INVESTIGATION OF (p, pxn) REACTIONS ON IODINE

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Formation of the radioactive isotopes A^{126}, I^{125}, I^{124}, I^{123}, I^{121}, and I^{120} from I^{127} was investigated by radiochemical methods. The isotopes were produced with 100, 170, 300, 480, and 660 Mev protons. The experimental data are analyzed and compared with the results of investigations of similar reactions on other elements. The fraction of K capture in I^{126}, I^{124}, I^{121}, and I^{120} was determined.

IN most radiochemical investigations where various elements are split by fast particles, not enough attention has been paid to the nuclei formed by the (p, xn), (p, pxn), and (p, 2pxn) reactions. Yet it is quite probable that a study of these reactions would yield additional data on the development of the intranuclear cascade, inasmuch as the radiochemical procedure makes possible observation of neutron emission.

The most suitable for the study of (p, pxn) reactions is I^{127}. It is possible to trace reactions with this nuclide over sufficiently wide range of x (from x = 1 to x = 7).

This article contains the results of a study of (p, pxn) reactions on iodine bombarded by protons of energies ranging from 100 to 660 Mev.

EXPERIMENTAL PROCEDURE

KI specimens weighing 0.1 g were prepared for the experiments. In the latest experiments of this series, specimens of elementary iodine (0.1 to 0.3 g) were sealed in thin-wall glass ampoules.* The proton beam was monitored by the yield of Na^{24} from the aluminum foil in which the irradiated specimens were rolled up.

The energy of the bombarding particles was varied by varying the radius of the synchrocyclotron circular beam with which the target was irradiated.

The iodine was separated from the bulk of the other radioactive products by double distillation from a nitrate solution, containing sodium nitrite. The final purification of the iodine (essentially removal of the bromine and the chlorine) was by two sequential extraction cycles: the iodine was extracted with chloroform from a 1 m solution in HNO_3, the chloroform layer was twice washed with water, the iodine was converted into an aqueous solution with the aid of Na_2SO_3, the iodide was again oxidized with the sodium nitrite and the iodine extracted with chloroform, the washing with water was repeated, and the iodine was reextracted in a solution of sodium sulphite.

The targets for the measurements were made in the form of AgI. All targets were scanned with a magnetic analyzer,[1] which made it possible to detect the decay in each component of the emitted radiation: x-rays, positrons, electrons, and gamma-quanta. The x-ray intensity decay curves plotted from the measured data consist of five periods: 60, 13, 4.5 days, 13 hours, and 1.8 hours. The positron component of radiation contains three half lives — 4.5 days, 18 hours, and 30 minutes, while the electron component contains only one — 13 days.

The calculated half lives of the various iodine isotopes are:

J^{126} (β^-, K) $T_{1/2}$ = 13 days;	J^{125} (K) $T_{1/2}$ = 60 days;
J^{124} (β^+, K) $T_{1/2}$ = 4.5 days;	J^{123} (K) $T_{1/2}$ = 13 hr;
J^{121} (β^+, K) $T_{1/2}$ = 1.8 hr;	J^{120} (β^+) $T_{1/2}$ = 30 min.

The x-ray decay curve was resolved into components so as to produce a best fit to the known values of the periods, and also to the probabilities of the K-capture fraction. The K-fraction capture for the I^{126}, I^{124}, and I^{121} isotopes was established as 50, 58, and 58% respectively. These values are obtained by averaging 10 to 12 readings. The obtained K-capture probabilities for I^{126} and I^{124} agree with the literature data (~58 and ~70%, Ref. 2). The K-capture fraction for I^{124} also agrees with the theoretical value (46%), and is

*In both cases the cross sections obtained were equal, within experimental errors. This suggests that the radioactive iodine does not volatilize from a KI target heated above 100°C in the high vacuum of the synchrocyclotron chamber.

somewhat too low for I^{121} (theoretical value 82%), but lies within the experimental error. No x-radiation was observed for I^{120}, in agreement with the theoretical values of the K-capture for this isotope (5 to 10%). The theoretical values were calculated using the formulas of Ref. 3.

To detect the presence of soft x-rays, the x-ray energy was determined by its absorption in aluminum. No soft gamma-ray component was observed, and the wavelength of the x-rays emitted by the I^{121} and I^{123} was found to be 0.46 A. This quantity is in good agreement with the expected value λ = 0.455 A (Ref. 4). A separate experiment has confirmed that no buildup of Te^{125m} ($T_{1/2}$ = 60 days) takes place at a gamma-ray energy of 0.35 Mev.[5]

To reduce the errors, the isotope yields were calculated from the data obtained by measuring the corpuscular radiation, using the K-capture fraction previously obtained. Only for I^{123} and I^{125} was the yield calculated by analysis of the decay curves of the electromagnetic-radiation activity.

EXPERIMENTAL RESULTS

Table I lists the cross sections for the production of light radioactive isotopes of iodine from I^{127} at various proton energies. The indicated deviations at 660 Mev are mean arithmetic values calculated from the results of five experiments, while the remaining cases represent averaged limits of yields obtained from 2 or 3 experiments. The next to the last column gives the total cross sections for the production of all the iodine isotopes; the last column indicates the average values of the emitted particles in reactions of the (p, pxn) type, obtained by averaging the cross sections.

The data obtained show that the energy dependences of the production cross sections of almost all of the isotopes are approximately the same. The reaction cross sections change little in the energy range from 300 to 600 Mev and increase with diminishing energy. For example, the total cross section for 100-Mev protons is almost three times that of 300 to 660 Mev ones. Figure 1 shows the dependence of the cross section on the energy of the incident protons for the various iodine isotopes.

The maximum yield at all proton energies is that of I^{126}. The yields of the remaining nuclides diminish gradually with increasing x. An exception is I^{121}, with a production cross section larger than that of the neighboring nuclides and fluctuating sharply with varying particle energies. There are

TABLE I

Proton energy, Mev	Production cross section × 10^{-27}, cm²							Average number of emitted particles
	I^{126} (p, pn)	I^{125} (p, p2n)	I^{124} (p, p3n)	I^{123} (p, p4n)	I^{121} (p, p6n)	I^{120} (p, p7n)	Sum over all isotopes	
660	51 ± 10	31 ± 4.6	17.3 ± 3	12 ± 1.5	16.3 ± 2.5	5.1 ± 1.5	133	3.7
480	70 ± 9	32 ± 5	19.5 ± 4.6	10.5 ± 3	27.5 ± 6.6	5.6 ± 1.8	165	3.6
300	53 ± 8	37 ± 7	28 ± 10	12 ± 2.1	50 ± 10	7.9 ± 2.1	188	4.3
170	64 ± 9	44 ± 9	54 ± 12	13.5 ± 2.4	20.5 ± 3.2	6.8 ± 1.1	203	3.6
100	126 ± 26	100 ± 26	50 ± 7	44 ± 11	105 ± 16	8.9 ± 3.6	434	4.0

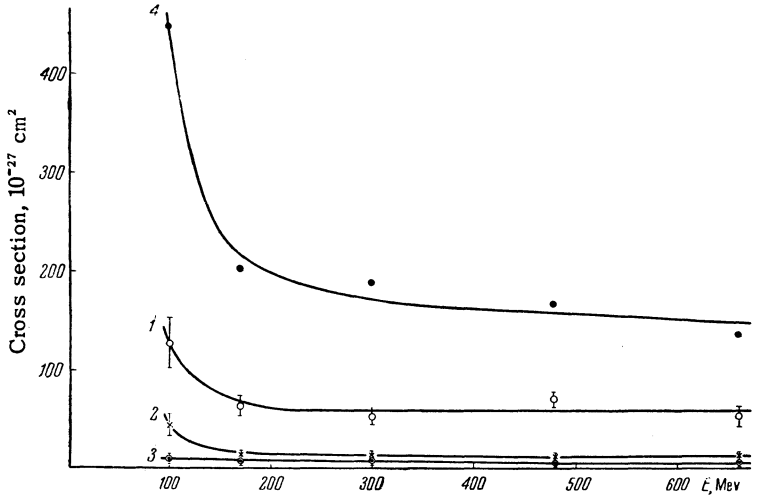

FIG. 1. Dependence of the cross sections of individual products on the proton energy. 1 – I^{126} (p, pn); 2 – I^{123} (p, p4n); 3 – I^{120} (p, p7n); 4 – total cross section.

TABLE II

Type of reaction	Co^{59}				Cu^{63}	Cu^{65}	Y^{89}	Cs^{133}		Th^{232}	U^{238}		
	100 Mev[8]	100 Mev[7]	240 Mev[7]	370 Mev[9]	100 Mev[13]	100 Mev[13]	240 Mev[10]	100 Mev[11]	240 Mev[11]	340 Mev[12]	100 Mev	200 Mev	340 Mev
(p, pn)	135	370 ± 180	120 ± 60	121 ± 60	120	1155	93 ± 15	890	59	40	93	67.5	85
(p, p2n)	31.5	—	—	(37)	70	—	> 23 ± 4	500	460	(35)	—	—	—
(p, p3n)	3	89 ± 45	22 ± 11	15.2 ± 3.8	—	80	< 28.2 ± 5	—	—	(35)	—	—	—
(p, p4n)	7.8	21 ± 4	6.6 ± 1.3	5.2 ± 1.3	—	37	15.8 ± 3	116	15	30 ± 3	—	—	—
(p, p5n)	—	—	—	(1.7)	—	—	} 2.3 ± 0.5	—	—	22 ± 5	—	—	—
(p, p6n)	—	—	—	—	—	—		15.4	4.5	17 ± 0.3	—	—	< 4
(p, p7n)	—	—	—	—	—	—	0.08 ± 0.04	—	—	—	—	—	—
(p, p8n)	—	—	—	—	—	—	—	—	—	—	0.41 ± 0.03	0.41	0.35
(p, p9n)	—	—	—	—	—	—	—	—	—	—	0.046	0.1	0.06
(p, p10n)	—	—	—	—	—	—	—	—	—	—	0.012	0.03	0.038
Sum of all products	177	480 ± 230	149 ± 62	180 ± 65	—	272	162 ± 27	—	—	179	—	—	—

not enough experimental data on hand* to explain the causes of such fluctuations. The greatest deviation is at 300 Mev. The yield of the (p, p7n) reaction is the smallest and varies little with proton energy.

The average number of emitted particles, for all energies, is somewhat greater than 3.2, which is the calculated average number of cascade particles, emitted by interaction between a 400-Mev proton and a nucleus with A = 100 (Ref. 6). This indicates that the observed products are due not only to knockout but also to evaporation of nuclides, particularly for the lighter iodine isotopes.

Our results are in sufficiently good agreement with the literature data in the compared energy interval (see Table II).

The figures in the parentheses in Table II are the interpolated cross sections of the products, not observed experimentally. With the exception of cesium, the atomic weight of each isotope is one less than that of the target nucleus.

We did not observe the relative increase in the cross section of the (p, p2n) reaction, compared with the (p, pn) reaction, with increasing proton energy, as noted in Ref. 11, although iodine and cesium have nearly equal atomic and mass numbers.

Comparison of our results with the literature data lead to certain conclusions concerning the dependence of (p, pxn) reactions on the atomic number of the target element. Naturally, it is possible to compare only results obtained at nearly equal proton energies. Therefore, all that will be said below pertains to (p, pxn) reactions on cobalt,[9] iodine, and thorium[12] at proton energies of 300 to 370 Mev (see Tables I and II). At other proton energies, these relations are less clearly pronounced, owing to the lack of coordination in the experimental data.

The first striking factor is that the total cross sections for the above elements are nearly the same: 180 ± 65, 188 ± 40, and 179 ± 10 millibarns for Co, I, and Th respectively. Nearly-equal cross section are found also for the most probable (p, pn) reaction, this cross section being almost the same (~ 40 mbn) for carbon[14,15] as for the (p, pn) reaction on iodine and thorium. Next, the greater the atomic number of the target, the higher the relative cross sections for the production of the light isotopes (see Fig. 2). For example, if the yield of the (p, pn) reactions is taken to be unity, then the relative cross sections for the production of Co^{55}, I^{123}, and Th^{228} by the (p, p4n) reaction are respectively $0.045^{+0.065}_{-0.02}$, $0.23^{+0.1}_{-0.05}$ and 0.75 ± 0.1 (Fig. 2).

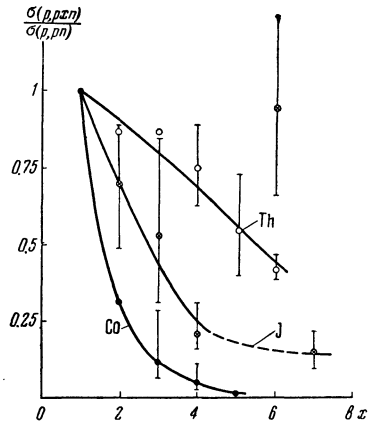

FIG. 2. Dependence of the ratio σ (p, pxn)/σ (p, pn) on the number of emitted neutrons, x, for cobalt, iodine, and thorium.

Such an increase in the yield is quite justified, since the increase in the excess neutrons over protons in the nuclei should favor the emission of neutrons and lead to an increase in the cross section

*Note added in proof (April 19, 1958). It is indicated in Ref. 18 that the 1.8-hour half life belongs to several iodine isotopes.

for the formation of products that are farther away from the initial nucleus.

The observed energy dependencies of the (p, pn) and (p, p2n) reactions can be explained in terms of the energy relations of the cross sections of the elementary nucleon-nucleon elastic cross sections. It is known, for example, that the cross sections of the (p, p) and (n, p) interactions are of approximately the same magnitude and are almost constant over the particle energy range from 200 to 260 Mev.[16,17]

In those cases, when the production of the isotopes cannot be explained as a result of nucleon knockout, we should not observe a similar dependence of the yield of the reaction products, due to the energy dependence of the elementary nucleon interactions. The relative constancy of the yield of I^{120} at all proton energies is apparently due to the fact that its production is caused by another mechanism, the evaporation of the nuclides.

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