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ABSTRACT

Iodine was bombarded with protons ranging in energy from 0.25 to 6.2 Bev and with 0.25-, 0.50-, and 0.72-Bev alpha particles. Reactions of the type (p,pxn), (p,2pxn), $(p,p\pi^+)$, $(p,p2\pi^+)$, $(p,n\pi^-)$, and $(\alpha,\alpha xn)$ to produce iodine, tellurium, antimony, and cesium isotopes were investigated. Upper limits in the range 0.01 to 0.1 mb were found for cross sections of reactions to produce Sb^{127} and Cs^{127}. For Te^{127}, upper limits in the range of 1 to 2 mb were found. This and other studies of reactions in which the product has the same mass number as that of the target are discussed in terms of the initial interaction. At all incident energies studied, the cross section for the formation of I^{126} via the (p,pn) or $(\alpha,\alpha n)$ reaction is significantly higher than that of the other (p,pxn) or $(\alpha,\alpha xn)$ reactions, with the possible exception of $(\alpha,\alpha 4n)$. [illegible] ([illegible]). The (p,pn) and probably the $(\alpha,\alpha n)$ reactions appear to be due primarily to knock-on collisions with surface neutrons. The excitation functions for the production of iodine isotopes by proton bombardment decrease between 0.25 and 0.72 Bev but remain relatively constant for higher energies. The (p,2pxn) reactions show a similar effect, but with the excitation functions becoming constant at about 2 Bev. These results are compared with Monte Carlo calculations of the proton-initiated nucleon cascade and of the subsequent evaporation of light particles.

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INTRODUCTION

The interaction of high-energy particles with nuclei is only poorly understood, despite a large amount of work on this problem.[1] The study of the reactions that least damage the target nucleus affords a hopeful means for progress towards a better understanding. We report here an investigation of this type on iodine under proton and alpha-particle bombardment. Iodine was chosen because of the favorable decay characteristics of the products from a variety of relatively simple reactions, e.g. $(p,n\pi^-)$, (p,n), $(p,p\pi^+)$, and $(p,p2\pi^+)$ which result in no change in mass number, (p,xn), (p,pxn), and $(p,2pxn)$, which result in a small change in mass number, and similar reactions with alpha particles. The comparison of the cross sections of proton- and alpha-induced reactions at the same incident energy is expected to provide further clues as to the mechanism of these reactions.

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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 0.25-, 0.50-, and 0.72-Bev (184-inch cyclotron). A lack of time prevented the investigation of the (p,xn) reactions and the (α,pxn) reactions to produce xenon nuclides.

The results of this work are first discussed in terms of the initial interaction. The subsequent processes that cause the escape of a few more particles are then considered. Some proton-induced reactions with indium are analyzed in greater detail in a subsequent paper.[2]

EXPERIMENTAL PROCEDURES[3]

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 lubricated glass disk by its own weight. This film material, after being dried at room temperature, was relatively homogeneous both as to iodine content and thickness. The iodine content of the films, which were used as targets, was roughly one-third by weight (15 to 35 mg I/cm^2).

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

After the bombardment, the target was cut from the target holder. The 3-mil aluminum foil was separated and mounted for counting Na^{24} to monitor the beam. The cellulose-acetate iodoform film was weighed and carefully dissolved in a few ml of fuming nitric acid. Approximately 20 mg of tellurium carrier (as tellurate ion), 20 mg of antimony carrier (as $SbCl_3$), and tracer amounts of Cs^{137} were added. Standard radiochemical separations were performed to obtain each element and its radioisotopes in pure form suitable for counting.[3-6] The cross-section determination of Sb^{127} was made by separating any Te^{127} that had grown into the purified antimony fraction after 32 to 36 hr.

An end-window gas-flow proportional counter was used to count electrons and positrons. A sodium-iodide (thallium-activated) crystal, 1.5 in. in diam. by 1-in. high, connected to a multi-channel differential pulse-height analyzer was used for gamma-ray counting. The number of a given type of particle emitted per disintegration shown in Table I was calculated from the decay scheme if known.[7] The value of this number listed for 6.2 h Cs^{127} is for the proportional counter and was determined by bombarding barium iodide with ≈ 40-Mev alpha particles and counting the purified cesium fraction on both types of detectors. The disintegration rate was determined from the x-ray and gamma-ray activities. When the decay scheme was not known 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 Wiles on the assumption that only

Table I

Number of particles of a given type emitted per disintegration

Nuclide	Type of radiation	Energy (Mev)	Particles or photons per disintegration
13.3 d I^{126}	β^+	0.39-1.25	0.453
	γ	0.382	0.34
	x-ray	0.028	0.40
60 d I^{125}	γ	0.0355	1.39
	x-ray	0.028	
4.5 d I^{124}	β^+	0.7-2.2	~0.30
	γ annih	0.51	~0.60
	x-ray	0.028	0.54
13 h I^{123}	γ	0.160	0.84[a]
	x-ray	0.028	0.89
1.6 h I^{121}	β^+	1.2,4.0	0.15
	γ	0.210	0.92
	x-ray	0.028	0.71
1.6 h I^{120}	β^+	4.0	0.90
	γ annih	0.51	1.80
110 d Te^{127m}	β^-	0.7	1.0
↓ 9.3 h Te^{127}	β^-	0.7	1.0
6 d Te^{118} ↓ 3.8 m Sb^{118}	β^+	3.1	0.8
2.5 h Te^{117}	β^+	2.5	0.65
3 h Te^{116} ↓ 15 m Sb^{116}	β^+	1.5,2.4	0.65
93 h Sb^{127} [b] ↓ 9.3 h Te^{127}	β^-	0.7	1.0
6.2 h Cs^{127}	β^+, etc.	0.7,1.1, etc.	0.28

[a] This nuclide is assumed to populate the 0.160-Mev level completely.

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

allowed beta transitions contribute significantly to the counting rate.[8] Also the ratio 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.[9] The value, 0.23, for I^{125} has been determined directly.[7]

The cross section of I^{120} was calculated from the positron activity, as determined by beta-particle and gamma-ray counting, by subtracting the contribution of I^{121}. The latter was estimated from the activity of the 0.21-Mev gamma ray. Because of the difficulty of resolving the decay of the x-ray activity, it was not possible to obtain an additional value for the cross section of I^{121}.

The experimental cross sections are based on previously determined values for the formation of Na^{24} from aluminum, which is used as a beam monitor.[10] The value at a proton energy of 250 Mev is 10.0 mb. Within experimental error, the cross section for higher energies is constant up to 6.2 Bev and is taken to be 10.5 mb. The corresponding cross sections for alpha particle bombardment have been measured only to 380 Mev. The value at 250 Mev is 27 mb.[11] At 500 Mev it is taken to be 22 mb and at 720 Mev, 16 mb, as obtained by extrapolation.

RESULTS

In Table II are listed the cross sections for formation of the iodine isotopes, as determined by measuring various types of radiation. In Table III are given the cross sections for the formation of isotopes of tellurium, antimony, and cesium by proton bombardments. The cross sections for the iodine isotopes are plotted in Figs. 1 and 2 as a function of the mass number of the product. The excitation functions for the iodine and tellurium isotopes from proton bombardment are shown in Figs. 3 and 4.

The over-all experimental accuracy of the measurements, including the mean deviations given in Table III, and Figs. 1 to 4, is approximately ± 25% for those nuclides with known decay schemes and for the incident energies at which the monitor cross section has been measured. Where only one measurement was made, no value for the mean deviation is indicated. 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. Furthermore, there is uncertainty about the half lives, and hence the cross sections, of Te^{116} and Te^{117}. No mass assignments are given for the short-lived neutron-deficient tellurium isotopes in reference 7. The half-life assignments used here,[12] namely, $\approx$ 3 hr for mass 116 and 2.5 hr for mass 117, are so close in value that no attempt was made to resolve the decay curves into these two components separately. The sum of the two cross sections is, therefore, given in Table III.

The reason for the consistent lack of agreement in the cross-section values for I^{123} from the x-ray and gamma-ray measurements in Table II is not known.

Table II

Cross sections in millibarns for the formation of iodine isotopes by high-energy protons and alpha particles as determined by counting various types of radiation[a]

Particle Energy (Bev)	Type of Radiation[b]	I^{126} (p,pn)	I^{125} (p,p2n)	I^{124} (p,p3n)	I^{123} (p,p4n)	I^{121} (p,p6n)	I^{120} (p,p7n)
p 0.25	x	75.9	49.5	46.0	41.2		
	γ	87.6			61.4	59.4	
	β^+			44.7			30.1
	β	78.2		60.5			29.5
	Av.	80.6	49.5	50.4	51.3	59.4	29.8
p 0.50	x	66.2	20.9	17.7	20.8		
	γ	69.2			32.4	25.0	
	β^+			24.4			14.1
	β	54.6		31.8			15.3
	Av.	63.3	20.9	24.6	26.6	25.0	14.7
p 0.72	x	58.9	15.2	11.0	14.2		
	γ	58.2			19.2	12.8	
	β^+			17.5			8.9
	β	46.7		29.1			12.3
	Av.	54.6	15.2	19.2	16.7	12.8	10.6
p 1.0	x	49.5	18.7	12.1	15.6		
	γ	81.8			28.9	17.0	
	β^+			18.3			13.4
	β	72.8		20.6			8.7
	Av.	68.0	18.7	17.0	22.2	17.0	11.0
p 2.0	x	68.4	20.4	15.1	11.8		
	γ	50.6			18.8	10.8	
	β^+			17.0			7.4
	β	59.0		22.8			6.6
	Av.	59.3	20.4	18.3	15.3	10.8	7.0

(continued)

Table II (continued)

Particle Energy (Bev)	Type of Radiation[b]	I^{126} (p,pn)	I^{125} (p,p2n)	I^{124} (p,p3n)	I^{123} (p,p4n)	I^{121} (p,p6n)	I^{120} (p,p7n)
p 4.0	x	51.0	22.4	14.9	12.2		
	γ	68.6			19.9	10.4	
	β^+			16.3			6.2
	β	60.3		20.7			6.5
	Av.	60.6	22.4	17.3	16.1	10.4	6.3
p 6.2	x	41.7	15.0	16.9	8.6		
	γ	49.4			12.4	6.2	
	β^+			12.5			3.4
	β	47.0		9.5			4.3
	Av.	46.0	15.0	13.0	10.5	6.2	3.9
		(α,αn)	(α,α2n)	(α,α3n)	(α,α4n)	(α,α6n)	(α,α7n)
α 0.25	x	105.6	39.3	26.6	56.3		
	γ	78			93.0	26.0	
	β^+			32.9			11.5
	β	69.6		51.8			20.3
	Av.	84.4	39.3	37.1	74.6	26.0	15.9
α 0.50	x	80.2	32.4	48.8	37.2		
	γ	68.1			57.0	41.5	
	β^+			30.6			27.1
	β	62.7		17.4			19.9
	Av.	70.3	32.4	32.3	47.1	41.5	23.0
α 0.72	x	56.4	20.0	14.6	23.3		
	γ	45.2			38.4	32.2	
	β^+			19.8			16.0
	β	40.8		28.3			11.4
	Av.	47.5	20.0	20.9	30.8	32.2	13.7

[a] The symbols inside the parentheses indicate one of the possible reactions to produce the given product.

[b] x - by x-ray counting, γ - by counting γ-ray given in Table I, β^+ - by counting annihilation radiation, β - by counting positrons with proportional counter, av. - average value of cross section.

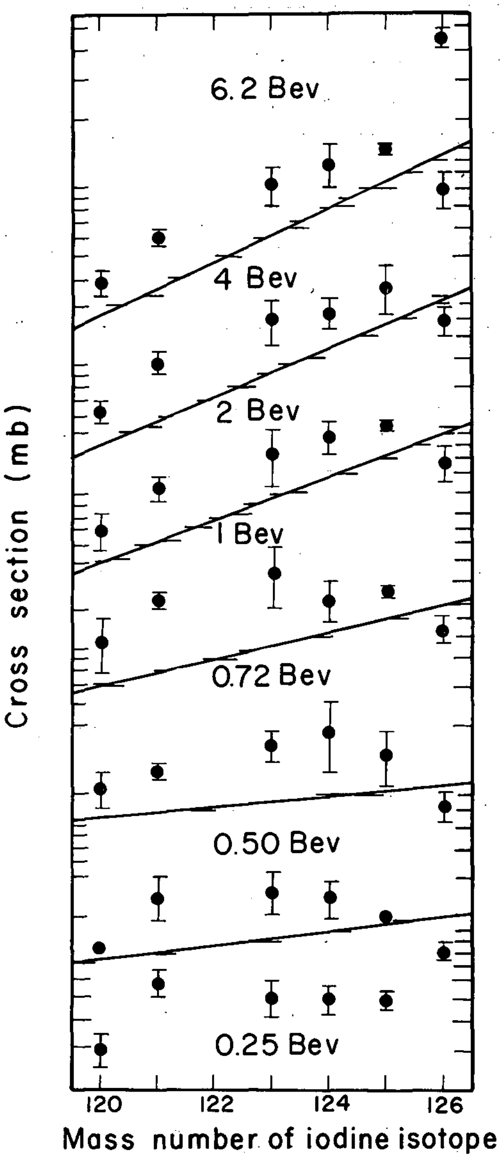
Table III

Cross sections in millibarns for the formation of antimony-127, cesium-127, and tellurium isotopes by high-energy protons[a]

Energy (Bev)	$Te^{116+117}$ (p,2p9n) + (p,2p10n)	Te^{118} (p,2p8n)	Te^{127}[b] $(p,p\pi^+)$	Te^{127m}[b] $(p,p\pi^+)$	Sb^{127} $(p,p2\pi^+)$	Cs^{127} $(p,n\pi^-)$
0.25	40.2 ± 7.8	64.5 ± 6.6	<1.5 ± .5	<0.5 ± .4	<0.010, < .05	<0.004, <0.005
0.50	30.6 ± 2.8	38.7 ± 1.8	<1.7 ± .3	<0.06 ± .01	<0.10, < .2	<0.008
0.72	23.6 ± 4.0	31.1	<2.6 ± 1.1	<0.6 ± .2	<0.014, < .03	<0.003, <0.011
1.0	20.2 ± 3.0	28.5 ± 1.0	<1.2 ± .7	<0.1	<0.009	---
2.0	7.0 ± 1.5	18.1	<2.6 ± 1.1	<0.6	<0.019	---
4.0	8.0 ± .7	12.7 ± .8	<0.4	---	<0.4	<0.013
6.2	7.4 ± 2.4	15.4 ± 3.7	<1.3 ± .2	<0.4	<0.009, <0.009, <0.12	<0.03, <0.05, <0.11

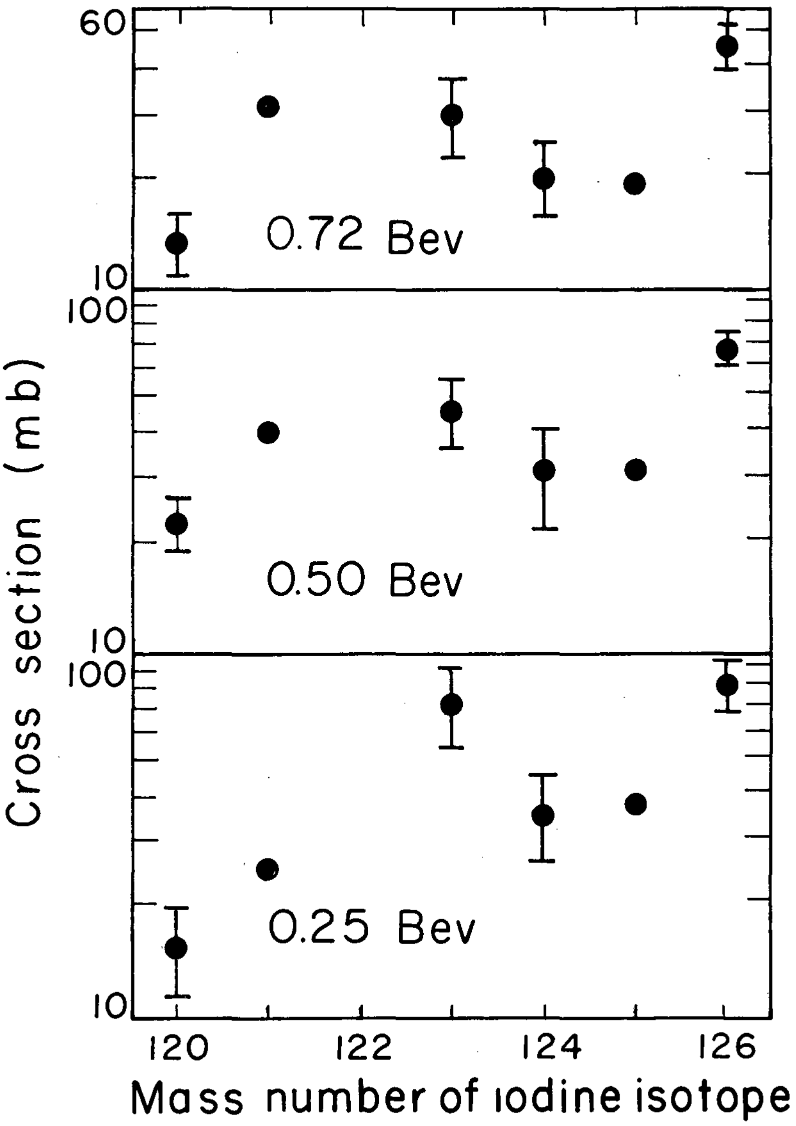
[a] The values following the ± signs are the mean deviation from the mean in the cases where more than one determination of the cross section has been made. The symbols inside the parentheses indicate one of the possible reactions to produce the given product.

[b] 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.



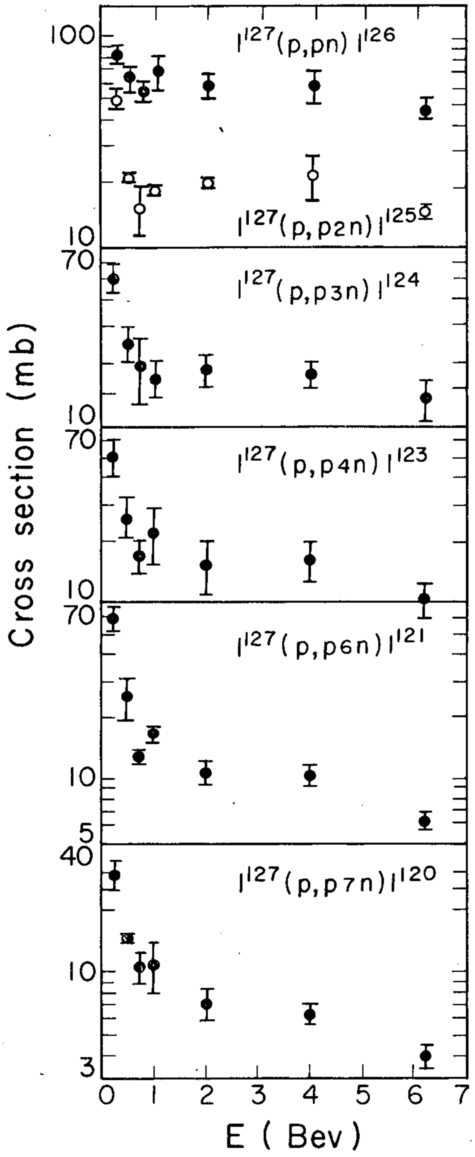
MU-18573

Fig. 1. Cross sections for the formation of iodine isotopes by bombardment of I^{127} with protons of different energies as a function of the mass number.



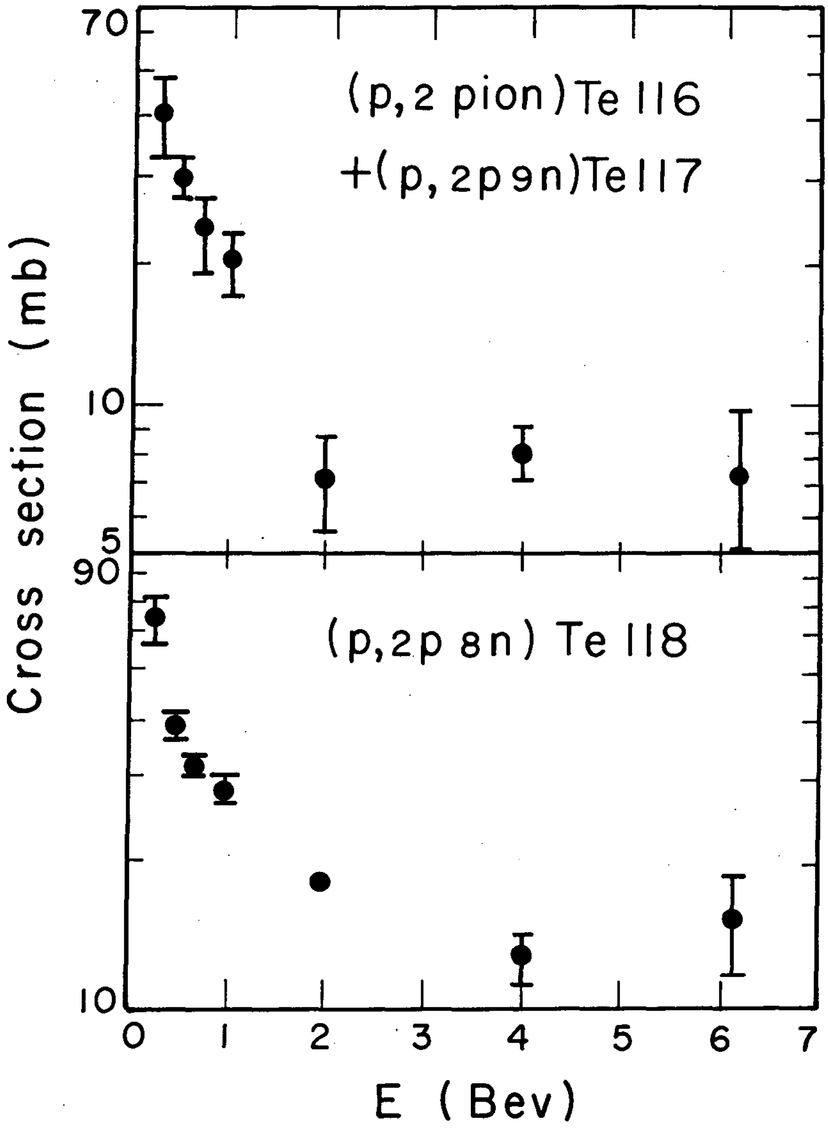
MU-18574

Fig. 2. Cross sections for the formation of iodine isotopes by bombardment of I^{127} with alpha particles of different energies as a function of the mass number.



MU-18575

Fig. 3. Excitation functions of iodine isotopes from proton bombardment of I^{127}. The symbol (p,pxn) represents one of several possible reactions that result in the given product. The points for I^{125} are shown as open circles for clarity.



MU-18576

Fig. 4. Excitation functions of tellurium isotopes from proton bombardment of I^{127}. The symbol (p,2pxn) represents one of several possible reactions that result in the given product.

DISCUSSION

The following general features of these results merit consideration:

(a) The cross sections of proton-induced reactions to form Sb^{127} and Cs^{127} are too small to be measured (Table III). As a result of the presence of $Te^{116+117}$ and Te^{118} with relatively large cross sections and possible contamination by secondary (n,p) reactions, it is not possible to determine the cross section for the formation of Te^{127} by our simple procedures, Table III.

(b) The cross section for the formation of I^{126} is significantly higher than that of the other iodine isotopes at all of the incident proton and alpha-particle energies studied (Figs. 1 and 2) with the possible exception of I^{123} from the alpha-particle bombardments. Part of the cross sections of the latter may be due to feed-in from the xenon parents. In the proton bombardments this effect was minimized by rapid purification of the iodine isotopes.

(c) The excitation functions for the formation of iodine isotopes, with the exception of I^{120} and I^{121} from alpha-particle bombardments, decrease between 0.25 and 0.72 Bev (Fig. 3 and Table II). This result for the alpha-induced reactions is tentative in view of the uncertainty of the monitor cross section at 0.5 and 0.72 Bev. In the case of the proton-induced reactions, the decrease in cross section is least pronounced, if present at all, for I^{126}. The excitation functions from the proton bombardments become relatively constant between 0.5 and 0.72 Bev and remain so up to 6.2 Bev. A similar effect can be seen in the excitation functions for the production of $Te^{116+117}$ and Te^{118} by proton bombardment (Fig. 4), but with the excitation function becoming constant at about 2 Bev.

In the following sections we will consider the significance of these results.

Reactions with No Change in Mass Number

The formation of products with the same mass number as that of the target nucleus can be discussed in relatively simple terms. For example, the proton-induced reactions to form Sb^{127}, Te^{127}, and Cs^{127} require the escape of one or more charged mesons from the target nucleus during the interaction. For I^{127} to be transmuted to Te^{127}, one unit of positive charge must be lost. This can occur most simply by the loss of a positive pion, namely through the reaction, $I^{127}(p,p\pi^+)Te^{127}$. Two units of positive charge must be lost for Sb^{127} to be formed. The simplest way for this to occur is by the loss of two positive pions, namely via the reaction, $I^{127}(p,p\pi^+)Sb^{127}$. In the case of Cs^{127}, on the other hand, two units of positive charge must be gained, e.g. through the reaction, $I^{127}(p,n\pi^-)Cs^{127}$. The formation of Xe^{127} and I^{127} can proceed most simply by the (p,n) and (p,p') reactions, respectively. The (p,p') reaction cannot be studied by the radiochemical method with iodine as a target since the product is stable. However, this reaction can be detected with target nuclei having an isomeric state of sufficiently long half life, e.g. In^{115} (Table IV).[2]

Other reactions can be assigned for each of the above isobars. In every case, the production of one or more additional pions or of other fundamental particles would be required. Thus, the emission of one or more neutral pions, or of negative and positive pions in pairs, may accompany every reaction without changing the identity of the final product. The same result may be obtained if a neutron and a positive pion is emitted in place of a proton, or, conversely, a proton and a negative pion instead of a neutron. However, the creation of additional particles requires energy, which must come from the

Table IV

The cross sections of reactions which result in no change in A for proton energies above 0.7 Bev[a]

		σ(mb) for ΔZ =					
		+2	+1	0	-1	-2	
Target	Energy (Bev)	$(p,n\pi^-)$	(p,n)	(p,p')	$(p,p\pi^+)$	$(p,p2\pi^+)$	Reference
Al^{27}	5.7				0.1		10
Mn^{56}	1.0 to 6.2	<0.003					13
Cu^{65}	5.7		3.1		0.22		14
In^{115}	2.0 to 6.2			~4.3[b]	0.21		2
I^{127}	0.72 to 6.2	<0.03			<3	<.02,<.4	This work
Ta^{181}	5.7		<1.5				15

---

[a] The symbols inside the parentheses indicate one of the possible reactions that produce the given product.

[b] This value is for the low-spin isomeric state.

incident projectile. These considerations are valid as well for nuclear reactions in general. In the discussions that follow, symbols written in the form $(p,p\pi^+)$, (p,pxn), etc. refer to all possible reactions that result in the same final nucleus unless indicated otherwise.

The attempt to measure the cross section for Te^{127} was unsuccessful (Table III). The cross section of the $(p,p\pi^+)$ reaction, however, has been measured for other targets, and in the Bev region is found to be 0.1 mb for Al^{27} and 0.2 mb for Cu^{65} and In^{115} (Table IV). In the case of Sb^{127} and Cs^{127}, only upper limits to the value of the cross section could be determined (Table III). In Table IV are listed the cross sections reported here and elsewhere for reactions induced by protons with energies well above the threshold for pion production, which result in no change in mass number.

The nature of the initial step in the reaction of a high-energy proton with a nucleus can be considered in the light of the cross-section values given in Table IV. The accepted viewpoint is that this step involves a collision of the incoming proton with an individual nucleon in the target nucleus. Thus, the (p,n), (p,p'), and $(p,p\pi^+)$ reactions are thought to proceed by the following knock-on collisions:[16]

$$(p,n):\quad p + \boxed{n} = \boxed{p} + n$$

$$(p,p'):\quad p + \boxed{\eta} = \boxed{\eta} + p$$

$$(p,p\pi^+):\quad p + \boxed{p} = \boxed{n} + p + \pi^+ \;,$$

where $\boxed{}$ indicates that the particle is inside the nucleus, and η represents either a proton or a neutron. As can be seen, these reactions, in which

$\Delta Z = 0, \pm 1$, can go to completion in one step. This is not the case for $|\Delta Z| > 1$. The minimum number of steps by which the latter type of reaction can occur is equal to $|\Delta Z|$. Thus we get

$$
\begin{aligned}
(p,n\pi^-):\quad p + \boxed{n} &= \boxed{p} + \boxed{p} + \pi^- \\
\hookrightarrow + \boxed{n} &= \boxed{p} + n
\end{aligned}
$$

and

$$
\begin{aligned}
(p,p2\pi^+):\quad p + \boxed{p} &= \boxed{n} + \boxed{n} + 2\pi^+ \\
\hookrightarrow + \boxed{p} &= \boxed{n} + p
\end{aligned}
$$

where one of the nucleons in the initial interaction must interact further to eject a nucleon not involved in the first collision in order to form the final product. Other mechanisms, in addition to those written above, are possible. The escape of negative mesons also provides a means for forming other nuclides with $\Delta Z \geq + 2$.

Thus, it is not surprising that the cross-section of the $(p,n\pi^-)$ reaction, requiring at least two events, is at least an order of magnitude smaller than the $(p,p\pi^+)$ reaction, which requires only one such event, despite their superficial similarity (Table IV). In a similar fashion, at high incident-proton energies, (p,2p) and (p,pn) reactions, which can go in one step, are found to be more probable than the (p,2n) reaction, which requires at least two steps.[14,15,17-21] The cross section of the $(p,p2\pi^+)$ is found to be small (Table IV) both for the above reason and because a second pion must be formed and then escape from the nucleus.

The case of $\triangle Z = 0$ is expected to have the largest cross section of the class of reactions for which $\triangle A = 0$. Not only does the (p,p') knock-on reaction, as written above, contribute to the same product, but other processes in which the incident proton passes through or near the nucleus also contribute. An example of the latter is the phenomenon of Coulomb excitation.

The next largest cross section is expected for the (p,n) reaction, which can also be initiated at energies below the onset of meson production. This is not true for the $(p,p\pi^+)$ reaction. At higher energies the (p,n) reaction can take place by (p,n), $(p,n\pi^0)$, and $(p,p\pi^-)$ processes, whereas there are no alternatives to the $(p,p\pi^+)$ process until the onset of multiple meson production. On the other hand, the (p,n) reaction cannot proceed by all the low-energy-transfer processes available to the (p,p') reaction.

The results, meager as they are, are consistent with these expectations (Table IV). The value of the cross section indicated for the In^{115} (p,p') reaction is, of course, a lower limit since only the isomer could be detected. This reaction and the $In^{115}(p,p\pi^+)Cd^{115}$ reaction are considered in detail in a subsequent paper.[2]

Reactions with Change in Mass Number

The results of the proton-induced reactions can be compared with calculations based on a two-stage mechanism proposed for high-energy nuclear reactions. In the first stage the incident particle interacts, as discussed above, with an individual nucleon in the target nucleus to initiate a cascade of nucleon-nucleon, and possibly, meson-nucleon collisions.[22] Reactions with aggregates of nucleons are neglected. Some of the nucleons (or mesons) participating in the cascade may escape. Others may remain in the nucleus. As a result of the cascade, the residual nucleus is left in an excited state. This energy of excitation is then released in the second stage by the evaporation of light particles[23-25] and, finally, when no more particles can be expelled, by the emission of gamma radiation. The occurrence of fission is not considered here. In the cascade stage the production of fundamental particles other than pions is also not treated. The importance of the latter will increase with the energy of the incident proton beam in the multi-Bev region.

Since cascade calculations were not made for the target nucleus, I^{127}, it is necessary to compare the data reported here with calculations based on Ru^{100} and Ce^{140}. The results of these calculations were received from the authors of reference 22 as a list of residual energies of excitation for each change in atomic number, ΔZ, and atomic mass, ΔA, from that of the target. From these values of ΔZ and ΔA the corresponding residual nuclei for the target I^{127} were obtained. The evaporation calculations were then made by Drs. I. Dostrovsky and Z. Fraenkel on the Weizmann Institute computer with various adjustments for pairing and shell corrections. The radius parameter was taken to be 1.3×10^{-13} cm. The results of these calculations can be compared directly with the experimental results at 1 and 2 Bev. Above this energy, no cascade calculations have been made. Below this energy, cascade calculations were available at 0.16 and 0.45 Bev. The experimental results were extrapolated to these energies with the aid of the work of Kuznetsova, Mekhedov, and Khalkin.[26] The calculated values include the contribution from decay of the parent nuclide. The fraction of the parent activity that had decayed before separation could be effected was estimated to be 100% for $Te^{116+117}$, Te^{118} and I^{120}, 50% for I^{121}, and 20% for I^{123}. This effect on the total cross section of the last two nuclides is relatively small.

The ratios of the calculated to experimental results are given in Fig. 5. The (p,pxn) products are iodine isotopes with mass numbers 127-x. The (p,2pxn) products are tellurium isotopes with mass numbers 126-x. No pairing or shell corrections were made for the values indicated by the solid points, which are based on Ru^{100}, or for the open-circle points, which are based on Ce^{140} These corrections were made for the values indicated by the open squares, which are based on Ce^{140}. In the latter case, two different sets of corrections were used at 0.45 Bev -- those of Newton[24,27] and of Cameron.[24,28] The results of these two calculations are the same within the statistical error of the calculation and are combined for presentation as open squares in Fig. 5. The open squares at 2 Bev are obtained with Newton's corrections only.

With the exceptions discussed below, neither the choice of nuclide on which the cascade calculation was made nor the details of the evaporation calculation affect the final value of the cross section very much. Thus we feel justified in extrapolating to I^{127} the cascade calculation made on Ru^{100} and Ce^{140}. The discrepancy in the comparison for I^{126} at 0.45 Bev is due to the difference in the cascade results for Ru^{100} and Ce^{140}. In the case of I^{120}, the discrepancy is due to the details of the evaporation calculation. The discrepancies at 2 Bev may be due to either or both causes.

It is to be expected that the sensitivity of the calculated cross section to the details of the evaporation calculation will be least for

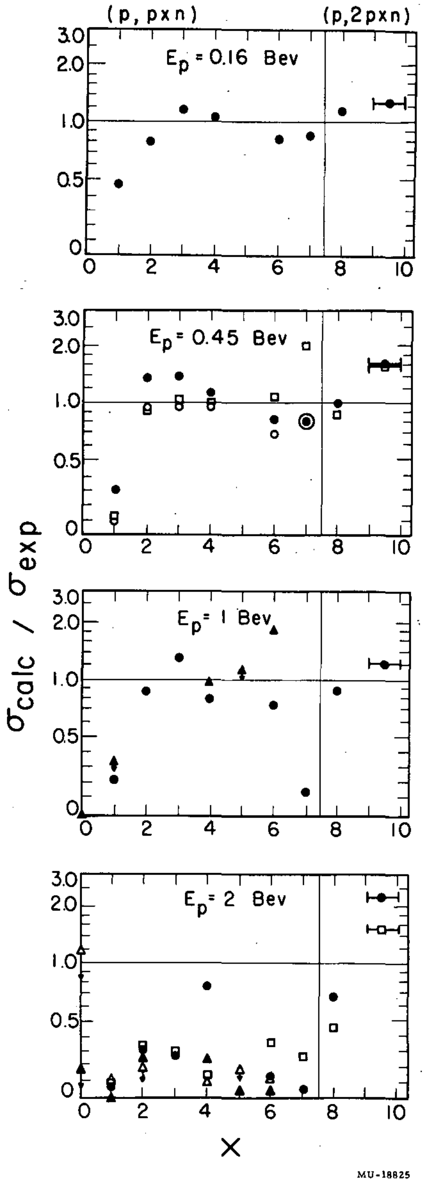


Fig. 5. The ratios of calculated to experimental cross sections for the reactions, $I^{127}(p,pxn)I^{127-x}$ and $I^{127}(p,2pxn)Te^{126}$-x. The ordinate scale is linear from 0 to 0.5 and logarithmic above 0.5. No pairing or shell corrections were made for ● based on Ru^{100} or for ○ based on Ce^{140}. Pairing and shell corrections were made for □ based on Ce^{140}. For details see text. The values for the $In^{115}(p,pxn)In^{115-x}$ reactions at 1 and 2 Bev are indicated by ▲ if based on Ru^{100} and by △ if based on Ce^{140}. Pairing and shell corrections were made, (see reference 2).

products that have masses close to that of the target. This is due to two factors. First, the existence of a Coulomb barrier tends to suppress the evaporation of charged particles.[23,29] Thus, reasonable changes in the evaporation calculation cannot affect significantly the predominance of neutron evaporation at the low energies of excitation which result in these products. Second, any change in the claculation is cumulative, because the excitation energy is released in a successive emission of particles. Therefore, the cross sections to form products which have masses farthest from that of the target will be affected most. Hence, the study of (p,pxn) reactions, where x is small, should primarily be a test of the cascade calculation for these relatively simple reactions.

The values of the (p,pn) reaction, calculated in this way, are different from those of the other reactions in being too small as compared to the measured values at all energies. This effect has been observed with other targets.[21,22,30] The experimental observations previously noted in points (b) and (c) of this discussion and in other work[10,20,21] are further indication that the (p,pn) type of reaction is unique. The cascade (and evaporation) calculations quoted here are based on the assumption that the nuclear density is constant from the center to the surface, where it drops abruptly to zero. Actually, there is strong evidence that the nuclear surface is diffuse.[31] The (p,pn) reaction is thought to occur primarily via collision with the surface neutrons.[10,21,22,30] A smaller density of nucleons in the region of the interaction would increase the probability for a single collision to occur followed by the escape of the products of the collision. This effect is undoubtedly more important for the higher incident energies with the possible production of mesons and other fundamental particles in the cascade process. Benioff has compared many (p,pn) cross sections at 3 to 6 Bev, taking into account the diffuse nature of the nuclear surface and the other structural details of the target nucleus.[10] Within a reasonable range of values for nuclear parameters that are not well known, he finds agreement between his calculated values for the cross section and those experimentally determined, including that for I^{126} reported here.

The similarity of the $(\alpha,\alpha n)$ results suggests that the mechanism of this reaction is like that ascribed to the (p,pn) reaction. In the alpha-particle-induced reactions, as well as those induced by protons, the cross sections to form I^{126} is significantly higher than that for either I^{125} or I^{124}. Even the values of the cross section of the $(\alpha,\alpha n)$ and (p,pn) reactions are similar at the same bombarding energy. However, a direct evaluation of the results of the alpha bombardments has not been made.

The calculated values for the cross sections of the other (p,pxn) and the (p,2pxn) reactions are in fairly good agreement with the experimental results at 0.16, 0.45, and 1 Bev (Fig. 5). The agreement is poorest for the (p,p7n) and (p,2p9,10 n) reactions at 0.45 Bev and lacking for the (p,p7n) reaction at 1 Bev. This is not surprising in view of the large experimental uncertainty in the measurement of these cross sections and the sensitivity of the calculation for reactions in which many particles are emitted. The success of the calculations in predicting the other cross sections is striking in view of the marked drop of the excitation functions with energy (Figs. 3 and 4). In this energy region the production and readsorption of mesons is considered to be a major means of energy transfer.[22,32] The sensitivity of the reactions studied here to the role of mesons is not known. That it cannot be large is suggested by the similarity of values obtained for the cross sections of the (p,pxn) and the (α,αxn) reactions. The effect of meson production and readsorption in the latter type of reaction is expected to be relatively small. However, the evidence for this is still fragmentary. Calculated values would have been useful for comparison with the results presented here for 0.72-Bev protons. The agreement at these energies has also been observed for other types of measurement.[22,33]

Thus, the failure to include the correct density distribution of nucleons in the surface appears to affect only the (p,pn) cross section at the lower energies to any marked extent. We would expect the nucleon-nucleon collisions that are involved in more complicated reactions to occur closer to the center of the nucleus, on the average. Hence, the character of the nuclear surface should affect the cascade phase of the calculation for (p,pxn) and (p,2pxn) reactions to a progressively smaller extent as the value of x increases. Because of experimental uncertainty it is not possible to assess the role of the nuclear surface in the (p,p2n) reaction from these measurements. However, it does appear that this reaction is much less sensitive to the nature of the nuclear surface than is the (p,pn) reaction.

At 2 Bev there is essentially no agreement between the calculated and the experimental values. Work of a similar nature on indium confirms this lack of agreement at 2 Bev.[2] Comparisons have been made of the measured and calculated sum of the cross sections to produce all nuclides of a given mass number for 340-Mev protons and for 2.2- and 5.7-Bev protons incident on copper.[14,22] As in the work reported here, good agreement was obtained at the lower energy. Barr, however, found that calculated values are too small by a factor of roughly 2 to 3 at the higher energies for products with masses near that of the target.[14] The reason for the disagreement of the experimental and calculated values at 2 Bev compared to the fairly good agreement at lower energies, except for the (p,pn) reaction, is not clear. It may be that inclusion of a proper description of the nuclear surface in the calculation will rectify the comparison. This seems to be the case for the (p,pn) reaction at incident proton energies in the multi-Bev range.[10] A discussion of this and other possibilities is deferred to a subsequent paper in which further pertinent evidence is presented.[2]

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