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INTERACTION OF HIGH-ENERGY PROTONS WITH INDIUM

David R. Nethaway and Lester Winsberg

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ABSTRACT

Indium was bombarded with protons ranging in energy from 1.0 to 6.2 Bev. Reactions of the type (p,pxn), (p,2pxn), (p,p'), and (p,pπ^+) that produce isotopes of indium and cadmium were investigated. The excitation functions are constant within experimental error in this energy region with possible exceptions for Cd^{115} and In^{115m} at 1.0 Bev. These results are compared with two types of calculation. In one treatment, the nucleus is considered to be a degenerate Fermi gas of nucleons. The cross sections that were calculated with this nuclear model at 2 Bev are much smaller than the experimental values. The second treatment takes into account the shell structure of In^{115}. The latter calculation was made for the (p,pn), (p,p'), and (p,pπ^+) reactions. Good agreement with the experimental results was found for the (p,pn) reaction at 4.1 and 6.2 Bev. The calculated values for the (p,pπ^+) reaction at 2, 4, or 6 Bev were too small by a factor of 5 to 100. The low values may be the result of an inadequate analysis of inelastic p-p scattering. The calculated value of the total cross section of the (p,p') reaction is larger than the measured value for In^{115m} at 1 Bev and is smaller at 4 and 6 Bev. The comparison of the experimental results with the calculated values is discussed in terms of the adequacy of the calculations.

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INTRODUCTION

Indium is favorable for studying reactions that cause relatively little change in the target nucleus. Both of its stable isotopes have isomeric states that permit investigation of the (p,p') reaction by radiochemical methods. The decay characteristics of the neighboring radioactive nuclides, including the occurrence of isomerism, are suitable for the study of other types of nuclear reactions. In the work reported here, indium was bombarded with protons accelerated by the Bevatron to energies of 1.0, 2.0, 4.1, and 6.2 Bev. The cross sections for the formation of indium and cadmium isotopes and of Be^7 were measured. The latter is of interest because it is one of the lightest nuclides that can be measured by radiochemical techniques.

As in the preceding paper on iodine,[1] the experimental results are discussed in terms of the initial interaction and the subsequent processes that cause the escape of a few more particles. The (p,pn), (p,p'), and $(p,p\pi^+)$ reactions are treated in more detail because of their relative simplicity. The (p,pn) reaction reported here has also been treated by Benioff.[2] The result for the formation of Be^7 is compared to similar studies with other targets.

*This work was performed under the auspices of the U. S. Atomic Energy Commission.

EXPERIMENTAL PROCEDURE[3]

The target assembly consisted of a 0.003-in. indium target foil and a 0.003-in. aluminum monitor foil. Three 0.001-in. aluminum guard foils were used to separate and cover the foils as a protection from recoil and secondary particles. The five foils (each 2 by 3/4 in.) were stacked together and held in a lucite target holder so that the edges were aligned as closely as possible. After the bombardment, the outer 1-in. of the foil stack was cut off and used for radiochemical analysis. Additional bombardments were performed in which the thickness of the indium foil was varied in order to estimate the extent of reactions produced by secondary particles.

The 0.003-in. indium foil (> 99.9% indium) was obtained from the Indium Corporation of America. Spectroscopic analysis of the indium showed the presence of 0.01% tin and zinc, 0.006% lead, and 0.002% copper. Typical detection limits for other elements were < 0.1% thallium and iron, < 0.05% cadmium and tungsten, and < 0.005% bismuth.

The incident proton beam was monitored by means of the $Al^{27}(p,3pn)Na^{24}$ reaction. The cross section for this reaction was taken as 10.5 mb for protons in the energy range of 1 to 6 Bev.[4] The error in this value is believed to be less than 10%. The beta radiation of the Na^{24} was counted directly in the aluminum foil without chemical separation.

After bombardment the indium foil was weighed and then dissolved in a solution of HCl and HNO_3 containing 10- to 20-mg quantities of beryllium and cadmium as carriers. The beryllium, cadmium, and indium fractions were separated and purified by standard radiochemical procedures.[5,6]

An end-window, gas-flow proportional counter was used to count beta particles and conversion electrons. The counting rate of a Na^{24} source in the proportional counter was compared with its absolute disintegration rate obtained by the coincidence counting technique. The comparison factor obtained in this manner was used to calculate the disintegration rates of those nuclides emitting energetic (> 1 Mev) beta particles. In the case of those nuclides emitting only lower-energy particles, it was necessary to apply individual corrections for backscattering, air and window absorption, self-scattering and self-absorption, and geometry.[7-10]

A gamma-ray scintillation pulse-height analyzer (50 and 100 channels) with a thallium-activated NaI crystal (1 in. by 1-1/2 in. diam) was used to count the gamma rays of particular energies. The variation of counting efficiency with gamma-ray energy was taken from the data of Kalkstein and Hollander.[11] The geometry calibration was obtained with standardized Na^{24} and Am^{241} sources.

In order to provide a means for comparing results presented here with those obtained elsewhere, we list the number of particles or photons emitted per disintegration in Table I for each nuclide measured.[12]

Table I

Number of particles and photons emitted per disintegration

Nuclide	Half life	Type of radiation	Energy (Mev)	Particles or photons per disintegration
Be^{7}	53d	γ	0.478	0.12
Cd^{107}	6.7h	e^{-}	0.090, 0.068	0.94
Cd^{109}	470d	e^{-}	0.084, 0.062	0.91
Cd^{115}	53h	β^{-}	1.11, 0.85, 0.60	1.00
Cd^{115m}	43d	β^{-}	1.61, 0.67	1.00
In^{109}	4.3h	γ	0.205	~0.7
In^{110m}	5.0h	γ	0.66	1.00
In^{111}	2.84d	γ	0.172, 0.247	0.89, 0.94
In^{113m}	104m	γ	0.393	0.65
In^{114m}	49d	β^{-}	1.98	0.95
		γ	0.191	0.18
In^{115m}	4.50h	γ	0.335	0.48

RESULTS

The measured values of the cross sections are presented in Table II as a function of proton energy and target thickness. Standard deviations are given in those cases where duplicate determinations were made. It is estimated that the over-all uncertainty in the cross sections due to errors in counting efficiencies, beta-counting correction factors, chemical yields, counting statistics, monitor cross section, etc., is about ±30%. The cross sections for the nuclides Cd^{107}, Cd^{109}, and In^{109} are less accurately known than the others because of uncertainties in the counting corrections. The low counting rates of Be^{7} and Cd^{115m} did not permit the accurate measurement of these nuclides.

Table II

Measured values for cross sections

Proton energy	1.0 Bev	2.0 Bev	4.1 Bev	6.2 Bev		
Target thickness	37 mg/cm^2	97 mg/cm^2	97 mg/cm^2	26 mg/cm^2	97 mg/cm^2	476 mg/cm^2
Nuclide	Cross sections (millibarns)					
Be^{7}					14.1±0.4	
Cd^{107}	26	32	26±2	27	29±3	27
Cd^{109}	35	51±2	44±3	45	52±6	74
Cd^{115}	0.03	0.06±0.01	0.066±0.001	0.05	0.071±0.004	0.13
Cd^{115m}	0.13	0.145±0.001	0.15±0.02	0.06	0.147±0.006	0.24
In^{109}	10	11				
In^{110m}	12	17				
In^{111}	16	21		17		26
In^{113m}	1.9	2.5				
In^{114m}	42	49±1	57±1	57	61±9	70
In^{115m}	1.7	4.1±0.6	5.0		4.2±0.6	

The yield listed for Cd^{109} has been corrected for the decay of In^{109}. All other cross sections except those for Be^{7}, In^{109}, and possibly Cd^{107} and In^{111} represent independent yields. Since the products Cd^{115}, Cd^{115m}, In^{114m}, and In^{115m} are formed exclusively from In^{115}, the cross sections reported here have been corrected for the isotopic abundance of In^{115} (0.958). The remainder of the products can be formed from both In^{113} and In^{115}.

In order to estimate how much of the yield was due to impurities in the target foil, a determination of the yield of Cd^{117} was made. This nuclide can be formed from In^{115} only by an extremely unlikely reaction, so that any found should be an indication of higher-Z impurities in the indium. The Cd^{117} was measured by separating and counting the radiations from the In^{117} daughter. The cross section obtained by this method is 0.007 mb or less. Because this is a small value, we will disregard the presence of impurities.

The particles that result from the interaction of protons with the target assembly may cause further reactions of a secondary nature. The production of Cd^{115} and Cd^{115m} should be especially sensitive to the presence of neutrons, since these isotopes can result from (n,p) reactions as well as from the $(p,p\pi^{+})$ reaction induced by incident protons. Furthermore, the cross section of the latter reaction is small. The variation of cross section for the formation of Cd^{115} at 6.2 Bev as a function of the target thickness indicates that the contribution from secondary particles is a small effect for the thinner targets (Table II). This has been confirmed by Fung and Turkevich in the case of the $Cu^{65}(p,p\pi^{+})Ni^{65}$ reaction at 440 Mev.[13] The variation in the cross section of Cd^{115m} is not a good test of this effect because of the relatively small radioactivity of this isomer. A smaller variation of measured cross section with target thickness is observed in the case of the other isotopes at 6.2 Bev.

DISCUSSION

A prominent feature of these results is the constancy, within experimental error, of the measured cross sections between 2.0 and 6.2 Bev, shown in Table II. We, therefore, expect the cross sections for the formation of indium isotopes at 2.0 Bev to be characteristic of the (p,pxn) reactions in this energy range (Fig. 1 and Table II). Presumably, this is also true for the cadmium isotopes, including those not detected. In the case of the Cd^{115} isomers, the ratio of isomer yields, as well as the total cross section for this isotope, is constant at these energies. There may be a deviation from constancy in the values of the cross sections at 1.0 Bev, especially for Cd^{115} and In^{115m} (Fig. 1 and Table II). In most cases this deviation is smaller than the experimental error. These observations and the actual values of the cross sections will be considered in terms of the mechanism of these reactions.

It is customary to assume that the collision of a high-energy nucleon with a nucleon inside a nucleus is identical with a collision between free nucleons at the same energy in the center of mass, with one restriction only: After the collision neither particle can be left in a state already occupied by a like particle. This assumption is basic to the two types of calculation that have been made for high-energy reactions. In one treatment, the nucleus is considered to be a degenerate Fermi gas of nucleons and to have a constant nuclear density.[14] The second type of calculation takes into account the specific shell structure of the target nucleus and the diffuse nature of the nuclear surface. Benioff's calculations of the second type[2] can be directly applied only to the reactions that leave the target nucleus relatively undamaged, e.g., the (p,pn), (p,p'), and ($p,p\pi^+$) cases reported here. The results shown in Table II and Fig. 1 will be analyzed in terms of these two nuclear models.

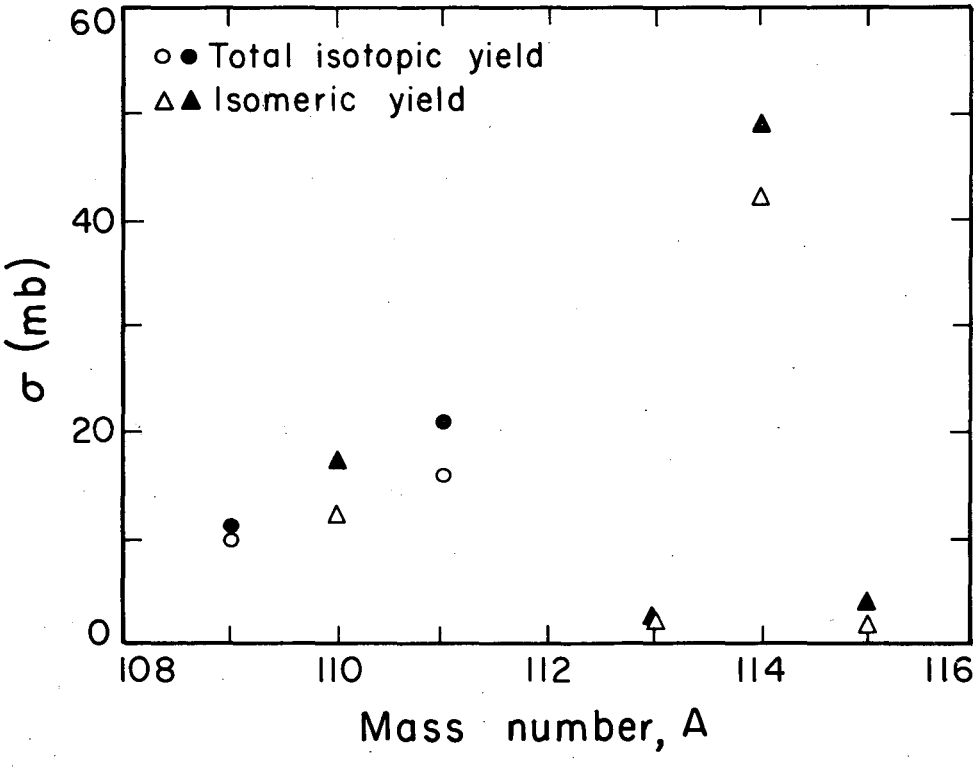

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Fig. 1. Cross sections for the formation of indium isotopes at 1.0 Bev (open circles) and at 2.0 Bev (closed circles).

A. Comparison Based on Fermi-Gas Model with Constant Nuclear Density

The calculations based on the Fermi-gas model are divided into two parts: (a) an initial prompt-cascade process, which results in an excited residual nucleus, and (b) the ensuing deexcitation by evaporation of light particles. The former calculation was actually made for the target nuclei, Ru^{100} and Ce^{140} with a radius parameter of 1.3×10^{-13} cm.[14] The nuclear density was taken to be constant throughout the nucleus. From these results at 1 Bev (Ru^{100} only) and at 2 Bev, the corresponding residual nuclei for the target In^{115} were obtained, as described in the preceding paper for I^{127}.[1] Dr. Z. Fraenkel made the evaporation calculation on the Weizmann Institute computer[15-17] with a radius parameter of 1.7×10^{-13} cm and a level-density parameter of A/10. Pairing and shell corrections were made. The radius parameter used in the latter calculation is different from that used for the cascade stage. The yield of neutrons and charged particles in the evaporation stage is relatively insensitive to changes in this parameter. The distribution of nuclei and their energies of excitation resulting from the cascade process was calculated for 654 events induced by protons incident on Ru^{100} at 1 Bev, and for 550 events with Ru^{100} and 563 events with Ce^{140} at 2 Bev. Complete evaporation calculations were repeated ten times for each inelastic event. (In approximately 5% of the cases, the protons were calculated to pass through the nucleus without any interaction.) The ratio of the calculated to experimental results are given in Table III. The values for the (p,pxn) reactions are also plotted in Fig. 5 of the preceding article[1] as solid triangles for

Table III

Ratios of calculated to experimental cross sections for the reactions $In^{115}(p,pxn)In^{115-x}$, $In^{115}(p,2pxn)Cd^{114-x}$, and $In^{115}(p,p\pi^{+})Cd^{115}$ for 1-Bev and 2-Bev protons.

		$\sigma_{calc}/\sigma_{exp}$		
Reaction[a]	Product detected	1 Bev Ru^{100} b	2 Bev Ru^{100} b	2 Bev Ce^{140} b
(p,p')	In^{115m}	0	< 0.17	< 1.09
(p,pn)	In^{114m}	$\lesssim 0.33$[c]	$\lesssim 0.01$[c]	$\lesssim 0.10$[c]
(p,p2n)	In^{113m}	< 8.1	< 0.27	< 0.18
(p,p4n)	In^{111}	0.95	0.25	0.10
(p,p5n)	In^{110m}	$\lesssim 1.1$[c]	$\lesssim 0.04$[c]	$\lesssim 0.18$[c]
(p,p6n)	In^{109}	1.8	0.06	0.12
$(p,p\pi^{+})$	Cd^{115}	0[d]	0[d]	0[d]
(p,2p5n)	Cd^{109}	0.33	0.01	0.14
(p,2p7n)	Cd^{107}	0.67	0.21	0.14

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

[b]The cascade calculation was made for the targets Ru^{100} and Ce^{140} and from these results the corresponding products for the target indium were obtained.

[c]The experimental result is for the high-spin isomer and is probably close to that for the isotope (see text and Fig. 1).

[d]No $(p,p\pi^{+})$ cases from calculation. One calculated case corresponds to 0.2 mb.

ratios based on Ru^{100} and as open triangles for ratios based on Ce^{140}. Each point indicated by an arrow directed downward represents an upper limit because the experimental result is for only one of the isomers.

The ratios for indium as a target are in general agreement with those for iodine at the same energy of the incident proton.[1] The calculated results for both iodine and indium are in better agreement with the experimental values at 1 Bev than at 2 Bev. The comparison at 1 Bev for several isotopes of indium is ambiguous, however, because of unmeasured isomers. Although the ratios for In^{109} and Cd^{109} are each far from 1.0 at this energy, the value for the sum of the calculated cross sections of the two nuclides divided by the sum of the experimental results is fairly close to unity. From this point of view, the agreement at 1 Bev is quite good for nuclides with mass number smaller than 113.

All of the calculated cross sections at 2 Bev, with the possible exception of the (p,p') calculation based on Ce^{140}, are much smaller than the measured values. This lack of agreement is also observed at this energy for iodine.[1] In view of our ability to measure only the excited state of In^{115}, the ratio for (p,p') based on Ce^{140} is only an upper limit and, therefore, may not represent an exception. The other cases, in which only upper limits were measured for similar reasons, are the isotopes of indium with masses 110, 113, and 114.

The value of the cross section for the formation of In^{110m} appears to be in line with the values for In^{109} and In^{111} (see Table II and Fig. 1). Measurements of pion-induced reactions in iodine yielding radioactive indium isotopes indicate that the high-spin isomers are formed with much larger cross

sections than the corresponding isomer with low spin.[18] From this we conclude that In^{110m} has a higher spin than does the ground state, in agreement with the known spins of isomers of other even-A isotopes of indium. According to this line of reasoning, we might expect the cross section for the formation of In^{114m} to be nearly equal in value to the total isotopic cross-section. The indium isomers with mass numbers 113 and 115 have a low spin (1/2) relative to that of the ground state (9/2). We therefore conclude that the measured cross-section for In^{113m} is much less than the total cross section for the isotope (Table II and Fig. 1). This reasoning may not be valid for $In^{115}(p,p')In^{115m}$ or, indeed, for $In^{115}(p,pn)In^{114m}$, both being rather special reactions.

In the cascade calculation referred to here, the nuclear density is assumed to drop abruptly to zero at the surface.[14] Since this assumption is not realistic,[19] we should not be surprised at the lack of agreement shown in Table III for the (p,pn), (p,p'), and $(p,p\pi^+)$ reactions. These three reactions, and others like them that can be attributed to a single collision inside the nucleus, should be especially sensitive to the nature of the nuclear surface. They are expected to occur only rarely in the interior of the nucleus because of the probability that the products of the initial collision will interact further to yield a different final nucleus.

The ratio given in Table III for the $(p,p\pi^+)$ reaction, namely zero, is probably not significant because of the statistical uncertainty of the calculation.

The cross section for the formation of Be^7 has been measured only at 6.2 Bev (Table II). No calculation of the cascade process has been made at

this energy. It is, therefore, not possible to make a comparison of the type just presented. The value of the cross section, 14.1 mb, appears to be in line with the values measured by Baker, Friedlander, and Hudis[20] with 3.0 Bev protons incident on a variety of targets, including $Ag^{107,109}$. In their study, little or no change was found in the values of the cross section as a function either of the target or the energy from approximately 2 to 3 Bev with the exception of gold. These results were analyzed by Hudis and Miller in terms of the two-stage mechanism discussed here,[21] namely, a prompt-cascade process followed by evaporation of light particles including Be^7. They were able to account for much, if not most, of the cross-section value by this mechanism for proton energies up to 2 Bev. As we have just seen, this type of calculation fails to account for the (p,pxn) and (p,2pxn) reaction at 2 Bev. A calculation that appears to account for one type of reaction and not another is clearly unsatisfactory.

B. Comparison Based on Shell Model and Diffuse Nuclear Surface

The cross sections of (p,pn), (p,p'), (p,n), and $(p,p\pi^+)$ reactions are expected to be especially sensitive to the initial interaction. The (p,pn) reaction is thought to occur primarily by a direct collision with a surface nucleon (see reference 1 for a discussion of this point). This is probably true of the (p,n) and $(p,p\pi^+)$ reactions also. (The production of the isomer of the target nucleus can occur by other types of reaction as well.) According to this viewpoint, two factors are important: (a) the structural details of the target nucleus, especially its surface, and (b) the nature of the

collision between nucleons and between mesons and nucleons. By taking these factors into account, Benioff has been able to analyze measurements of (p,pn) reactions induced in a variety of targets by multi-Bev protons.[2] These calculations were made with harmonic-oscillator wave functions.

The (p,pn) Reaction

We can use his results to calculate the cross sections of the reaction In^{115} (p,pn) to produce both the isomeric and the ground states of In^{114}. The value of the radius parameter, used for this calculation, is 1.07×10^{-13} cm.[19] The cross sections for the formation of In^{114m} are calculated in this way to be 44 ± 5 mb at 4.1 Bev, as compared to the experimental value of 57 ± 17 mb, and 41 ± 5 mb at 6.2 Bev, as compared to the experimental value of 59 ± 18 mb. The errors indicated for the calculated values are Benioff's estimate of the uncertainty of the total proton-neutron collision cross sections plus that due to the possible contribution of processes that follow the initial interaction.[2] Other uncertainties in the calculation are not included in the indicated error. The uncertainty indicated in the experimental values is the 30% error previously assigned. Because of the possible contribution of secondary reactions in thick targets, the value of 70 mb at 6.2 Bev is not included in the average.

The calculated and experimental values agree within the indicated uncertainties. This calculation has not been made at 2 Bev. At this energy we would expect a slightly larger calculated value than for the higher energies because of the larger total p-n collision cross section and the smaller meson multiplicity. The latter effect would allow a greater probability for the products of the initial interaction to escape.

At 4 and at 6 Bev, the calculated cross section for the formation of the ground state of In^{114} is 5 mb, or approximately 10% of the total (p,pn) cross section. The calculation of the isomer ratio is based on reference 2. Apparently, the high-spin isomer is formed in preference to the low-spin isomer.

Reactions with No Change in Mass Number

The collision processes contributing to (p,p'), (p,n), and $(p,p\pi^+)$ reactions can be estimated in a similar way. In the calculations given below we assume that these reactions proceed as follows: The incident proton penetrates the nucleus for a distance that depends on the density of nucleons and the total p-p and p-n collision cross sections. The incident proton then collides with a neutron or proton in one of the shells that are available for the nuclear reaction under consideration. One of the two nucleons and any mesons that have been produced in this collision escape from the nucleus. The second nucleon is left behind but cannot have an energy smaller than a certain value, E_F, which would leave it in a state already occupied. On the other hand, it must have an energy less than a certain value, $E_F + \Delta E$. Otherwise, it or another particle will escape. In that event, a different type of reaction will occur. We will assume that all energies are allowed in this range. This assumption is partially justified if collective states and single-particle states of one or more nucleons are available for accomodating the energy of the second nucleon. The mechanism by which any of these states may be directly excited is obscure. We will disregard complex questions like this in order to proceed with an unsophisticated calculation that may shed light on the nature of these nuclear reactions.

We will first develop a method to calculate the cross section, $\sigma_{\Delta E}$, for producing a nucleon with an energy in an allowed range, $E_F < E < E_F + \Delta E$, for elastic and inelastic collisions. We will then determine the value of ΔE for each available shell. This will permit us to determine the values of $\sigma_{\Delta E}$. Finally, we will modify the results of Benioff's treatment of the (p,pn) case in order to complete the calculation of the (p,p'), (p,n), and (p,pπ^+) reaction.[2]

Above 1 Bev, the differential cross section for elastic nucleon-nucleon scattering can be expressed as

$$\frac{d\sigma}{d\Omega} = \text{constant} \cos^N\theta. \tag{1}$$

The value of N was determined from p-p scattering data and is assumed to be the same for p-n scattering.[22] From this can be derived the following expression for $\sigma_{\Delta E}$ if the struck nucleon is at rest ($E_F = 0$):

$$\sigma_{\Delta E} = [1 - (1 - 2\Delta E/E_p)^{N+1}] \ \sigma_0, \tag{2}$$

where E_p is the energy of the incident proton, and σ_0 is the total elastic cross section.

The values of $\sigma_{10}(\Delta E = 10 \text{ Mev})$ are given in Table IV for protons of various energies incident on protons and on neutrons. Also listed are the values of N and σ_0 from reference 22, as well as those of $1 - (1 - 2\Delta E/E_p)^{N+1}$.

Two features of these results that merit attention are the relative constancy of σ_{10}/σ_0 from 1 to 6 Bev and the constancy of σ_{10} from 4 to 6 Bev.

It is not possible to calculate, in such a simple manner, the value of $\sigma_{\Delta E}$ for $E_F \neq 0$. The values of σ_{10} for $E_F = 18.78$ Mev ($E/M_0c^2 = 0.020$) have been computed on an IBM-701 computer for E_p equal 2, 4, and 6 Bev (Table V).[22]

Table IV

The cross section, σ_{10}, to produce a nucleon with an energy less than 10 Mev in elastic p-p and p-n collisions as a function of the proton energy, E_p, in Bev.[a] $d\sigma/d\Omega = \text{const} \cos^N\theta$

E_p	N	$\sigma_{10}/\sigma_o = 1-(1-0.02/E_p)^{N+1}$	σ_o(p-p) (mb)	σ_{10}(p-p) (mb)	σ_o(p-n) (mb)	σ_{10}(p-n) (mb)
1.0	4	0.0961	19.9	1.91	17.3	1.66
1.5	8	0.1138	20.4	2.32	12.5	1.42
2.0	11	0.1136	18.0	2.04	10.1	1.15
3.0	14.5	0.0985	13.4	1.32	7.1	0.70
4.0	18	0.0908	9.6	0.87	5.3	0.48
5.0	24.5	0.0972	8.6	0.84	5.0	0.49
6.0	37	0.1192	7.3	0.87	4.1	0.49

[a]The values of N and σ_0, the total elastic cross section, are from reference 22.

Table V

Cross section, σ_{10}, for elastic p-p and p-n collisions to produce a nucleon with an energy less than 10 Mev above E_F, the Fermi energy in Mev.

E_p (Bev)	σ_{10}/σ_o		σ_{10}(p-p) (mb)			σ_{10}(p-n) (mb)		
	E_F=0,	18.78.	E_F=0,	10,	18.78.	E_F=0,	10,	18.78
1.0			1.91	1.70	1.51[a]	1.66	1.47	1.31[a]
2.0	0.0950	0.0887	2.04	1.81	1.60	1.15	1.02	0.90
4.0	0.0910	0.0718	0.87	0.77	0.69	0.48	0.43	0.38
6.0	0.1367	0.0953	0.87	0.78	0.70	0.49	0.44	0.39

[a]Estimated value (see text).

Table VI

The cross section, σ_{10}, for inelastic p-p and p-n collisions as a function of E_F(in Mev) for two different assumptions about the momentum of the pion in the center of mass.

E_p (Bev)	Pion momentum	σ_{10}(p-p) (mb)			σ_{10}(p-n) (mb)		
		E_F=0,	10,	18.78.	E_F=0,	10,	18.78.
2.0	0	0.24	0.39	0.53	0.27	0.46	0.62
	p_n[a]	0	0.04	0.08	0	0.05	0.10
4.0	0	0.13	0.15	0.16	0.13	0.15	0.16
	p_n[a]	0	0.01	0.01	0	0.01	0.01
6.0	0	0.10	0.16	0.21	0.10	0.16	0.21
	p_n[a]	0	0.01	0.01	0	0.01	0.01

[a]Here p_n is the final momentum of the nucleon in the center-of-mass system.

This calculation was made for a degenerate Fermi gas of nucleons. This is not strictly correct in the present context. However, $\sigma_{\Delta E}$ does not depend strongly on E_F. We will assume that it is also insensitive to the nature of the occupied nucleon states. As a check on the computation, the values of σ_{10} for $E_F = 0$ were also determined. At each value of the Fermi energy, the computed values of σ_{10}/σ_0 were almost identical for p-p and p-n collision. The average value from the two types of collision, given in the second and third columns of Table V, was used in the calculation. For $E_F = 0$, the average deviation of the computed values (second column, Table V) from that obtained by use of Eq. (3) (third column of Table IV) is approximately 10%. This deviation is statistical in origin. The values of σ_{10} for $E_F = 0$ in Table V are taken from Table IV. The ratio of σ_{10} at $E_F = 18.78$ Mev to that at $E_F = 0$ is 0.79 ± 0.01 at the three energies for both p-p and p-n collisions and is assumed to have this value at 1.0 Bev. The value of E_F for the nucleons that are important in these simple nuclear reactions is approximately 10 Mev.[2] The values of σ_{10}, obtained for $E_F = 10$ Mev by linear interpolation, are given in Table V.

The values of σ_{10} arising from inelastic collision were also computed by the method given in reference 22 for two values of E_F, 0 and 18.78 Mev (Table VI). The value listed for $E_F = 10$ Mev was obtained by linear interpolation. The calculation was made for two different assumptions about the momentum of the pions that are produced in inelastic nucleon-nucleon collisions, in order to test the sensitivity of the results to the details of the collision process. In one calculation, the pion momentum was assumed to be zero in the center of mass; in the other, it was assumed to be equal to the final nucleon momentum in the center of mass (for further information see reference 22). As will be seen

later, the major contribution to the (p,p') and (p,n) reactions is from the elastic collisions. For these reactions it is necessary to obtain only an order-of-magnitude value for the contribution of inelastic nucleon-nucleon collisions. However, only inelastic collisions can contribute to the $(p,p\pi^+)$ reaction. We will proceed with the latter calculation anyway as a possible guide to later, more accurate calculations.

As can be seen from Table VI, the two assumptions give very different but small values for the inelastic collisions. The resulting values of σ_{10} (inelastic) at 2.0 Bev are 0.22 ± 0.18 mb for p-p collisions and 0.26 ± 0.21 mb for p-n collisions. For both p-p and p-n collisions at 4 and 6 Bev the values are 0.08 ± 0.08 mb.

To a good approximation, we have

$$\sigma_{\Delta E} = \Delta E \cdot \sigma_{10}/10 \tag{3}$$

at various values of E_F. This can be readily seen in the elastic case for $E_F = 0$; cf. Eq. (2).

The value of ΔE can be calculated from the equation

$$\Delta E = E_B - E^*, \tag{4}$$

where E^* is the least energy required to move the nucleon from its shell in the target nucleus and E_B is the neutron binding energy of the final nucleus. None of the three reactions can occur if ΔE is less than zero. The value of E_B for protons (the proton binding energy plus the effective Coulomb barrier) is rarely smaller than that for neutrons in the case of targets with relatively large nuclear charge.

In calculating the (p,p'), (p,n), and (p,pπ^+) cross sections, it is necessary to determine the probability, M, integrated over the entire nucleus, that the incoming proton will arrive at a point in the nucleus where an appropriate collision occurs, followed by the escape of a proton (or neutron) in the elastic case, or by the escape of a nucleon and mesons in the inelastic case.

The value of M for each shell was determined from Benioff's values of $M_{p,pn}$,[2] interpolated to the radius parameter, 1.07×10^{-13} cm. A correction was made for the entrance cross section at each incident-proton energy. We have taken the average of the total p-p and p-n cross sections, σ_T, for this calculation.[22] These values of σ_T in mb are 42.0 at 1.0 Bev, 42.2 at 2.0 Bev, 33.4 at 4.0 Bev, and 31.7 at 6.0 Bev. Benioff used 30 mb. For the escape cross section of the nucleons and mesons in the (p,pn) reaction he used 180 mb. In the (p,p') and (p,n) reactions resulting from elastic p-p and p-n collisions, the corresponding escape cross section is merely σ_T.

For the inelastic case, we have subtracted the cross section of one nucleon from 180 mb to obtain the appropriate exit cross section. The average value, 143 mb, was used in this calculation for the energy range of 1 to 6 Bev. According to Benioff, the correction varies inversely as the square root of the entrance and exit cross sections.[2] Therefore, we get

$$M = \frac{(30 \times 180)^{1/2}}{\sigma_T} M_{p,pn} \tag{5}$$

for the elastic case, and

$$M = \left(\frac{30 \times 180}{\sigma_T \times 143}\right)^{1/2} M_{p,pn} \tag{6}$$

for the inelastic case.

The contribution of each shell, σ_ℓ, to the total cross section can be calculated from

$$\sigma_\ell = (\Delta E \cdot n_{p \text{ or } n} \cdot M)_\ell \, g\sigma_{10}/10, \tag{7}$$

where $n_{p \text{ or } n}$ is the number of protons or neutrons in the shell, and g is a factor that depends on the type of collision.

All of the elastic p-p collisions that result in the retention of a nucleon lead to the (p,p') reaction. For this case, we have g = 1. Elastic p-n collisions can lead to the (p,p') or to the (p,n) reaction with equal probability, according to Eq. (1). Thus, we have g = 1/2 for these cases.

The inelastic collisions can also contribute to the (p,p'), (p,n), and $(p,p\pi^+)$ reactions. Of the reactions between two protons that lead to single meson production,

$$p + p = p + p + \pi^0 \tag{8}$$

and

$$p + p = p + n + \pi^+, \tag{9}$$

the latter can contribute to the (p,p') or to the $(p,p\pi^+)$ reaction. A similar effect will be present for multiple-meson production. The production of deuterons can also occur. This type of event will probably not result in the nuclear reactions under consideration. The inelastic p-n collisions can be analyzed in the same way. We will assume that one-half of σ_{10} from the inelastic p-p and p-n cross sections will contribute to the (p,p') reaction, i.e., g = 1/2 for this case. For similar reasons, we assume that g = 1/2 for the inelastic contributions to the (p,n) reaction. Collisions of the type given by Eq. (9) but not Eq. (8) can contribute to the $(p,p\pi^+)$ reaction. Hence, we take g = 1/4 for the $(p,p\pi^+)$ reaction.

Our estimate of the product, $g\sigma_{\Delta E}$, for inelastic p-p and p-n collisions and for elastic p-n collisions is admittedly poor. The data that pertain to this question are incomplete. We will, therefore, not attempt to refine the treatment given here at this time.

Finally, the total cross section will be the sum of the values of σ_ℓ from the elastic and inelastic p-p and p-n collisions that contribute to the nuclear reaction in question.

Calculations will be made only for the(p,p') and $(p,p\pi^+)$ reactions. The $In^{115}(p,n)Sn^{115}$ reaction cannot be studied by radiochemical methods because the product is stable. The discussion that follows for the (p,p') reaction can be applied, with the appropriate value of E_B, to the (p,n) reaction. The latter case is relatively simple because only neutron shells are involved in the (p,n) reaction according to the mechanism we are considering.

<u>The (p,p') reaction</u>. The energies of the shells, E_s, in In^{115} were estimated from the theoretical treatment of Ross, Mark, and Lawson[23] and are given in the third column of Table VII for protons and Table VIII for neutrons in the shells designated in the first column. The number of protons (or neutrons) in each shell is given in the second column.[24] In the fourth column of Tables VII and VIII are listed the values of ΔE for the (p,p') reaction. The neutron binding energy, E_B, was calculated from Wapstra's table of masses to be 9.4 Mev.[25] The value of ΔE for the $1g^{9/2}$ shell, which is occupied by an odd number of protons, is equal to E_B because we have $E^* = 0$. In the case of all the other shells, a nucleon pair must be broken. We have taken the pairing energy for the protons of In^{115} to be 1.4 Mev and for the neutrons to be 1.3 Mev.[26] Because two unpaired nucleons are formed, the value of E^* for these

Table VII

Values of ΔE for protons in the $In^{115}(p,p')$ reaction and for neutrons in the $In^{115}(p,p\pi^{+})Cd^{115}$ reaction

Shell	n_p	E_s (Mev)	$\Delta E(p,p')$ (Mev)	$\Delta E(p,p\pi^{+})$ (Mev)
$1g^{9/2}$	9	0	9.4	6.0
$2p^{1/2}$	2	-0.3	6.3	2.9
$2p^{3/2}$	4	-2.0	4.6	1.2
$1f^{5/2}$	6	-2.4	4.2	0.8

Table VIII

Values of ΔE for neutrons in the $In^{115}(p,p')$ reaction

Shell	n_n	E_s (Mev)	ΔE (Mev)
$1h^{1/2}$	2	0	6.8
$1g^{7/2}$	8	-2.0	4.8
$2d^{5/2}$	6	-2.3	4.5

shells is equal to twice the pairing energy minus the value given in the third column. The shells listed in Tables VII and VIII are the only ones for which ΔE is greater than zero, according to Ross, Mark, and Lawson.[23] The deeper shells are members of shell systems containing a magic number of nucleons. Hence, there is a large gap in energy to the next lower shell.[24]

The values of ΔE given in the last column of Table VII are for the $(p,p\pi^+)$ reaction (see below).

The values of σ_ℓ and $\sigma(p,p')$ were calculated by means of Eq. (7) and are shown in Table IX. Also included for comparison are the experimental values from Table II. We have extended Benioff's treatment to lower energies than are justified for the (p,pn) reaction. His calculations were made with the assumption that the particles from the primary interaction leave the nucleus with the same direction as the incident proton.[2] At the lower energies this assumption is still valid for the elastic part of the (p,p') and (p,n) reactions. Otherwise, the remaining nucleon would have too high an energy for this type of reaction.

The contribution of inelastic p-p and p-n events to the (p,p') reaction is calculated to be insignificant. This is also true of the (p,n) reaction. The calculated values of $\sigma(p,p')$ vary with the energy of the incident proton like $\sigma_0(p\text{-}p)$ and $\sigma_0(p\text{-}n)$ (Table IV). This is contrary to the trend of the experimental excitation functions. The cross section of the $In^{115}(p,p')In^{115m}$ reaction at 1 Bev is the smallest of the measured values. Its value at 4 or 6 Bev is larger than the calculated value for the total (p,p') reaction by a factor of two or three. Of course, the discrepancy would be greater were we able to add the cross section for the formation of the ground state to the measured value.

Table IX

Calculated and experimental cross sections of the reaction $In^{115}(p,p')$ and the calculated contribution, σ_ℓ, from proton and neutron shells

	Calculated						
	E_p = 1.0 Bev	E_p = 2.0 Bev		E_p = 4.0 Bev		E_p = 6.0 Bev	
Shell	el	el	inel	el	inel	el	inel
		σ_ℓ from p-p collisions (mb)					
$1g^{9/2}$	1.64	1.73	0.06	0.93	0.02	0.99	0.02
$2p^{1/2}$	0.21	0.23	0.01	0.12	0.00_3	0.13	0.00_3
$2p^{3/2}$	0.31	0.33	0.01	0.18	0.00_4	0.19	0.00_5
$1f^{5/2}$	0.25	0.27	0.01	0.15	0.00_4	0.15	0.00_4
Sum	2.41	2.56	0.09	1.38	0.03	1.46	0.03
		σ_ℓ from p-n collisions (mb)					
$1h^{11/2}$	0.19	0.13	0.02	0.07	0.01	0.07	0.01
$1g^{7/2}$	0.32	0.22	0.03	0.12	0.01	0.13	0.01
$2d^{5/2}$	0.36	0.25	0.03	0.13	0.01	0.14	0.01
Sum	0.87	0.60	0.08	0.32	0.03	0.34	0.03
$\sigma_T(p,p')$[a]	~3.5 ± 0.2	3.33 ± 0.17 mb		1.76 ± 0.06 mb		1.86 ± 0.06 mb	

	Experimental			
		E_p = 2.0 Bev	E_p = 4.1 Bev	E_p = 6.2 Bev
$\sigma_T(p,p')$[b]	1.7	4.1 ± 0.6 mb	5.0 mb	4.2 ± 0.6 mb

[a]Total calculated cross sections for elastic plus inelastic interactions.

[b]Values from Table II.

A possible explanation of these discrepancies is Coulomb excitation of the target nucleus. To our knowledge, the theory of this process has not been developed for the relativistic range of energies encountered here. We are, therefore, unable to estimate the magnitude of this effect.

The many uncertainties in the calculation are difficult to assess. Hence, the comparison of the calculated and experimental cross sections at any one energy may not be very meaningful. However, the trends of the excitation functions are probably significant. The fact that the trends are not in agreement indicates that the calculation is incorrect or that the isomer ratio changes with energy.

Because of the contribution of the $In^{115}(p,p2n)In^{113m}$ reaction, the $In^{113}(p,p')In^{113m}$ reaction could not be studied here. This type of investigation requires the use of the separated In^{113} isotope as a target.

<u>The $(p,p\pi^+)$ reaction</u>. The $In^{115}(p,p\pi^+)Cd^{115}$ cross sections can be analyzed in the same way. However, this case is different in an important respect: only inelastic p-p collisions contribute to the $(p,p\pi^+)$ reaction.

A new set of values is needed for ΔE. These are given in the last column of Table VII. In calculating ΔE we have assumed that the incident proton provides, in some unspecified way, the energy required to change In^{115} into Cd^{115}. In this point of view, E^* is merely the minimum excitation energy of the Cd^{115} nucleus for various proton configurations. Thus, when a $1g^{9/2}$ proton is replaced by a neutron, we get $E^* = 0$ and $\Delta E = E_B = 6.0$ Mev,[25] the neutron binding energy in Cd^{115}. We assume here that there are eight $1g^{9/2}$ protons in the ground state of Cd^{115} and that the other proton shells have the energies, E_s, as shown in Table VII. Therefore, the values of ΔE have been calculated

in the same way as for the (p,p') reaction but with E_B = 6.0 Mev. They are listed in Table VII.

The cross sections of the $(p,p\pi^+)$ reaction and the individual values of σ_ℓ are given in Table X, as calculated by means of Eq. (7) with the values of M previously determined by means of Eq. (6). The values of σ_{10} that go into the calculation are those due to inelastic p-p collisions at E_F = 10 Mev, given in Table VI. The calculation was repeated with the sets of values based on the two assumptions about the momentum of the pion in the center-of-mass system; (a) that it is equal to the final nucleon momentum, or (b) that it is zero.

Also shown in Table X for comparison are the experimentally determined $(p,p\pi^+)$ cross sections from Table II. The value obtained at 6.2 Bev with the thickest indium target is not included because of possible contamination from secondary reactions.

The calculated values disagree completely with the experimentally measured $(p,p\pi^+)$ cross sections. The assumption that the momentum of the pion in the center-of-mass system is zero gives values that are too low by a factor of about 100. The calculated values based on the other assumption are small by a factor of 5 or 10.

It is apparent that the calculation needs improvement. A major source of uncertainty results from the inadequate treatment made here of inelastic nucleon-nucleon scattering. This point will be taken up in the following section.

Table X

Calculated and experimental cross sections of the reaction $In^{115}(p,p\pi^+)Cd^{115}$ and the calculated contribution, σ_ℓ, in microbarns (μb) from proton shells for two different assumptions about the momentum of the pion in the center of mass

Shell	Calculated E_p = 2.0 Bev	E_p = 4.0 Bev	E_p = 6.0 Bev
	Momentum of π = momentum of nucleon		
$1g^{9/2}$	32	14	15
$2p^{1/2}$	3	1	1
$2p^{3/2}$	3	1	1
$1f^{7/2}$	2	1	1
$\sigma_T(p,p\pi^+)$	40 μb	17 μb	18 μb
	Momentum of π = 0		
$1g^{9/2}$	3	1	1
$2p^{1/2}$	0.3	0.1	0.1
$2p^{3/2}$	0.3	0.1	0.1
$1f^{5/2}$	0.2	0	0
$\sigma_T(p,p\pi^+)$	4 μb	1 μb	1 μb
	Experimental E_p = 2.0 Bev	E_p = 4.1 Bev	E_p = 6.2 Bev
$\sigma_T(p,p\pi^+)$[a]	210 μb	220 μb	160 μb

[a]Values from Table II

CONCLUSION

The preceding discussion may be summarized as follows:

(a) The values of the cross sections for the formation of indium and cadmium isotopes are essentially constant for incident-proton energies from 1.0 to 6.2 Bev. Possible exceptions are the values for Cd^{115} and In^{115m} at 1.0 Bev.

(b) The values of all the cross sections as calculated on the basis of the Fermi-gas model with constant nuclear density at 2 Bev are too small, compared to the experimental values. There is good agreement at 1 Bev for nuclides with mass number less than 113.

(c) The calculation for the reaction, $In^{115}(p,pn)In^{114m}$, at 4.1 and 6.2 Bev, made by taking into account the details of the nuclear structure of indium, agrees with the experimental values of the cross section within the uncertainties of the measured and calculated values. The corresponding reaction to form the ground state of In^{114} is calculated to be approximately 10% of the total (p,pn) cross section.

(d) The calculated value of the total cross section of the (p,p') reaction at 4 and 6 Bev is smaller than the measured value of that part leading to In^{115m} only. At 1 Bev the measured value for In^{115m} is smaller than the total calculated value.

(e) The calculated values of the $(p,p\pi^{+})$ reaction are 1/5 to 1/100 of the measured values.

It is obvious from these observations and from the results of the preceding study on iodine[1] that our understanding of nuclear reactions induced by high-energy particles is incomplete.

Thus, processes other than direct interactions may contribute to these reactions in which only a small amount of energy is transferred to the nucleus. An example of this is Coulomb excitation of the target nucleus to the isomeric state in the case of the (p,p') reaction. Presumably, the cross section for such a process would depend sensitively on the spins of the ground and excited states. Several other targets, in addition to indium, are suitable for such a study. Excitation of the giant resonance, which has been observed with gamma-ray irradiation,[27] probably can occur with high-energy charged particles. This process could lead to the loss of one or two units of mass by the target nucleus. The good agreement found for the cross section of the (p,pn) reaction, calculated by means of Benioff's treatment,[2] with the experimental value suggests that this process does not contribute in an important way to the (p,pn) reaction. A comparison of (n,n') reactions, which cannot involve Coulomb excitation, with the (p,p') reaction, which can, should provide direct information on the importance of Coulomb excitation.

The (p,n) and $(p,p\pi^+)$ reactions require some kind of direct interaction between the incident proton and a nucleon in the target. According to the analysis presented in the section entitled "Discussion", the (p,n) and (p,p') reactions proceed by way of elastic p-p and p-n collisions. The $(p,p\pi^+)$ reaction can occur only by means of an inelastic process. Thus the study of these three reactions with various targets affords an opportunity for assessing the relative importance of elastic and inelastic nucleon-nucleon collisions and of processes such as Coulomb excitation. A careful investigation of the energies the retained nucleon may have is needed. For this purpose more information on excited nuclear states than is now available is certainly desirable.

An adequate study of $(p,p\pi^+)$ reactions requires the careful analysis of inelastic p-p scattering data. Because this is a major effort in itself, we have not attempted to do this. However, the general procedure outlined here together with such a careful analysis may be successful in evaluating the results of $(p,p\pi^+)$ experiments.

The over-all calculation for (p,pxn) and (p,2pxn) reactions has been made only for the Fermi-gas model of the nucleus. The results of the study reported here on indium and in the preceding paper on iodine[1] indicate that such an analysis predicts the correct cross sections of these reactions for x greater than 1 at energies of 1 Bev and less with few exceptions and fails to do so at 2 Bev. The excitation functions of almost all reactions that have been studied in the multi-Bev region of proton energies are constant within experimental error.[28] It is difficult for us to explain these observations except that there are serious defects in the cascade calculations for incident-proton energies above 1 Bev. The inclusion of a proper description of the nuclear surface is, of course, required in the calculation. However, we cannot see that this by itself will lead to the prediction of constancy in the excitation functions at the higher energies.

Perhaps the assumption, basic to the calculations, that nucleon-nucleon scattering inside a nucleus is in no essential way different from that for free nucleons, except for exclusion, is incorrect. It would be interesting to see what modifications in this assumption lead to better agreement with the experimental results. Meson production and readsorption is presumably an effective means for producing nuclear excitation. Therefore a possible modification in the calculations would be to keep the meson

multiplicity constant in the multi-Bev range of incident proton energies. Whether this improves the comparison or not remains to be seen.

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