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Radiation Laboratory
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INTERACTION OF HIGH ENERGY PROTONS AND ALPHA PARTICLES WITH IODINE-127

Inge-Maria Ladenbauer

Printed for the U.S. Atomic Energy Commission

INTERACTION OF HIGH ENERGY PROTONS AND ALPHA PARTICLES WITH IODINE-127

Contents

Abstract 3

I. Introduction 4

II. Experimental Procedures 4

1. Preparation of the target material 4

2. Target arrangement 5

3. Chemical separation procedures 5

a. Iodine purification 6

b. Tellurium purification 6

c. Antimony purification 6

d. Cesium purification 7

4. Sample mounting 8

III. Counting and Treatment of Data 8

1. Calculation of cross sections 8

2. Beta counting 9

3. Gamma-ray counting 9

4. Decay characteristics 11

IV. Results and Discussion 11

1. Reactions of the type (p,pxn) and (α,αxn) 18

2. Reactions which require the emission of pions 18

3. The production of several tellurium isotopes with masses other than 127 21

Acknowledgments 22

References 23

INTERACTION OF HIGH ENERGY PROTONS AND ALPHA PARTICLES WITH IODINE-127

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Radiation Laboratory
University of California, Berkeley, California

March 1958

ABSTRACT

Iodine was bombarded with protons ranging in energy from .25 to 6.2 Bev and with .25 to .72 Bev alpha particles. The cross sections for reactions of the type (p,pxn), (p,2pxn), $(p,p\pi^+)$, $(p,p2\pi^+)$, $(p,p2\pi^-)$ and the corresponding alpha reactions to produce various iodine and tellurium isotopes were measured.

The cross section for the formation of iodine-126 via the (p,pn) reaction is significantly higher than that of the (p,pxn) reactions to form iodine isotopes at all the incident proton energies. With the alpha particles bombardments a similar effect is noted for iodine-126 as compared to iodine-127 and iodine-125. Excitation functions for the production of iodine and tellurium isotopes, other than tellurium-127, decrease rapidly between .25 to 1 Bev and show only little change from 1 Bev to 6.2 Bev.

The upper limits for the cross sections of reactions to produce Sb^{127} and Cs^{127} were found to be .01 to .1 mb and for Te^{127} to be 1 to 2 mb.

*On leave from the 2nd Chemical Institute, University of Vienna, Austria.

INTERACTION OF HIGH ENERGY PROTONS AND ALPHA PARTICLES WITH IODINE-127

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University of California, Berkeley, California

March 1958

I. INTRODUCTION

The interaction of high energy protons and alpha particles with iodine to produce neighboring radioactive nuclides has been investigated in order to gain insight into the mechanism of high energy nuclear reactions. Iodine was chosen for this study because of the favorable decay characteristic of the products from a variety of relatively simple reactions e.g., $(p,p2\pi^-)$, (p,n), $(p,p\pi^+)$ and $(p,p2\pi^+)$ which result in no change in mass number, and (p,xn), (p,pxn) and $(p,2pxn)$ which result in a small change in mass number, in addition to similar reactions with alpha particles.

Unfortunately, a lack of time prevented the investigation of the (p,xn) reaction and (α,pxn) reactions to produce xenon nuclides.

The energy of the incident protons was in the range of 0.25 to 6.2 Bev from the 184-inch cyclotron and the bevatron. The energies of the alpha particles were .25, .50 and .72 Bev (184-inch cyclotron). The comparison of the cross sections of proton- and alpha-induced reactions at the same incident energy should provide clues as to the mechanism of energy transfer.

II. EXPERIMENTAL PROCEDURES

1. Preparation of the target material.

The targets were prepared from sheets of cellulose acetate containing known amounts of iodine in the form of iodoform. These sheets were prepared by dissolving the iodoform in a small amount of organic solvent and mixing this solution with Duco Cement. The mixture was poured on a glass disk, which had been lubricated with a small amount of silicone grease, and was pressed to the desired thickness with a second glass disk by its own weight. This film material, after being dried at room temperature, was relatively homogeneous both as to the iodine content and the thickness. The iodine content of the films, which were used as targets, was:

I. 41.34% Iodine . . . . . 34.42 mgI_2/cm^2
II. 42.97% Iodine . . . . . 18.42 mgI_2/cm^2
III. 23.19% Iodine . . . . . 15.27 mgI_2/cm^2
IV. 33.29% Iodine . . . . . 29.34 mgI_2/cm^2

The sheets with the highest iodine content were used at the bevatron. The accuracy of these values was about 3%.

In order to determine the loss of iodoform as a result of its volatility, films were put under vacuum for five hours. The iodine loss was about 1%. Since the duration of the exposures at the bevatron were of the order of 1 hour, the iodine loss from the films was negligible. The length of bombardments at the 184-inch cyclotron were from 30 seconds to one and a half minutes. In order to minimize the loss of iodine in the longer cyclotron bombardments, the beam was pulsed on and off at 5 second intervals.

Attempts to use polyethylene and paraffin as film materials were unsuccessful because of difficulty in destroying the film with fuming nitric acid in the first step of the chemical procedure.

2. Target arrangement.

The target consisted of a stack of foils in the following order: 1 mil aluminum, the iodine-containing foil, 1 mil aluminum, 3 mil aluminum monitor of known weight, and 1 mil aluminum. The beam passed through the foil in this sequence. The leading edge of the stack was machined down in order to insure that all foils receive the same beam exposure. For the cyclotron bombardment the stack was tightly covered with an additional 1 mil aluminum sheet in order to prevent loss of iodoform by heating of the target.

3. Chemical separation procedures.

After the bombardment the target was cut from the target holder. The 3 mil aluminum foil was separated and mounted for counting sodium-24 in the standard way. The cellulose-acetate iodoform foil was weighed and carefully dissolved in a few ml of fuming nitric acid. To prevent the loss of iodine, a reflux condenser may be used, although this is not necessary if care is exercised. Approximately 20 mg of tellurium carrier (as tellurate ion), 20 mg of antimony carrier (as $SbCl_3$), and tracer amounts of cesium-137 were added. Aliquots of the solution were taken for separate analysis of the cesium, iodine, tellurium,

and antimony-127 fraction. In later experiments all of the target material was used either for the analysis of the iodine fraction or for the analysis of all the other products.

a. Iodine purification:[1]

For the iodine analysis about 2 ml 0.5 M sodium nitrite solution and a volume of carbon tetrachloride equal to that of the tellurium fraction were added. The resulting iodate was reduced to elementary iodine with saturated sulfurous acid, added dropwise, and was then extracted into carbon-tetrachloride. This layer was treated with a solution of sodium bisulfite to reduce the iodine to iodide ion. The excess of sulfur dioxide was boiled off, and the iodine was oxydized in nitric acid solution with sodium nitrite to elementary iodine. This extraction was repeated for 3 times. After the last reduction, the sulfur dioxide was boiled off, and the iodide was precipitated from 1 M nitric acid solution with silver nitrate. After filtering and careful washing, the precipitate was dried, weighed and mounted for counting.

b. Tellurium purification:[2,3]

For the tellurium analysis the solution was evaporated to near dryness, with the addition of concentrated hydrochloric acid, to get rid of the nitric acid. This step was repeated 3 times. The residue was dissolved in concentrated hydrochloric acid and the tellurium was precipitated as the sulfide with hydrogen sulfide. The sulfide was centrifuged and the supernant liquid was kept for the antimony and cesium purification. After the tellurium sulfide was dissolved in boiling concentrated sulfuric acid and a few drops of perchloric acid, selenium carrier was added to the ice-cold hydrochloric solution. The selenium was precipitated with sulfur dioxide and was discarded. More selenium was added to the solution, and the precipitation was repeated. The solution was diluted to a 3 N concentration of hydrochloric acid and was boiled. Tellurium was then precipitated with sulfur dioxide. The tellurium was again dissolved, and the purification was repeated. Finally the tellurium was filtered, carefully washed, dried, weighed and mounted for counting.

c. Antimony purification:

For the antimony analysis the solution set aside in the tellurium procedure was diluted and hydrogen sulfide gas was passed in to precipitate antimony sulfide. The supernant solution was kept for the cesium purification. (The time of the separation was noted). The antimony sulfide was dissolved in concentrated hydrochloric acid. The solution was heated to boil off the hydrogen

sulfide and was diluted. The antimony was precipitated as the metal with chromous chloride. The sample was weighed after filtering, washing and drying. In about 32-36 hours the tellurium-127 activity growing in as the daughter of antimony-127, was essentially at its maximum value. The antimony and the filter paper were dissolved in red fuming nitric acid and a known amount of tellurium carrier was added. The tellurium procedure described above was applied again. The sample was weighed and mounted. The decay of the sample was followed on a beta proportional counter, connected to a traffic counter, for about 4 to 5 half-lives.

d. Cesium purification:[4]

The solution which remained after the precipitation of antimony sulfide was evaporated nearly to dryness for several times with concentrated hydrochloric acid. The residue was dissolved in 15 ml ice cold concentrated hydrochloric acid, which had been presaturated with hydrochloric gas. To the clear solution, which was being stirred vigorously, 5 drops of 0.4 M solution of silicotungstic acid were added. A white crystalline precipitate of silicotungstic acid was formed, which coprecipitated the tracer amounts of cesium and rubidium. After centrifugation, decantation and washing the precipitate was dissolved in a few drops of water (conductivity water) and was reprecipitated with 15 ml ice-cold concentrated hydrochloric acid. This procedure was repeated 6 times to separate cesium from rubidium. The latter separation must be very clean in order to remove rubidium nuclides with about the same half life as cesium-127. Finally the white precipitate was dissolved in 1 ml water. A column of Dowex-50 cation exchange resin with the approximate dimensions 4 cm x 0.5 cm, was previously prepared from 250 to 500 mesh resin in the ammonium form. The column was carefully washed with water. The 1 ml solution, which contains the cesium and possibly rubidium contamination was pipetted on top of the column and was passed through the column at a rate of 2 to 3 drops per minute. The column was washed with 2 ml water and with 1 ml 1 M hydrochloric acid in order to separate rubidium and cesium. The cesium was finally eluated with concentrated hydrochloric acid, 3 drops were collected on each of several platinum disks. The disks were dried under an infra-red lamp and were counted with the beta proportional counter. The platinum disk with the most activity was then counted for at least 5 half lives on the top shelf. With the procedure described here the best results were obtained. However, this procedure was not used at the beginning. This is the reason for some higher results in the first few experiments.

4. Sample mounting.

The precipitates were filtered with the aid of a filter chimney[5] having a diameter of approximately 19 mm. The precipitate was collected on a previously weighed filter paper of the corresponding size, placed on a sintered glass disk. The resulting area of the sample was about 2.7 to 2.8 cm^2. After washing, drying, and weighing the precipitate, the filter paper with the sample was placed on a double-sided scotch tape, which was centered on a standard aluminum sample holder. A plastic film with a thickness of 4.2 mg per cm^2 was placed over the sample and secured to the aluminum card with the aid of scotch tape. When the counting was completed some of the samples were given to the analytical group for chemical analysis. The latter determinations checked the original weighings very well.

III. COUNTING AND TREATMENT OF DATA

1. Calculation of cross sections.

For all the bombardments the cross section for the formation of any particular nuclide x is given by:

$$\sigma_x = \frac{A_{xo}\,(1 - e^{\lambda_{Al}\,t_B})\,F_{Al}\,N\,\sigma_{Al}}{A_{Al}o\,(1 - e^{-\lambda_x\,t_B})\,F_x}$$

In this equation,

A_{xo}: the activity of the given nuclide at the end of bombardment.

$A_{Al}o$: the activity of the beam monitor sodium-24 at the end of bombardment.

λ_{Al}, λ_x: the specific decay constants.

$$N = \frac{(\text{weight of Al/cm}^2) \cdot (\text{atomic weight of iodine})}{(\text{weight of iodine/cm}^2) \cdot (\text{atomic weight of aluminum})}$$

σ_{Al}: cross section for the reactions, $Al^{27}(p,3pn)Na^{24}$ and $Al^{27}(\alpha,4p3n)Na^{24}$.

$F = CY \cdot GF \cdot D \cdot ABS \cdot E$.

CY: chemical yield.

GF: geometry factor of the counter.

D: the number of particles being counted which are emitted per disintegration.

ABS: factor to correct for absorption of the radiation by the sample cover, added absorber (if any), air, and window of the counter.

E: counting efficiency.

F_{Al}: the coefficient CY, D, and E are equal to 1. For beta counting GF for Na^{24} and for x are essentially equal and are, therefore, not included. When the gamma activity of the unknown is being determined, GF for Na^{24} is included and is taken to be 0.458 (average of 3 counters) for the top shelf of the proportional counter, is determined by D. W. Barr.[6]

The activity of antimony-127 at the end of the bombardment is obtained from the 9.3 hour tellurium-127 daughter activity by the formula:

$$A_{Sb} = \frac{\lambda_{Sb} - \lambda_{Te}}{\lambda_{Sb}} \cdot \frac{A_{Te}}{e^{-\lambda_{Sb} t_y} - e^{-\lambda_{Te} t_y}} \cdot e^{-\lambda_{Sb} t_x}$$

where t_x: is the time after which the antimony was separated from the original solution.

t_y: is the time the tellurium was separated from the antimony fraction.

A_{Te}: is the tellurium activity at the time t_y.

2. Beta counting.

An end-window gas flow proportional counter described by D. W. Barr[7] was used to count electrons and positrons. The factor D was obtained from the decay scheme and is given below. The absorption correction was calculated from a curve of the absorption half thickness vs. energy for beta particles. The self-scattering, back-absorption, and self-absorption corrections were included in the geometry factor. When it was desired to eliminate conversion electron, a 3 mil aluminum absorber was used. Positron counting rates were multiplied by a factor of 1.12 to correct for the difference in back-scattering of positrons and electrons.

3. Gamma-ray counting.

A sodium iodide (thallium activated) crystal, 1.5 inches in diameter by 1 inch high, connected to a Penco 100-channel differential pulse height analyzer, was used for gamma-ray counting. The covering of the crystal was 3 mil aluminum (20 mg/cm^2) with magnesium oxide, equivalent to 1 mg/cm^2 aluminum, as a filler. The absorption correction from this source as well as the intervening air, the beryllium or steel absorbers which are used when counting positrons in order to produce annihilation radiation, and the sample covering was calculated from absorption coefficients given by Compton and Allison[8] and by Davisson and Evans.[9] Self-absorption in the sample itself was small and was, therefore, neglected. The geometry factor for the top shelf of the counter was measured to be 10.8%

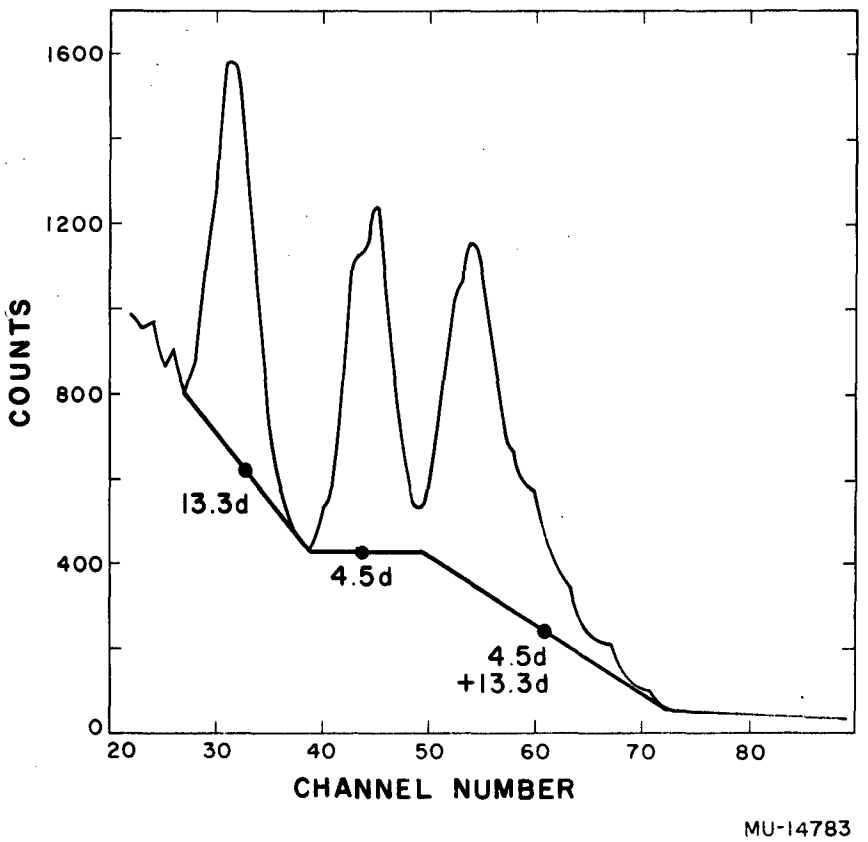

1600
1200
800
400
0
COUNTS
13.3d
4.5d
4.5d
+13.3d
20
30
40
50
60
70
80
CHANNEL NUMBER
MU-14783

Fig. 1

with an Am^{241} source, calibrated by alpha counting. In Fig. 1 is shown a typical gamma-ray spectrum of iodine activities several days after the end of the bombardment. The Compton background was obtained from the average of the counting rates on either side of the peak (indicated by a solid point) multiplied by the peak channel width.

4. Decay characteristics.

The factor, D, which is the number of a given type of particle emitted per disintegration, was calculated from the decay scheme if known. Otherwise, this factor was calculated theoretically. Thus the positron branching ratios of I^{120}, I^{121}, Te^{116}, and Te^{117} and their daughters were estimated by the method of P. R. Wiles on the assumption that only allowed beta transitions contribute significantly to the counting rate. Also the rate of electron capture by the L-shell to that by the K-shell for the isotopes of iodine other than 60 d I^{125} was calculated to be approximately 0.1, according to Brysk and Rose.[10] In the fourth column of Table I the values of the factor, D, are given for the nuclide listed in the first column and for the radiation listed in the second and third columns. The last column indicates the references used for calculating D.

The cross section of I^{120} was determined from the positron activity by means of beta-particle and gamma-ray counting minus the contribution of I^{121}. The contribution of the latter to the beta-particle counting is

$$\frac{.15 \times .458}{.92 \times .108 \times .62} \; A_o \; (.21 \text{ Mev } \gamma \text{ of } I^{121})$$

For gamma-ray counting this correction is

$$\frac{.15 \times 2 \times .165}{.92 \times .62} \; A_o \; (.21 \text{ Mev } \gamma \text{ of } I^{121}).$$

The values, .15 and .92, are obtained from Table I. The values, .458 and .108, are the geometry factors mentioned above. The photopeak counting efficiency for the 0.21 Mev γ is .62 and that of the two annihilation gamma rays is .165.

IV. RESULTS AND DISCUSSION

The experimental cross sections, listed in Tables II and III, are based on the cross section for the formation of sodium-24 from aluminum which is used as a beam monitor. The value at a proton energy of 250 Mev is 10.0 mb.[7] Within experimental error the cross section for higher energies is constant up to 6.2 Bev and is taken to be 10.5 mb.[7] The corresponding cross sections for alpha particle bombardment have been measured only to 380 Mev. The value at 250 Mev

Table I. The Number of Particles of a Given Type Emitted/Disintegration

Nuclide	Type of Radiation	Energy (Mev)	Particles or Photons per Disintegration (D)	Reference
13.3 d I^{126}	$\beta^{\pm}$	.39-1.25	0.453	12
	γ	.382	0.34	12
	x-ray	.028	0.40	12,10
60 d I^{125}	γ	.0355	1.39	12
	x-ray	.028		
4.5 d I^{124}	β^{+}	.7-2.2	~.30	12
	$\gamma_{annih.}$	.51	~.60	12
	x-ray	.028	0.54	12,10
13 h I^{123}	γ	.160	0.84*	12
	x-ray	.028	0.89	12,10
1.6 h I^{121}	β^{+}	1.2,4.0	0.15	11
	γ	.210	0.92	12
	x-ray	.028	0.71	12,10
1.6 h I^{120}	β^{+}	4.0	0.90	11
	$\gamma_{annih.}$	.51	1.80	11
9.3 h Te^{127}	β^{-}	.7	1.0	12
↑				
110 d Te^{127m}	β^{-}	.7	1.0	12
6 d Te^{118} ↓ 3.8 m Sb^{118}	β^{+}	3.1	0.8	11,12
2.5 h Te^{117}	β^{+}	2.5	0.65	11
3 h Te^{116} ↓ 15 m Sb^{116}	β^{+}	1.5,2.4	0.65	11,12
93 h Sb^{127}** ↓ 9.3 h Te^{127}	β^{-}	.7	1.0	12
6.2 h Cs^{127}		.7,1.1	0.05***	11,12

*This nuclide is assumed to populate the .160 Mev level completely.

**Tellurium-127 is separated from the parent activity in order to determine the cross-section of 93 h Sb^{127}.

***The limiting value given by reference 12 is smaller than the value calculated according to reference 11. The value listed here is a pure assumption.

Table II.* The Cross Sections in Millibarns for the Formation of Iodine Isotopes by High Energy Protons and Alpha Particles

Energy of Incident Protons or Alphas	I^{126}(13.3 d) (p,pn)	I^{125}(60 d) (p,p2n)	I^{124}(4.5 d) (p,p3n)	I^{123}(13 h) (p,p4n)	I^{121}(1.6 h) (p,p6n)	I^{120}(1.6 h) (p,p7n)
6.2 Bev	45.4 ± 4.7	14.38 ± 0.44	12.8 ± 2.5	10.3 ± 1.85	6.2 ± 0.6	3.9 ± 0.9
4 Bev	59.2 ± 11.4	21.4 ± 5.3	17.5 ± 5.7	15.8 ± 4.1	10.4 ± 1.2	6.2 ± 0.7
2 Bev	58.3 ± 6.7	19.5 ± 0.6	18.4 ± 6.7	15.0 ± 4.4	10.7 ± 1.5	7.0 ± 1.3
1 Bev	67.3 ± 12.7	17.9	16.7 ± 5.5	24.2 ± 6.2	17.0 ± 2.1	11.8 ± 3.3
720 Mev	56.4 ± 6.8	14.5 ± 4	19.1 ± 6.6	16.4 ± 4.1	12.8 ± 1	10.6 ± 1.9
500 Mev	62.4 ± 8.8	20 ± 0.3	25.8 ± 4.8	26.1 ± 6.3	25 ± 5.5	14.9 ± 0.6
250 Mev	79.5 ± 7.0	47.3 ± 4.3	49.7 ± 7.2	50.4 ± 11.0	59.4 ± 7.6	29.8 ± 4.8
	(α,αn)	(α,α2n)	(α,α3n)	(α,α4n)	(α,α6n)	(α,α7n)
720 Mev	46.6 ± 4.8	19.1	20.7 ± 5.1	30.3 ± 8.1	32.2	13.2 ± 2.8
500 Mev	69.2 ± 5.0	31.0	31.6 ± 10.1	46.3 ± 10.7	41.5	23.0 ± 4.1
250 Mev	82.9 ± 12.1	37.6	36.6 ± 10.1	73.4 ± 19.6	26.0	15.9 ± 4.4

*See note on bottom of Table III

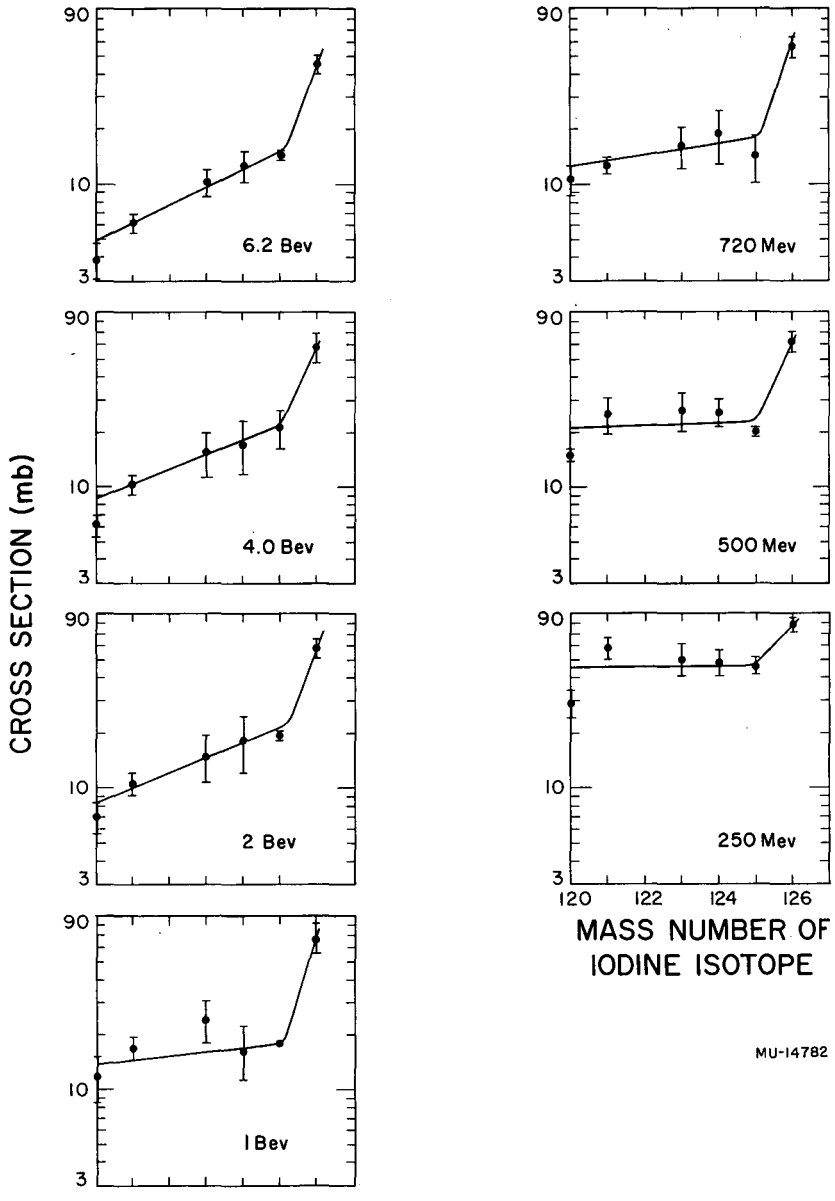

CROSS SECTION (mb)
90
10
3
6.2 Bev
4.0 Bev
2 Bev
1 Bev
720 Mev
500 Mev
250 Mev
120
122
124
126
MASS NUMBER OF
IODINE ISOTOPE
MU-14782

Fig. 2.

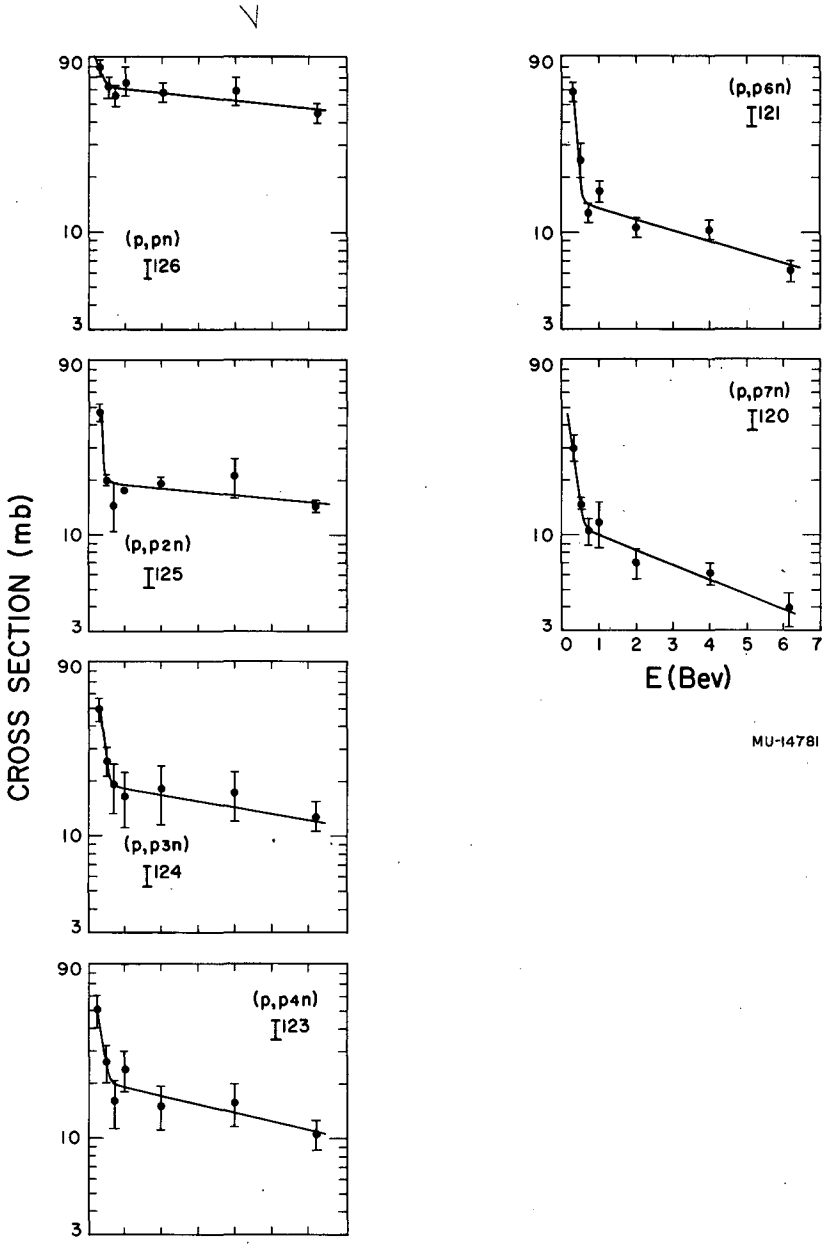

CROSS SECTION (mb)
90
10
3
(p,pn)
I126
(p,p2n)
I125
(p,p3n)
I124
(p,p4n)
I123
(p,p6n)
I121
(p,p7n)
I120
0 1 2 3 4 5 6 7
E (Bev)
MU-14781

Fig. 3.

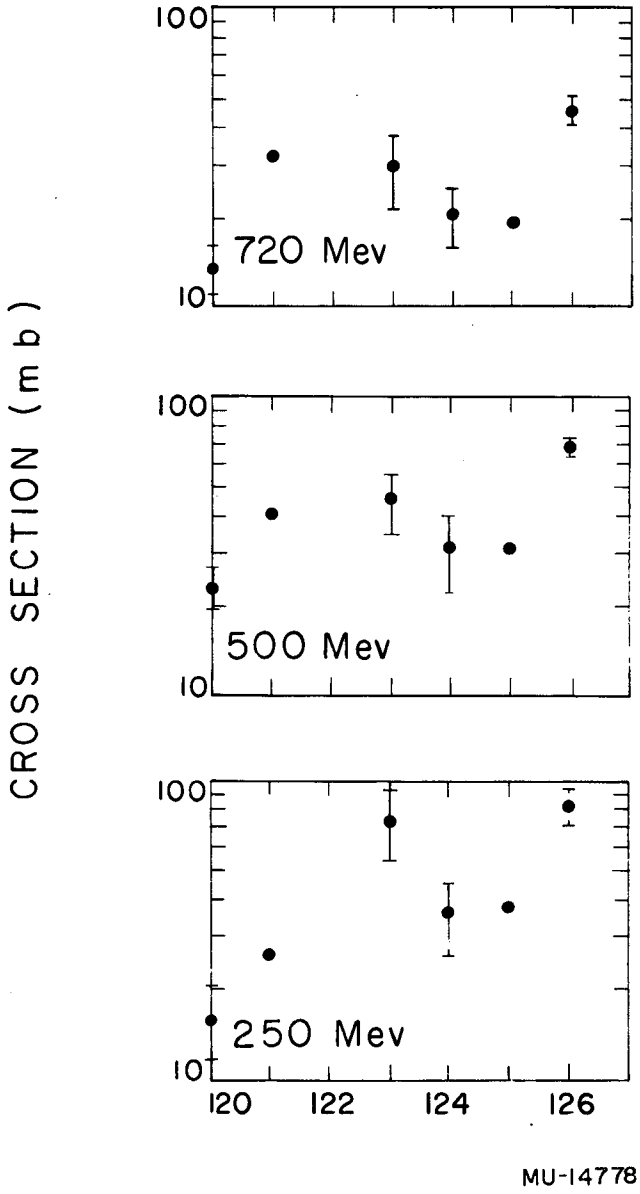

CROSS SECTION (mb)
100
10
720 Mev
500 Mev
250 Mev
120
122
124
126
MU-14778

Fig. 4.

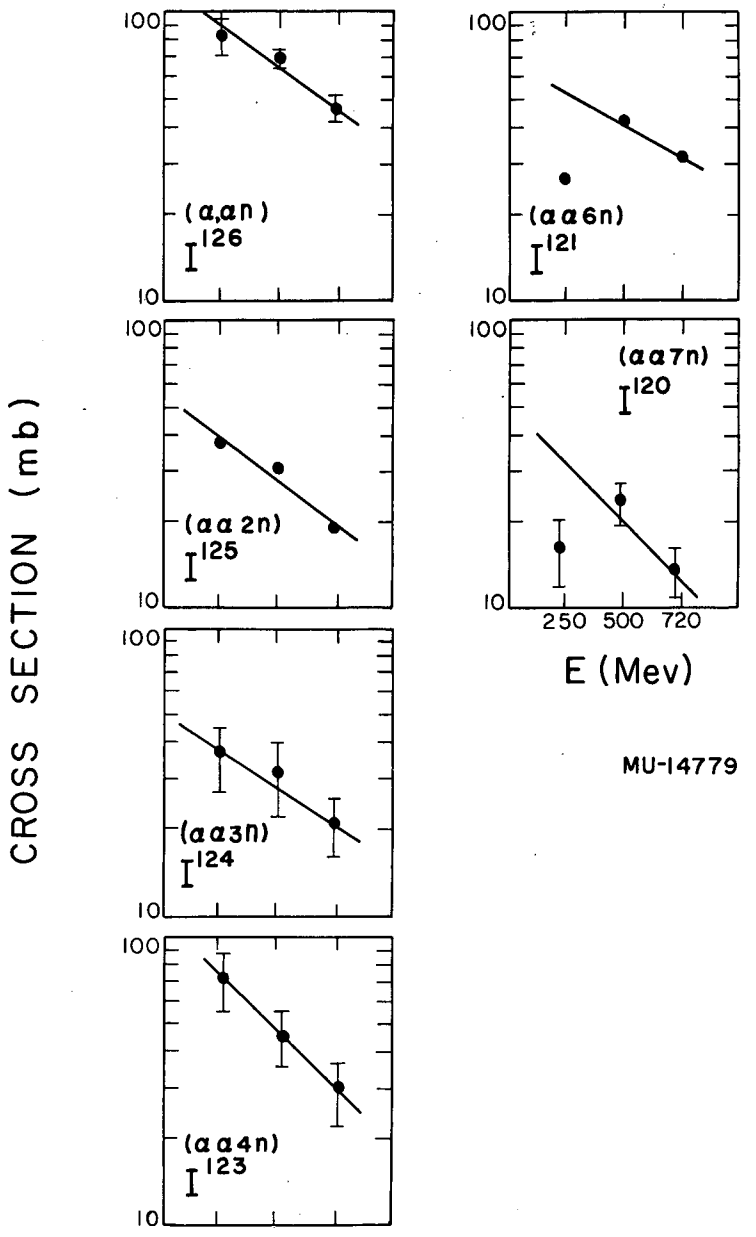

CROSS SECTION (mb)
100
10
(α,αn)
I126
(αα6n)
I121
(αα2n)
I125
(αα7n)
I120
(αα3n)
I124
(αα4n)
I123
250 500 720
E (Mev)
MU-14779

Fig. 5.

is 27 mb, and at 500 Mev and at 720 Mev it is taken to be 22 and 16 mb respectively as obtained by extrapolation.[13]

The overall experimental accuracy of the measurements, including the mean deviations given in Tables II and III, is approximately ±25% for those nuclides with known decay schemes and for the incident energies at which the monitor cross section has been measured. The accuracy of the other cross sections is not known. There is an additional uncertainty in the alpha-particle bombardments because only one experiment was made at each energy. The cross sections for the formation of the iodine isotopes are plotted in Fig. 2 and 4 as a function of the mass number of the product. The excitation functions for the formation of iodine and tellurium isotopes are shown in Figs. 3, 5, and 6.

1. Reactions of the type (p,pxn) and (α,αxn).

In Fig. 1 it is seen that the cross section for the formation of iodine-126 is significantly higher than that of the other iodine isotopes at all of the incident proton energies studied. With the alpha-particle bombardments a similar effect is noted for iodine-126 as compared to iodine-124 and iodine-125, Fig. 3.

The excitation functions for the formation of iodine-126 by proton bombardment drops a small amount between 250 Mev and 500 Mev, but within experimental error remains constant from 270 Mev to 4 and perhaps even 6 Bev, Fig. 3 and Table II. D. Nethaway[14] observed that the cross section for the $In^{115}(p,pn)In^{114m}$ reaction is also relatively constant from 200 to 6.2 Bev. The work of S. S. Markowitz[15] and A. Caretto and G. Friedlander[16] confirms this general behavior of (p,pn) reactions for various other targets.

The drop in cross section between 250 and 500 Mev incident proton energy for the other iodine isotopes is larger, being a factor of approximately two. The fall-off in the excitation functions above this energy is larger for the lighter iodine masses, Fig. 3.

The higher cross sections for the formation of iodine isotopes of mass 122 and 123 in the alpha-particle bombardments, as compared to those of masses 124 and 125, may be due to (α,pxn) reactions to form xenon isotopes, followed by decay to the iodine daughter activities.

2. Reactions which require the emission of pions.

The production of tellurium-127 directly from iodine-127 requires the loss of one unit of nuclear charge without a change in mass. The simplest reaction of this type is $(p,p\pi^+)$ and requires that the incident proton energy be sufficient to produce a pion. Unfortunately, the yield of tellurium-127 is

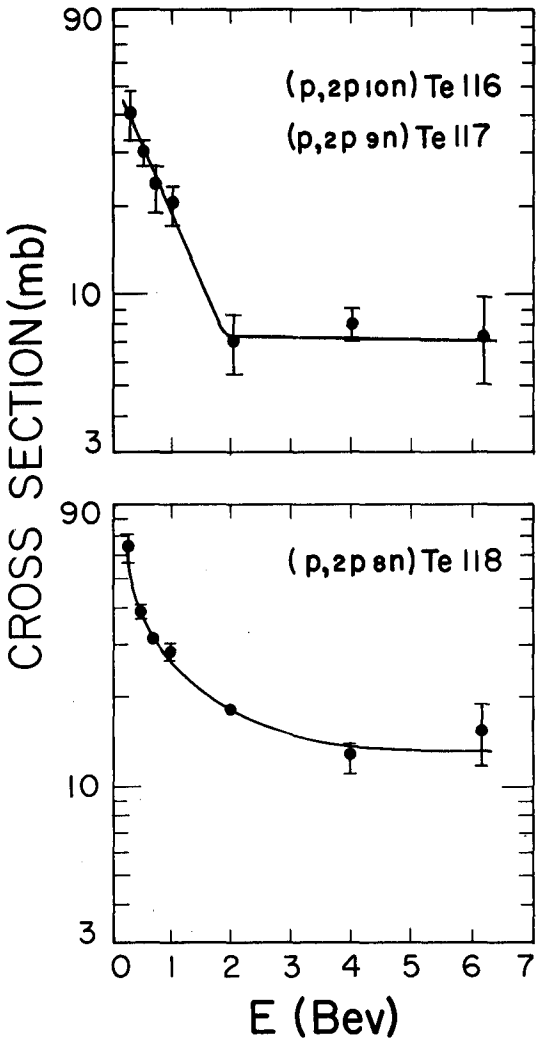
Table III.* The Cross Sections in Millibarns for the Formation of Antimony-127, Cesium-127, and Tellurium Isotopes by High Energy Protons

Energy of Incident Protons	Te^{116}+Te^{117}(2.75 h) (0,2p9n) + (p,2p10n)	Te^{118}(6 d) (p,2p8n)	Te^{127}(9.3 h)** (p,pπ^+)	Te^{127}(110 d)** (p,pπ^+)	Sb^{127}(93 h) (p,p2π^+)	Cs^{127}(6.2 h) (p,p2π^-)***
6.2 Bev	7.44 ± 2.4	15.4 ± 3.7	1.32 ± 0.16	.41	<.009,.123,.009	<.30,.66,16
4 Bev	8.0 ± .7	12.7 ± .8	.39	--	<.43	<.074
2 Bev	7.0 ± 1.5	18.1	2.56 ± 1.08	.65	<.019	--
1 Bev	20.2 ± 3.0	28.5 ± 1	1.19 ± .7	.118	<.009	--
720 Mev	23.6 ± 4.0	31.1	2.58 ± 1.12	.608 ± .237	<.014,.032	<.015,.062
500 Mev	30.6 ± 2.8	38.7 ± 1.8	1.71 ± .27	.059 ± .007	<.10,.22	<.045
250 Mev	40.2 ± 7.8	64.5 ± 6.6	1.5 ± .52	.47 ± .44	<.010,.051	<.025,.028

*The values following the ± signs are the mean deviation from the mean in the cases where more than one determination of the cross section has been made. On the second line of Tables II and III and the tenth line of Table II are indicated one of several possible reactions to produce the given product.

**These values are probably upper limits because of the difficulty of resolving the decay curves and because of possible contamination from secondary (n,p) reactions.

***The limits for Cs^{127} are based on an assumed value of 0.05 for D (Table I).



MU-14780

Fig. 6

small relative to that of the other tellurium isotopes. It was, therefore, not possible to resolve the tellurium decay curves with sufficient accuracy to get a reliable value for the $(p,p\pi^+)$ cross section. In addition, there is a possibility of contamination from secondary (n,p) reactions. Thus, the cross sections which are given in Table III for this reaction are probably only upper limits. This is confirmed by the value at 250 Mev, which is in essential agreement with the others, since the $(p,p\pi^+)$ reaction is not possible at this energy.

The production of antimony-127 from iodine-127 requires the loss of two units of nuclear charge. Since the cross section for this reaction is expected to be very low in comparison to that of the other antimony isotopes, it is necessary to purify the antimony fraction first and then, after sufficient time has elapsed, separate the daughter tellurium-127 activity. Because of the low counting rates which were obtained and the possibility of contamination, the values which are listed for this reaction in Table III are also to be considered only as upper limits to the correct value.

The production of cesium-127 requires a gain of two units of nuclear charge. The values for the cross section to form this nuclide, listed in Table III, are based on the assumption that the branching ratio for beta decay is 0.05. For the same reasons given in the case of antimony-127, the values in Table III are only upper limits.

3. <u>The production of several tellurium isotopes with masses other than 127.</u>

The half-lives of the tellurium isotopes with mass 116 and 117 are reported as being 3 and 2.5 hours, respectively. Since these activities were measured only on beta proportional counters, the decay curves could not be resolved into these two components separately. The sum of the two cross sections is therefore, given in Table III. The excitation functions for these two tellurium isotopes and for tellurium-118 are shown in Fig. 6. In general, they resemble those of other reactions in which a similar number of nucleons are emitted, as a result of bombardment by high energy protons.

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Figure Captions

Page

-10- Fig. 1 Typical gamma spectrum of 5.4 d I^{124}, indicating the presence of annihilation radiation (510 kev) and 600 kev gamma radiation, and 13.3 d I^{126} with 380 kev and 650 kev gamma radiation.

-14- Fig. 2 Cross sections for the formation of iodine isotopes from bombardment of iodine-127 by protons of different energies as a function of the mass number.

-15- Fig. 3 Excitation functions of iodine isotopes from proton bombardment of iodine-127. The symbol (p,pxn) represents one of several possible reactions which result in the given product.

-16- Fig. 4 Cross sections for the formation of iodine isotopes from bombardment of iodine-127 by alpha particles of different energies as a function of the mass number.

-17- Fig. 5 Excitation functions of iodine isotopes from alpha-particle bombardment of iodine-127. The symbol (α,αxn) represents one of several possible reactions which result in the given product.

-20- Fig. 6 Excitation functions of tellurium isotopes from proton bombardment of iodine-127. The symbol (p,2pxn) represents one of several possible reactions which result in the given product.