voltage supply connected to various "high-meg" resistors ranging from 1×10^7 to 1×10^{11} ohm. These currents were measured by the drop of potential which they produced across a 10 000 ohm resistor calibrated by the National Bureau of Standards. A Rubicon Type B potentiometer was used for the calibrations. The counts/coulomb ratio was determined at ten different current values as 1090±6 counts/coulomb. A repeat calibration performed one year later agreed with the above figure within the quoted standard deviation.

C. Target Preparation

The optimum target thickness for this work was a compromise between reaction yield and energy definition and was taken as approximately 0.0001 inch or 2–5 mg/cm². This corresponds to a deuteron attenuation of ~300 kev in the target. Additional information on the targets used is given in Table I.

Target disks of zirconium, molybdenum, and titanium were cut from thin metal foils with a punch die of known diameter, and then cemented onto Mylar backing. For the investigation of the $S^{34}(d,\alpha)P^{32}$ re-

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[1] O. U. Anders and W. W. Meinke, Document number 4999, American Documentation Institute, Library of Congress, Washington, D. C. (Revised June, 1956).

[2] N. Jarmie and J. D. Seagrave, Los Alamos Scientific Laboratory Unclassified Report LA-2014, March, 1956 (unpublished).

[3] K. L. Hall and W. W. Meinke, J. Inorg. Nuclear Chem. **9**, 193 (1959).

[4] The apparatus and procedures outlined in this section and the experimental results given later are described in considerably more detail in the Ph.D. thesis of O. U. Anders, University of Michigan, 1957 (unpublished); and U. S. Atomic Energy Commission Report AECU-3513, April, 1957 (unpublished).

[5] O. M. Bilaniuk and P. V. C. Hough, Phys. Rev. **108**, 305 (1957).

[6] K. L. Hall, U. S. Atomic Energy Commission Report AECU-3126, 1955 (unpublished).

[7] W. A. Higinbotham and S. Rankowitz, Rev. Sci. Instr. **22**, 688 (1951).

TABLE I. Data on cyclotron targets.

	Zr	Mo	Ti	ZnS
Preparation[a]	foil	foil	foil	vacuum evaporation
Supplier	Foote Mineral Company	Fansteel Metallurgical Company	Titanium Corporation of America	Merck
Purity	99.89%(<0.1% Hf)	99.9%	~99.4%	reagent grade
Thickness (mg/cm²)	3.51±0.01	4.992±0.005	4.525±0.005	1.65±0.01
Evenness[b]	<2%	<3%	<3%	<1%
Substrate	1 mil Mylar	1 mil Mylar	1 mil Mylar	1 mil Mylar
Diameter (inches)	1.474±0.002	1.474±0.002	1.474±0.002	2.264±0.004

[a] The thin foils were rolled by the Arnold Engineering Company from thicker stock supplied by us.
[b] Standard deviation from perfect evenness.

action the targets were prepared by vacuum-evaporating zinc sulfide from a hot tungsten filament onto 0.001-inch thick Mylar substrate. With the use of collimators the target area of the zinc sulfide deposit could be defined precisely.

All targets were mounted on $\frac{1}{16}$-inch thick aluminum frames with circular openings of the same diameter as the target deposits. This prevented stray deuterons which did not penetrate the target from being collected in the Faraday cage.

The thickness of the foil targets was determined by weighing the foil disks with a micro balance before mounting. For the zinc sulfide the increase in weight of the target frame after the vacuum evaporation gave a measure of its thickness. The evenness of the target materials over the entire target area was measured with a beta thickness gauge described elsewhere.[8]

D. Chemical Separations[4]

Absolute disintegration rates of beta emitters can be measured directly by 4π beta counting, if proper precautions are taken to minimize inert bulk material and foreign activities in the counting samples. So called "carrier-free" chemical separation techniques were thus used for the purification of the (d,α)-reaction products yielding the desired activities in weightless form.

The irradiated target plus its Mylar substrate was first dissolved in a strongly acid oxidizing medium to obtain a homogeneous solution. The following separation steps were then used for individual elements.

1. Yttrium

The bulk of the zirconium was precipitated as hydroxide by addition of ammonia. The yttrium activity was then coprecipitated with calcium as the fluoride. The fluoride precipitate was converted to sulfate and the yttrium coprecipitated as the hydroxide with more zirconium. The precipitate was then dissolved in saturated hydrochloric acid solution and the yttrium activity separated in carrier-free form by passing the solution through a Dowex 2 anion exchange resin column. The yttrium passed through the column while the zirconium and niobium were adsorbed.

2. Niobium

The niobium was first coprecipitated as the hydroxide on 2 mg of aluminum carrier. After several dissolutions in hydrochloric acid and reprecipitations with ammonium hydroxide the precipitate was redissolved in saturated hydrochloric acid and then applied to a small column of Dowex 2 resin. After elution of the aluminum with $7M$ hydrochloric acid the niobium activity was eluted with $4M$ hydrochloric acid and recovered carrier-free.

3. Scandium

The scandium activity was first coprecipitated with titanium oxide and redissolved in hydrochloric acid. The titanium oxide was then reprecipitated homogeneously with sodium bicarbonate, leaving the scandium in solution. It was further purified by passing the solution saturated with hydrochloric acid and chlorine through a Dowex 2 column. The carrier-free scandium was finally collected as a radiocolloid from a 3% hydrogen peroxide solution that was $7M$ in ammonium hydroxide.

4. Phosphorus

The phosphorus activity was selectively adsorbed on a Dowex-50 ferric hydroxide column[9] and eluted with sodium hydroxide. The eluate was then passed through a Dowex-50 cation exchange column in the hydrogen state yielding the phosphorus activity in carrier-free form.

E. Tracer Determination of Radiochemical Yield

For measurement of the absolute yields of the nuclear reactions it was important to know the fraction of (d,α)-reaction product, formed in the bombardment, which was measured in the counting sample. It was thus necessary to determine the chemical yields of the carrier-free chemical separations. This was done by adding a known amount of carrier-free tracer to the solution in which the irradiated target was to be dissolved. The tracers used were long-lived radioactive isotopes of the same element as the (d,α) products.

[8] O. U. Anders and W. W. Meinke, Rev. Sci. Instr. 27, 416 (1956).

[9] L. D. McIsaac and A. Voigt, U. S. Atomic Energy Commission Report ISC-271, June, 1952 (unpublished).

They could be identified by their characteristic radiations and half-lives which in all but two cases differed from the studied reaction products themselves.

The tracers used were counted with the 4π counter shortly before the bombardment. The thin backing film with the tracer was then severed from the 4π-counting frame and carefully added to the solution in which the bombarded target was to be dissolved.

Homogeneous solutions resulted by treating the targets and tracer with strongly oxidizing, hot acid media. In the cases of zirconium and molybdenum hot concentrated sulfuric acid was used to which at times a few drops of nitric acid and 3% hydrogen peroxide were added until all the charred organic material was completely oxidized to yield a homogeneous solution.

In the case of the titanium targets the Mylar substrate was first dissolved by the above treatment and the titanium foil added after the hydrogen peroxide had been decomposed by heating. The zinc sulfide targets were first treated with a mixture of carbon tetrachloride, bromine and nitric acid to dissolve the zinc sulfide and oxidize the sulfide to sulfate. After this the Mylar substrate was dissolved in concentrated sulfuric acid, the terephthalic acid hydrolized, precipitated by dilution with water and redissolved in dilute sodium hydroxide.

Since complete isotopic exchange was thus obtained in all cases, the reaction products and the tracers followed the same chemical purification steps and could be counted and identified in the counting samples by their characteristic half-lives.

F. Absolute Counting[4]

Table II summarizes the pertinent nuclear data for the reaction products. For all but one reaction the absolute disintegration rates of the samples were determined directly by 4π beta counting. The counting samples were prepared by depositing aliquots of the carrier-free reaction product solutions onto gold-plated VYNS film of approximately 10 $\mu g/cm^2$ thickness.[10] After evaporation to dryness the samples were covered with a similar film before counting.

TABLE II. Pertinent nuclear data.[a]

Isotope	Half-life	Decay[b]	Energy (Mev)
Y^{88}	105 days	E.C.	0.016 (x ray)
Y^{90}	64.18 hr	β^-	2.26
Y^{92}	3.46 hr	β^-	1.3, 2.68, 3.6
Nb^{90}	14.6 hr	β^+	0.55, 0.86, 1.5
Nb^{92}	10.1 days	E.C.	0.0179 (x ray)
Nb^{95}	35 days	β^-	0.16
Nb^{95m}	84 hr	γ ($\sim$100% e^-)	0.217
Nb^{96}	23 hr	β^-	0.75, 0.37
Sc^{44}	4.10 hr	β^+; (also E.C.)	1.47
Sc^{44m}	2.44 days	γ ($\sim$12% e^-)	0.265
Sc^{46}	85 days	β^-	0.36
Sc^{47}	3.43 days	β^-	0.45, 0.61
Sc^{48}	1.83 days	β^-	0.64
P^{32}	14.22 days	β^-	1.71
P^{33}	24.2 days	β^-	0.25

[a] See reference 4.
[b] Most of these isotopes also emit γ rays.

Counting of the samples was carried out with two Borkowski-type 4π counters which were constructed for this purpose so as to have identical characteristics.[11] The two counters were operated as methane flow proportional counters with two Model 192X Ultrascalers (Nuclear Chicago) and found to be completely interchangeable. They yielded identical counting rates for long-lived standards and counted calibrated sources from the National Bureau of Standards within the calibration errors.

Counting plateaus of 1000 volts with slopes less than 0.2% per 100 volts were achieved with the counters. From these characteristics it could be assumed that 100% efficiency was closely approximated for carrier-free counting samples such as Y^{90} and P^{32}, emitting relatively energetic beta rays. When very weak beta rays had to be counted, small corrections were applied for self-absorption, which in no case introduced errors of more than 2% of the absolute count rates.

In the case of the $Zr^{90}(d,\alpha)Y^{88}$ reaction, the reaction product decayed mainly by electron capture with emission of characteristic x rays and absolute measurements with 4π counters were not feasible. The disintegration rates were determined here by coincidence counting.[12] A sample of carrier-free Y^{88} was prepared and its absolute disintegration rate determined by coincidence measurement of the 1.8- and 0.9-Mev gamma rays. Corrections were applied for chance coincidence and for the Compton contribution of the 1.9-Mev gamma rays in the range of the 0.9-Mev gamma peak.

This standard was then used to calibrate a 4-inch diameter x-ray proportional counter, filled with a 10:1 mixture of krypton-methane at 2 atmospheres pressure. This counter was found to have a sensitivity of 6.9% for the photopeak of the 14.1 kev K-x rays of strontium. An inherent error of approximately 8% was assumed for the absolute counting of Y^{88} with this "calibrated" x-ray counter.

Analysis of the decay curves from each bombardment was carried out by the standard "peeling off" technique. In the sulfur and molybdenum bombardments decay curves resulted which could not be completely resolved by this method due to the presence of two components having half-lives differing by less than a factor of 2. In these cases the method described by Freiling and Bunney[13] was used to resolve the two components. It is estimated that errors of not much more than 1% were inherent in the determination of the disintegration

[10] B. D. Pate and L. Yaffe, Can. J. Chem. **33**, 15 (1955).
[11] C. J. Borkowski and T. H. Handley, Oak Ridge National Laboratory Report ORNL-1056, 1951 (unpublished).
[12] J. L. Putman, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 835.
[13] E. C. Freiling and L. R. Bunney, Nucleonics **14**, 9, 112 (1956).

rates of the different components in the more favorable cases.

III. RESULTS[4]

A. Zirconium Bombardments

The cross sections obtained for the zirconium bombardments are summarized in Table III. Also included are the standard deviations estimated from a combination of the systematic errors in the measurements discussed above. The main source of error for these zirconium bombardments was the uncertainty of the chemical yield. This was primarily caused by the difficulties of counting the x rays of the long-lived Y^{88} tracer. The decay of the reaction products from the bombardments was followed with the 4π counters for many months and on the order of 200 points taken for each sample.

The absolute cross section for the (d,α) reaction yielding 64-hr Y^{90} with (7.56±0.05)-Mev deuterons was measured by two independent experiments with considerably better agreement than indicated by the estimated experimental errors. These two experiments constitute the only case where a double determination of the cross section was performed, but they may give some indication of the precision of this investigation.

The cross sections for the reaction $Zr^{94}(d,\alpha)Y^{92}$ were determined from the 3.46-hr Y^{92} components in the decay of the samples.

The energy dependence of the (d,α) cross section for deuteron energies below 7.56 Mev was determined by the stacked foil technique. Since a relative curve could be normalized to the absolute points, it was not necessary to determine absolute yields for every energy. This fact was verified by absolute determinations that were carried out for deuteron energies of 4.78 and 6.97 Mev.

The determination of the cross sections of the $Zr^{90}(d,\alpha)Y^{88}$ reaction, having as its product the long-lived (105-*d*) Y^{88}, required a long bombardment to produce sufficient yield for measuring. Four foils were bombarded by the stacked foil technique for 10 hours and then worked up as absolute samples. The targets were at first permitted to cool until all the 64-hr Y^{90} had decayed out. After this the chemical separation of Y^{88} was carried out and the yield traced with Y^{90} tracer. Finally the samples were counted with the x-ray counter over a period of several months. The relatively large standard errors quoted with the cross section values of this reaction are due mainly to the error inherent in the efficiency value for the x-ray counter.

B. Molybdenum Bombardments

The (d,α) reaction products from molybdenum include seven isotopes with 11 different activities although only those listed in Table II were observed in this investigation. Nb^{92} decaying by electron capture with a half-life of 10 days could be identified by the characteristic x rays with the x-ray spectrometer, but did not contribute sufficiently to the 4π beta decay curves to be resolvable. The 13-hour activity also reported for Nb^{92} could not be identified. By resolving the niobium beta-decay curve obtained with the 4π counters into only four components, any contribution by this 13-hr Nb^{92} would be added to the Nb^{90} component, decaying with a 14.6-hr half-period. Any contribution of the Nb^{92} was thus included in the calculations of the $Mo^{92}(d,\alpha)Nb^{90}$ cross section, making the reported value an upper limit for the (d,α) cross section for the Mo^{92} parent.

The chemical yield for these runs was traced with the most readily available niobium isotope, the 35-day Nb^{95}. Since Nb^{95} is produced in considerable quantity by the deuteron bombardment of molybdenum, tracing of the separation yield was done by difference. Two bombardments were required for this purpose. The first established the relative yield of Nb^{95} versus the other components of the decay curve, when no Nb^{95} tracer had been added. The second established the chemical yield in the following way. The amount of Nb^{95} produced during the bombardment was calculated from the ratio established by the previous experiment and the count rates of the other components, and subtracted from the total amount of Nb^{95} present in the counting sample. The difference was then due to the added tracer and was used to establish the chemical yield.

The cross section values obtained from the experiments are given in Table IV. The relatively large error for the $Mo^{97}(d,\alpha)Nb^{95m}$ reaction is mainly due to poor statistics. The value for the $Mo^{97}(d,\alpha)Nb^{95}$ reaction includes the $Mo^{97}(d,\alpha)Nb^{95m}$ reaction, since the isomer

TABLE III. Cross sections for the $Zr(d,\alpha)Y$ reactions.

Average deuteron energy (Mev)	σ (millibarns)
$Zr^{92}(d,\alpha)Y^{90}$	
7.56±0.05[a]	3.66 ± 7%
7.56±0.05[a]	3.72 ± 6%
7.56±0.05	3.79 ± 10%
6.97±0.08[a]	2.60 ± 7%
6.37±0.08	1.39 ± 10%
5.02±0.1	0.33 ± 10%
4.78±0.15[a]	0.197± 8%
3.89±0.2	0.045± 20%
2.48±0.3	0.008± 50%
$Zr^{94}(d,\alpha)Y^{92}$	
7.56±0.05[a]	3.90 ± 7%
7.56±0.05	4.3 ± 10%
6.97±0.08[a]	2.89 ± 7%
6.37±0.08	1.73 ± 10%
5.02±0.1	0.39 ± 10%
4.78±0.15[a]	0.329± 7%
3.89±0.2	0.035± 20%
2.48±0.3	0.000±100%
$Zr^{90}(d,\alpha)Y^{88}$	
7.56±0.1[a]	2.28 ± 12%
7.09±0.15[a]	1.63 ± 13%
5.2 ±0.6[a]	0.50 ± 20%
3.7 ±1.5[a]	0.00 ±100%

[a] Absolute experiments.

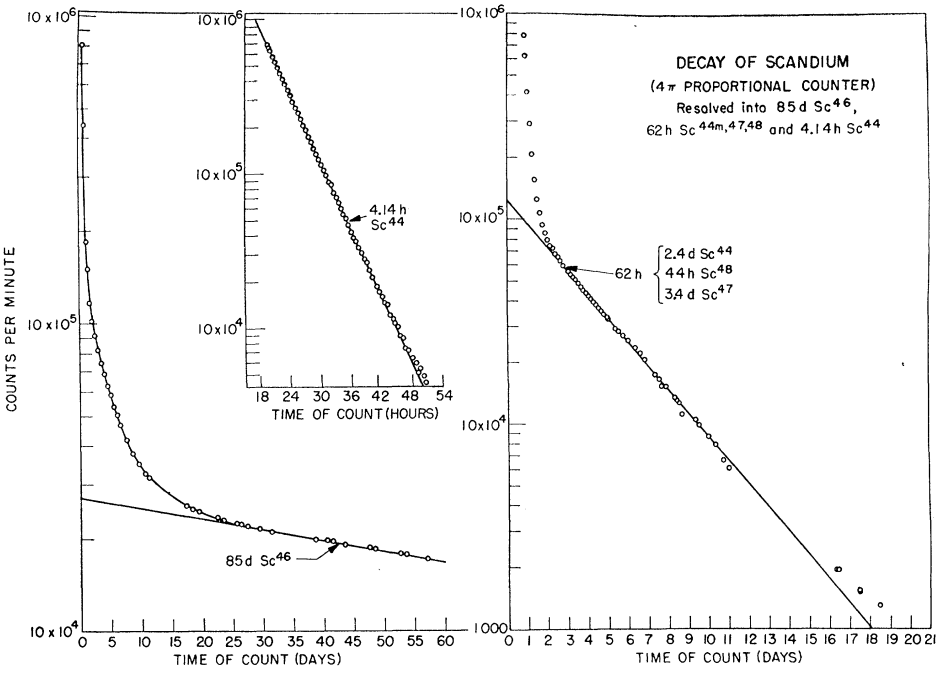

FIG. 1. Complex β-ray decay curve of Ti(d,α)Sc reaction products.

decays to the ground state and contributes somewhat to the total Nb^{95} resolved from the decay curve. Small corrections for self-absorption of the 0.16-Mev beta-rays emitted by Nb^{95} were applied to the counting data.

The excitation function for the $Mo^{97}(d,\alpha)Nb^{95}$ reaction was determined by the stacked foil technique. No tracers were employed for the yield evaluation, but strict conformity of the simultaneously performed radiochemical separations permitted a relative error limit of not more than about 5% for the chemical yields.

C. Ti(d,α)Sc Reactions

Although very good measurements were obtained for the decay curves of the Ti(d,α)Sc reaction products, resolution of the curves was only possible for the 85-day Sc^{46} and the 4.1-hr Sc^{44}. The combined components of Sc^{46}, Sc^{44m}, and Sc^{47} forming the 62-hr line seen in Fig. 1 could not be resolved into the three activities by the means available.

TABLE IV. Cross sections for the Mo(d,α)Nb reactions.

Average deuteron energy (Mev)		σ (millibarns)
	$Mo^{97}(d,\alpha)Nb^{95}$	
7.71±0.05[a]		2.35± 6%
7.54±0.05		2.3 ±10%
5.61±0.1		1.63±10%
3.82±0.25		0.65±20%
2.25±0.3		0.6 ±50%
	$Mo^{97}(d,\alpha)Nb^{95m}$	
7.71±0.05[a]		0.98±10%
	$Mo^{98}(d,\alpha)Nb^{96}$	
7.71±0.05[a]		2.53± 5%
	$Mo^{92}(d,\alpha)Nb^{90}$	
7.71±0.05[a]		2.95± 5%

[a] Absolute experiments.

The cross sections obtained from these bombardments are given in Table V. The value reported for the cross section of the (d,α) reaction of Ti^{46} is to be considered only a partial cross section value, since the amount of Sc^{44m} formed could not be measured and the simultaneous decay of the Sc^{44} by the electron-capture process was not considered in the calculations. Application of a correction for the latter effect would increase the value obtained for the (d,α) cross section by about 6±1%, while the relative yield of the $Ti^{46}(d,\alpha)Sc^{44m}$ reaction is estimated to be of the order of 5% of the $Ti^{46}(d,\alpha)Sc^{44}$ reaction.

The most readily available long-lived scandium isotope which could be used as tracer is the Sc^{46} with a half-life of 85 days. Since Sc^{46} was also produced by the reaction of deuterons on the titanium targets, a method similar to the one described for the case of the molybdenum bombardments had to be used for tracing the Ti(d,α)Sc reaction products. Self absorption corrections of 1% were applied for the Sc^{46} count rates.

D. $S^{34}(d,\alpha)P^{32}$ Reaction

The only available long-lived phosphorus activity other than P^{32} is P^{33}. It is formed in a nuclear reactor as a by-product of P^{32} production. To obtain sufficient P^{33} tracer for this experiment, a 10 mC P^{32} shipment was obtained from the Oak Ridge National Laboratory and allowed to decay for seven months. The relative abundance of P^{33} in this sample was thus increased to approximately 66%. Before use the phosphorus tracer

TABLE V. Cross sections for the Ti(d,α)Sc reactions.

Average deuteron energy (Mev)		σ (millibarns)
	$Ti^{48}(d,\alpha)Sc^{46}$	
7.71±0.05[a]		28.53±6%
	$Ti^{46}(d,\alpha)Sc^{44}$	
7.71±0.05[a]		52.39±5%

[a] Absolute experiment.

was purified by an adaptation of the radiochemical procedure outlined above.

The following method of tracing the chemical yield of the bombardment was used. Two samples of the P^{33}-P^{32} tracer mixture were prepared and counted with the 4π counter. One of the samples was used for tracing the bombardment, the other was preserved as a reference and followed in its decay. In both the tracer sample and the bombardment product the P^{33} component was resolved from the decay curve after corrections for self-absorption had been applied. The chemical yield of the separation was thus established. The amount of P^{32} added with the tracer P^{33} to the bombardment product was also determined.

Although the half-life of P^{32} had been experimentally checked during these investigations,[14] to prove the noninterference of the $S^{36}(d,\alpha n)P^{33}$ reaction, uncertainties in the "known" half-life of P^{33} made the decay curve analysis difficult. A half-life for P^{33} of 24.2 days seemed to fit the data best.

The excitation curve for this reaction was again determined by the stacked foil technique and chemical separations performed in parallel. The results are presented in Table VI.

IV. DISCUSSION

For the cases studied, the (d,α) reaction is the only one which could produce the observed activities except

TABLE VI. Cross sections for the S(d,α)P reactions.

Average deuteron energy (Mev)		σ (millibarns)
	$S^{34}(d,\alpha)P^{32}$	
7.73±0.05[a]		330.3± 7%
7.73±0.05		330 ±10%
6.55±0.1		126 ±10%
5.05±0.1		63 ±15%
3.15±0.3		39 ±20%
0.7 ±0.5		28 ±30%

[a] Absolute experiment.

[14] O. U. Anders and W. W. Meinke, Nucleonics **15**, 12, 68 (1957).

possibly the reaction $Ti^{49}(d,\alpha n)Sc^{46}$ ($Q=-3.9$ Mev) versus $Ti^{48}(d,\alpha)Sc^{46}$ ($Q=+4.2$ Mev). Reactions yielding the same products as the (d,α) reaction are the (d,Tp); (d,He^3n); ($d,2d$); (d,dpn), and ($d,2p2n$) reactions. The Q values of the most favored of these, the (d,Tp) reaction, lie at ~19.8 Mev below the values for the corresponding (d,α) reaction and thus could not occur for deuteron energies below 8 Mev in the cases studied.

Table VII lists the Q values for the reactions studied together with the cross sections found for 7.7-Mev deuterons. There exists little correlation between them and it appears that most of the variations in cross section can be accounted for by the height of the Coulomb barrier.

It may be significant that the cross section for the (d,α) reaction on Zr^{90} with a closed neutron shell and a closed proton $2p$ sub-shell is definitely lower than those of the (d,α) reactions on Zr^{92} and Zr^{94} for which the Coulomb barrier is the same.

TABLE VII. Q values of reactions studied.[a]

Reaction	σ (millibarns)	Q (Mev)
$S^{34}(d,\alpha)P^{32}$	330.3 ±23.1	+5.1
$Ti^{46}(d,\alpha)Sc^{44}$	52.4 ± 2.6	+4.2
$Ti^{48}(d,\alpha)Sc^{46}$	28.5 ± 1.7	+4.2
$Zr^{90}(d,\alpha)Y^{88}$	2.34± 0.28	+5.5
$Zr^{92}(d,\alpha)Y^{90}$	3.75± 0.26	+8.8
$Zr^{94}(d,\alpha)Y^{92}$	4.01± 0.28	+8.4
$Mo^{92}(d,\alpha)Nb^{90}$	2.95± 0.14	+7.9
$Mo^{97}(d,\alpha)Nb^{95}$	2.35± 0.14	+9.9
$Mo^{98}(d,\alpha)Nb^{96}$	2.53± 0.12	+8.5

[a] These values are based on the atomic mass compilation given by A. H. Wapstra, Physica **21**, 367 (1955).

The excitation function for the $S^{34}(d,\alpha)P^{32}$ reaction shows no threshold. It is suspected that there was some contribution of the $S^{32}(n,p)P^{32}$ reaction which has the same product. If such interference did occur it would add the same amount to the cross-section values at all measured energies.

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