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EXCITATION FUNCTIONS FOR REACTIONS OF BEV PROTONS ON INDIUM

David R. Nethaway
(Master's Thesis)

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ABSTRACT

Indium was bombarded with protons in the energy range 2 to 6 Bev. Cross sections are reported for the $(p,p\pi^+)$, (p,pn), and (p,p') reactions, as well as those for the formation of Be^7 and several neutron deficient isotopes of cadmium and indium. It was found that the (p,pn) yield increases slowly in the energy range 2 to 6 Bev, while the $(p,p\pi^+)$ and (p,p') yields are approximately constant. The variation of the (p,pn) and $(p,p\pi^+)$ yields with target thickness is discussed. The yields of several isomeric levels are correlated with their nuclear spin.

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I. INTRODUCTION

Studies are presently being made of the fission-spallation products of several elements when exposed to the 6 Bev proton beam of the Bevatron at Berkeley. Among these target elements are uranium,[1] tantalum, copper, and several light elements. It was felt desirable to measure the cross sections for several particular reactions using a target material in the intermediate-mass region. This would help determine any mass dependence of certain reactions, and would be of considerable interest in the extension of data taken at lower bombarding energies.

Meson production becomes increasingly important in nuclear reactions as the bombarding energy is increased from a few hundred Mev into the Bev region.[2] The meson formation and reabsorption processes provide an important mechanism for the transfer of energy to the nucleons. The mesons produced by the primary nuclear collisions have a rather large chance of undergoing further interactions with nucleons, and so thereby further contribute to the nuclear excitation. Meson reabsorption has been shown to be greater in heavy nuclei.[3]

S. Fung and A. Turkevich[4] gave experimental proof of the $(p,p\pi^+)$ reaction using radiochemical methods by measuring the cross section for Ni^{65} production from Cu^{65} at energies up to 440 Mev. They showed that the cross section increased steadily from the threshold at about 200 Mev. J. W. Jones[5] measured the yield of Mg^{27} from Al^{27} with 430 Mev protons, and found substantial agreement with the value for Ni^{65} from Cu^{65}, if allowance was made by means of an $A^{2/3}$ dependence for a decrease in yield due to a decrease in cross-sectional area.

Measurements have also been made at 6 Bev on the cross section for the Cu^{65} $(p,p\pi^+)$ Ni^{65} reaction by D. W. Barr,[6] and for the Al^{27} $(p,p\pi^+)$ Mg^{27} reaction by P. A. Benioff.[7] It was found that the yields have increased by approximately a factor of two at 6 Bev, over those at 400 Mev.

Meson production might be expected to have an effect on the yields of other reactions. Such reactions as $(p,p\pi^0)$ and $(p,n\pi^+)$ would raise the observed apparent (p,p') cross section. A much larger effect on the apparent (p,p') yield could also be produced by a mechanism involving a low energy transfer by protons of very high angular momentum. This low energy excitation would leave the nucleus with insufficient excitation energy for nucleon emission, and would be seen as an increased yield of an isomeric level.

The yields of the (p,pn) reaction have been measured by S. Markowitz[8] for several target elements and for bombarding energies up to 3 Bev. It was found that in the energy range 1 to 3 Bev the (p,pn) cross section increases slowly, on the order of 10%, and that in general the cross sections were higher in the imtermediate-mass region than in the light element and possibly also the heavy element regions. The yields of the (p,pn) reaction on carbon[3] and cerium[9] have also been measured up to 3 Bev and found to be essentially constant above 1 Bev.

The cross sections for formation of Be^7 are being measured in this laboratory for a number of target elements. Be^7 is of special interest, as it is the lightest nuclide (except for H^3) that can be measured radiochemically, and it is hoped that the mechanism involved in its production can be better understood through these studies. The production of Be^7 was measured by Hudis, Baker, and Friedlander[10] from targets of carbon, aluminum, copper, silver, and gold at energies up to 2.2 Bev. They concluded that, except possibly for the carbon target, the Be^7 was formed principally by direct ejection from the excited nucleus. Other measurements of Be^7 yields from aluminum and copper targets at energies up to 2 and 3 Bev have also been reported.[11,12,13]

Indium was chosen as the target material in this investigation because of its intermediate mass, its availability as a foil, and the fact that the $(p,p\pi^+)$ reaction leads to a pair of isomers, both of which are susceptible to radiochemical analysis. The ratio of the yields of the two isomers (Cd^{115}—Cd^{115m}) is of considerable interest in determining the relationship between the yield of an isomeric state and its nuclear spin. Current theory suggests that higher spin states are more heavily populated at higher excitation energies. Another reason for

chosing indium is the fact that In^{115} has an isomeric state which makes it possible to measure the (p,p') yield.

In this investigation the yields of the following reactions were measured:

$$In^{115}\ (p,p\pi^{+})\ Cd^{115},\ Cd^{115m}$$

$$In^{115}\ (p,p')\ In^{115m}$$

$$In^{115}\ (p,pn)\ In^{114m}$$

$$In^{115}\ (p,--)\ Be^{7}$$

as well as those for the formation of several other neutron-deficient indium and cadmium isotopes. The indium was bombarded with protons in the energy range 2.0 to 6.2 Bev in order to determine the energy dependence of the various reactions.

By measuring the isotopic yield curve for indium it was possible to predict some of the missing isomeric yields and thereby determine the nuclear spin--yield relationships. It was hoped that an understanding of the effect of nuclear spin on isomeric yield would enable one to make a better interpretation of those cross section measurements where it is impossible to measure the yields of all the isomers of a particular nuclide.

II. EXPERIMENTAL PROCEDURES

A. Arrangement of Target

Each target consisted of a stack of foils (3/4" x 2") arranged as shown in Fig. 1. The 3 mil aluminum foil was used for a beam monitor, and the 1 mil aluminum foils were used as a protection from recoil and secondary particles. The foils were stacked together so that the edges were aligned as closely as possible with the aid of a magnifying glass, and held in place with a few small pieces of scotch tape. They were then inserted into a lucite holder especially designed for bevatron targets. The edge of the foil stack protruded 1-1/4" from the end of the lucite holder. After the bombardment the outer 1" of the foil stack was cut off with scissors and used for radiochemical analysis, and the remainder of the foils was discarded. The loss of radioactivity in the unused portion was negligible.

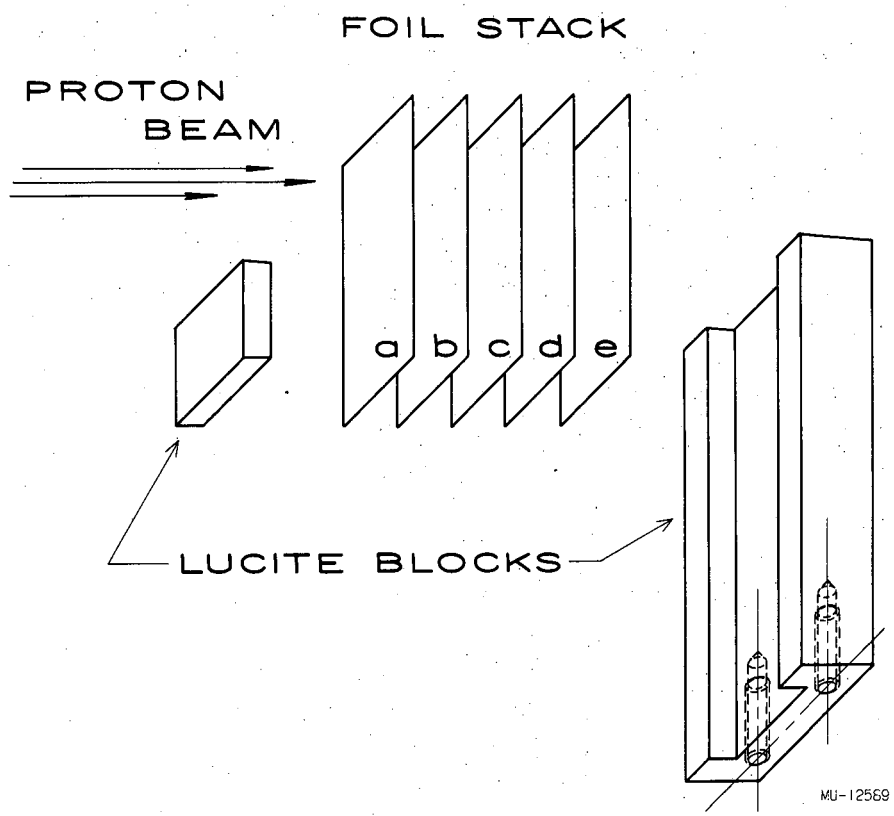

Figure 1. Details of foil stack and lucite holder

a,c,e	1 mil aluminum foils	2" x 3/4"
b	3 mil indium foil	
d	3 mil aluminum foil	

Ideally, it would be best to use a bare indium foil as thin as possible, in order to minimize secondary reactions caused by neutrons and other light particles produced from reactions in the target foils. Since the (n,p) cross section can be much higher than that for the $(p,p\pi^+)$ reaction, it is best to keep the neutron flux as low as possible. Similarly the apparent (p,p') and (p,pn) cross sections could be raised by interfering secondary reactions.

However, in order to measure the proton beam, it is necessary to use an additional aluminum foil as an external monitor, as no internal monitor is available. Indium foil much thinner than three mils lacks sufficient structural strength to withstand the motion of the target during bombardment. Since the proton beam travels in a circular orbit of constant radius, it is necessary to have the target out of the orbit during the acceleration period. The target is then inserted briefly into the beam at the right moment by means of an air-driven ram.

Most of the experiments were made using the foil assembly described above, with a total thickness of 97 mg/cm^2. Two additional bombardments were made using a thicker (476 mg/cm^2), and a thinner (26 mg/cm^2) target to determine the effect of target thickness on several of the cross sections. The thicker target was made up of a 3 mil aluminum foil, eight 3 mil indium foils, and a 1 mil aluminum guard foil. The thinner target consisted of a piece of 1 mil indium foil scotch taped to a 1 mil aluminum foil. The 1 mil indium was obtained by rolling out a piece of 3 mil foil.

B. Target Material

The 3 mil indium foil was obtained from the Indium Corporation of America and had a stated purity of 99.9+%. Spectroscopic analysis of the indium showed the presence of 0.01% tin, 0.01% zinc, 0.002% copper, and 0.006% lead. Typical detection limits for other elements were: < 0.1% for thallium, iron; < 0.05% for cadmium, tungsten; < 0.005% for bismuth. The aluminum foils were cut from ordinary 2-S aluminum stock.

C. Beam Monitor

In order to determine absolute cross sections it was necessary to have some measure of the number of incident protons striking

the desired target area. This was accomplished by means of the Al^{27} (p,3pn) Na^{24} reaction, which has fairly well-known cross sections at the energies used. The radiations from the three mil aluminum monitor foils were counted directly in a proportional counter, after short-lived activities had decayed.

The cross section for this reaction is only known approximately in the energy range 2 to 6 Bev, but additional measurements will almost certainly provide a more accurate value in the near future. The cross section for the reaction C^{12} (p,pn) C^{11} has been measured up to 4.1 Bev[14,15] and the ratio of the cross sections for the formation of C^{11} and Na^{24} has been measured up to 3 Bev,[3,16] so that the cross section for Na^{24} formation can be computed and the results extrapolated to 6 Bev. For the results reported in this paper, the Na^{24} formation cross section was assumed to be constant from 2.0 to 6.2 Bev and equal to 10.5 millibarns. The error in this value is estimated to be less than ± 30%.

D. Chemical Separations

1. Initial separations:

After bombardment the indium foil was weighed and then dissolved in a solution of HCl, HNO_3, and 10-20 mg quantities of the appropriate carrier solutions. The excess acid was boiled out, and the solution taken almost to dryness. Fifty ml of 4.5 M HBr were added and the solution contacted with 75 ml of diethyl ether for 1 - 2 min. The aqueous phase (containing the cadmium and the beryllium) was separated from the ether phase (containing the indium). The HBr was boiled out of the aqueous phase, and the Be $(OH)_2$ was precipitated with excess NH_4OH. The Be $(OH)_2$ was then saved for further purification. The NH_4OH was boiled out of the supernatant solution with addition of NaOH pellets. The resulting Cd $(OH)_2$ precipitate was then saved.

The original ether phase, containing the indium, was washed two times with 25 ml of 4.5 M HBr. The ether was then evaporated and the solution taken up in dilute HCl. An aliquot was taken from this solution which contained approximately 40 mg of indium. This aliquot was then used in the indium chemical separations.

2. Purification of beryllium fraction:

The procedure used was a modification of one given by G. M. Iddings.[17] The Be $(OH)_2$ precipitate was dissolved in HCl, and Fe $(OH)_3$ was precipitated three times with NaOH and discarded. The final supernatant solution was acidified with HCl and Be $(OH)_2$ precipitated with NH_4OH. The Be $(OH)_2$ precipitation was repeated using saturated NH_4Cl. The Be $(OH)_2$ was dissolved in a minimum amount of HCl, and 15 ml of a 0.5 M Na_2SO_3 -- 1 M $NaHSO_3$ buffer solution added. The beryllium was then extracted from this solution into 30 ml of 0.4 M TTA (thenoyltrifluoracetone) in benzene. The organic phase was washed with H_2O (twice), 8 M HNO_3 (twice), H_2O, 1 M NaOH (twice), and H_2O. The beryllium was then extracted (twice) back into 15 ml of a 2:1 formic acid-HCl mixture. Be $(OH)_2$ was precipitated from this with excess NH_4OH, and then dissolved in 1 ml of HNO_3. The solution was evaporated to dryness and dried for one hour at 1000°C. The BeO was then slurried into a filter chimney and mounted for counting of the radiations.

3. Purification of cadmium:

The procedure used was the one given by H. G. Hicks,[17] which consists of two Fe $(OH)_3$ scavenging precipitations with NH_4OH, a Cd $(OH)_2$ precipitation with NaOH, a mixed palladium-antimony sulfide scavenging precipitation from 2 M HCl, absorption on a Dowex-A-1 resin anion column, followed by a 0.1 M HCl wash and elution of the cadmium with 1.5 M H_2SO_4, and a CdS precipitation from hot 0.7 M H_2SO_4. The CdS was then slurried into a filter chimney and mounted.

4. Purification of indium:

The procedure used was a modification of one given by G. A. Cowan.[18] Excess NH_4OH was added to the indium aliquot precipitate In $(OH)_3$ in the presence of milligram quantities of hold-back carriers of cadmium, silver, palladium, molybdenum, copper, nickel, and cobalt. The In $(OH)_3$ was dissolved in 1 M HCl. 2 ml of 5% sulfosalicyclic acid (in H_2O), 5 ml of a 1 M acetic acid -- 2 M sodium acetate buffer, and 1 mg of antimony carrier were added. The sulfides were then precipitated with H_2S. 1 M HCl was added to the precipitate and the solution boiled. The Sb_2S_3 precipitate was then discarded. These steps were

then repeated from the beginning. In $(OH)_3$ was again precipitated with NH_4OH. To the precipitate were added 10 mg silver, 4 mg zirconium, 15 ml of 1 M HCl, and 1/2 ml of H_3PO_4. The mixed AgCl and $Zr_3(PO_4)_4$ precipitate was discarded. In $(OH)_3$ was again precipitated with NH_4OH, and then dissolved in 1 M HCl. 2 ml of 5% sulfosalicyclic acid and 5 ml of the acetate-acetic acid buffer were added and In_2S_3 precipitated with H_2S. The In_2S_3 was slurried into a filter chimney and mounted. It was found that the In_2S_3 was not very satisfactory as a form for counting, as it occasionally gave a very lumpy sample. Very smooth samples are desired in order to minimize errors in absolute beta counting.

E. Sample Mounting

The samples were slurried into a filter chimney[19] with an inside diameter of 18.5 mm. The precipitate was collected on a circle of Whatman Filter Paper #42 of 7/8" diameter, placed over a sintered glass frit. This arrangement gave a sample with an area of about 2.7 cm^2. The precipitates were usually washed with a very dilute aerosol solution and with acetone and dried for a half-hour at 110°C. The filter paper with the sample was then placed on a 1" square piece of double-sided scotch tape, which in turn was centered on a standard aluminum sample holder, 2-1/2" x 3-1/2" x 0.052". A 1" square piece of 0.00025" mylar film was placed over the sample and stuck on the edges to the scotch tape. Ordinary scotch tape was then placed around the edges of the mylar film to attach it more firmly to the aluminum plate. The mylar film has a thickness of 0.9 mg/cm^2.

After sufficient counting the samples were submitted to the analytical group for chemical analysis, so that the chemical yields could be obtained.

III. TREATMENT OF DATA

A. Calculations

For a continuous bombardment the cross section for the formation of any particular product, x, is given by:

$$\sigma_x = \frac{A_x^o \; W_m \; M_x \; (1-e^{-\lambda_m t}) \; \sigma_m}{A_m^o \; W_x \; M_m \; (1-e^{-\lambda_x t})}$$

where A_x^o and A_m^o are the disintegration rates of the product, x, and of the beam monitor, Na^{24}, at the end of the bombardment; W_x and W_m are the weights of the indium foil and the monitor foil; M_x and M_m are the atomic weights of indium and aluminum; λ_x and λ_m are the decay constants of the product, x, and of Na^{24}; t is the length of the bombardment; and σ_m is the cross section for the reaction Al^{27} (p,3pn) Na^{24}.

For the case where the half-lives of the product, x, and of Na^{24} are long compared to the bombardment time, t, then the above expression can be simplified to:

$$\sigma_x \approx \frac{A_x^o \; W_m \; M_x \; T_{1/2x} \; \sigma_m}{A_m^o \; W_x \; M_m \; T_{1/2m}}$$

where $T_{1/2x}$ and $T_{1/2m}$ are the half-lives of the product, x, and of Na^{24}.

Due to the occasional erratic nature of the bevatron, it is sometimes necessary to make the above calculations for multiple bombardments. The expression for the cross section becomes:

$$\sigma_x = \frac{A_x^o \; W_m \; M_x \; \Sigma \, I_i \; (1-e^{-\lambda_m t_i})(e^{-\lambda_m t_{i\ldots n}}) \; \sigma_m}{A_m^o \; W_x \; M_m \; \Sigma \, I_i \; (1-e^{-\lambda_x t_i})(e^{-\lambda_x t_{i\ldots n}})}$$

where t_i is the length of the ith bombardment, $t_{i\ldots n}$ is the time from the end of the ith bombardment to the end of the last bombardment, and I_i is the relative intensity of the ith bombardment. The above expressions were used to convert the various disintegration rates into absolute cross sections.

Since the products Cd^{115}, Cd^{115m}, In^{115m}, and In^{114m} are formed exclusively from In^{115}, the cross sections reported have been corrected for the isotopic abundance of In^{115} (95.8%). The remainder of the products whose yields have been measured can be formed from both In^{113} and In^{115}. Therefore these cross sections will represent the elemental yield.

B. Beta Counting

An end-window, gas-flow proportional counter was used to count beta particles and conversion electrons. In order to convert

the observed counting rates into disintegration rates, several corrections must be applied. Of these, the most important are geometry, backscattering, air and window absorption, self-scattering and self-absorption, branching decay, and chemical yield.

The effective geometry of the various shelves of the proportional counter was determined by means of a Na^{24} source. The absolute disintegration rate of the Na^{24} was measured by means of the coincidence counting technique.[20] The Na^{24} source was then mounted on an aluminum backing plate and beta counted. A factor, F, was obtained which related the observed counting rate on some particular shelf to the absolute disintegration rate.

$$F = \frac{\text{observed counting rate}}{\text{disintegration rate}}$$

This factor was then a combined factor, containing the various corrections for geometry, air and window absorption, self-scattering and self-absorption, and backscattering. Since these factors are essentially constant for high energy β^- particles, the factor, F, can be used, along with the corrections for chemical yield and branching decay, to convert counting rates into disintegration rates for all β^- particles of over 1 Mev energy.

The above calibration was repeated using a Co^{60} source, which has a lower energy beta of 306 kev. After applying the corrections noted above, the factors obtained agreed with those from the Na^{24} calibration to within ± 2-1/2% on all shelves. The disintegration rate of the Co^{60} was obtained by the same coincidence counting technique.

The value of F for the top shelf, which was the one most frequently used, was 0.46. This corresponds to a pure geometry of 0.32. It is normally better to use a lower geometry shelf, if possible, as this minimizes errors due to sample placement. However, the counting rates were usually too low to use a smaller geometry. The counting efficiency of beta particles of all energies was assumed to be unity. This was somewhat verified in that the factors for Co^{60} (306 kev) agreed with those for Na^{24} (1.39 Mev), even on the top shelf.

For lower energy beta particles and conversion electrons, it was necessary to apply all the correction factors individually, as the combined factor, F, was no longer applicable. Since conversion electrons are monoenergetic and beta particles have a continuous energy distribution with a peak at 1/3 to 1/2 of the maximum energy, it was decided to use an effective energy equal to twice the conversion electron energy in assigning values to the various correction factors. In this way the electron energy would correspond to the peak in the beta energy distribution. This method introduces quite a large uncertainty in the air and window absorption, and self-scattering and self-absorption factors.

The backscattering factors, F_{bs}, given by B. P. Burtt[21] were used. All samples were mounted on aluminum backing plates, so that saturation backscattering was reached.

The air and window absorption factors, F_w, were calculated from the formula

$$F_w = e^{-\mu t}$$

where t is the air plus window thickness in mg/cm^2, and μ is the absorption coefficient. The values of μ were either measured by taking absorption curves, or were calculated using the formula given by Gleason, Taylor, and Tabern:[22]

$$\mu = 0.017\ E_{max}^{-1.43}$$

where E_{max} is the beta particle maximum energy in Mev. The air and window thickness of the top shelf of the proportional counter was 1.51 mg/cm^2.

The self-scattering and self-absorption factors, F_{ssa}, were either measured experimentally, or taken from the data of W. Nervik and P. Stevenson.[23]

The disintegration rate will now be given by the equation

$$A = \frac{\text{(observed counting rate)}}{\text{(chemical yield) (geometry) } (F_{bs})\ (F_{ssa})\ (F_w)(Y)}$$

where Y is a factor grouping the corrections for branching decay and electron conversion.

In order to provide a more accurate means of comparing results presented here with those obtained elsewhere, the "overall counting efficiency", C. E., of each isotope will be given. The "overall counting efficiency" will be defined as the product of F_{bs}, F_{ssa}, F_w, and Y for that sample whose thickness is such that this product is a maximum.

$$\underline{C.\ E.} = F_{bs} \cdot F_{ssa} \cdot F_w \cdot Y \quad (\text{max.})$$

C. Gamma Counting

A gamma-ray scintillation pulse-height analyzer with a Tl-activated, NaI crystal was used to count the gamma-rays of particular energies. The NaI crystal was in the form of a cylinder 1" high by 1-1/2" in diameter. To convert gamma counting rates into disintegration rates it is necessary to correct for geometry, counting efficiency, branching decay, electron conversion, and chemical yield.

The geometry factors of the various shelves of the counter were measured with an Am^{241} source. The absolute disintegration rate was determined by alpha counting in a chamber which has 52% geometry. It was assumed that the branching ratio between the 59.7 kev gamma-ray and the alpha group was 0.37. The integrated photopeak counting rate was measured, and was corrected for the escape peak loss by means of the data of P. Axel.[24] The counting efficiency of the 59.7 kev gamma was taken to be unity. Thus the geometry factor was given by:

$$\underline{G.\ F.} = \frac{(\text{integrated photopeak counting rate})(0.52)}{(\text{alpha counting rate})(0.37)(\text{escape peak loss})}$$

The variation of counting efficiency with gamma-ray energy at various distances from the crystal was obtained from the data of Kalkstein and Hollander.[25] The geometry calibration was checked by counting the 1.37 Mev gamma-ray in the standardized Na^{24} source. The two methods gave results which agreed to ± 2%. The geometries most frequently used were 34.4% and 10.5%.

D. Decay Characteristics

The decay characteristics leading to the conversion of counting rates into absolute disintegration rates will be discussed in detail for each isotope.

1. Be^7.

The 478 kev gamma-rays of Be^7 ($T_{1/2}$ = 52.9 d.) were counted in the gamma scintillation counter. It was assumed that the internal conversion was negligible, and that the 478 kev transition occurred in 12%[26] of the disintegrations. The counting efficiency was 19.3%.[25]

2. Cd^{107}.

The conversion electrons from the 93 kev transition of Ag^{107m} following decay of Cd^{107} (6.7 hr.) by electron capture[27] were counted in a proportional counter. The contribution from the decay of the parent, In^{107}, into Cd^{107} was considered to be negligible. The maximum "overall counting efficiency" was 0.58. Due to errors in counting conversion electrons, this value may be in error by ± 50%.

3. Cd^{109}.

The conversion electrons from the 88 kev transition of Ag^{109m} which follows the decay of Cd^{109} (470 d.) by electron capture were counted in a proportional counter. The maximum "overall counting efficiency" was 0.51. This value may be in error by ± 50%. It was necessary to separate the decay of Cd^{115m} from that of Cd^{109} by means of an analytical method. A correction was made for the decay of In^{109} which occurred before the cadmium-indium chemical separation was made, so that the final cross section represents an independent yield of Cd^{109}.

4. Cd^{115}.

The 1.11, 0.85, and 0.60 Mev β^- particles from the decay of Cd^{115} (53 hr.) and the conversion electrons from the decay of In^{115m} (4.5 hr.) were counted in a proportional counter. The decay of Cd^{115} and Cd^{115m} are entirely separate[28] and hence each will represent an independent yield. The decay of Ag^{115} was assumed to contribute a negligible amount. The counting rate due to Cd^{115} was determined by subtracting the activities due to Cd^{115m} and Cd^{109} from the gross decay data. The maximum "overall counting efficiency" for Cd^{115} is 2.14. Due to inaccuracies in counting conversion electrons, this value may be in error by as much as ± 20%.

5. Cd^{115m}.

The 1.61 and 0.67 Mev β^- particles from the decay of Cd^{115m} (43 d.) were counted in a proportional counter. The cadmium chemical

purification was delayed sufficiently so that the amount of Ag^{105} (40 d.) which would be formed from decay of Cd^{105} would be negligible. There is a potentially large error in the Cd^{115m} determination due to the very low counting rates found, coupled with the interference from the Cd^{109} activity. The maximum "overall counting efficiency" for Cd^{115m} is 1.54. This value is probably accurate to ± 5%.

6. In^{109}.

The 205 kev gamma-rays of In^{109} (4.3 hr.) were counted in the gamma scintillation counter. The decay scheme for this isotope is not known sufficiently well, so that it was necessary to assume that the 205 kev transition occurs in 100% of the disintegrations, and that the electron conversion was small. The counting efficiency was 64%. The cross section reported includes any contribution from Sn^{109}.

7. In^{110m}.

The 661 kev gamma-rays following decay of In^{110m} (5.0 hr.) by electron capture were counted in a gamma scintillation counter. The correction for conversion was 1.004, and the counting efficiency was 11%. The cross section measured was an independent yield, as the decay of the Sn^{110} parent was small.

8. In^{111}.

Both the 172 kev and the 247 kev gamma-rays which follow the decay of In^{111} (2.84 d.) by electron capture were counted in a gamma scintillation counter. 100% of the decay proceeds through these two transitions. The corrections for electron conversion were 1.12 (172 kev) and 1.064 (247 kev). The counting efficiencies were 74% (172 kev) and 51% (247 kev). No correction was made for decay of the Sn^{111} parent into In^{111}.

9. In^{113m}

The gamma-rays corresponding to the 393 kev isomeric transition of In^{113m} (104 m.) were counted in a gamma scintillation counter. The correction for electron conversion was 1.55, and the counting efficiency was 25%. The measured cross section represents an independent yield.

10. In^{114m}.

The 1.98 Mev β^- particle emitted by In^{114} after decay of

In^{114m} (49 d.) by isomeric transition was counted in a proportional counter. 62.2 mg/cm^2 of aluminum absorber were used to remove low energy electrons. The 1.98 Mev β^- occurs in 94.6% of the disintegrations.[29] The combined factor, F, was used to convert counting rates into disintegration rates after correcting for absorption by the aluminum absorber. The absorption coefficient for the 1.98 Mev β^- was measured by taking absorption curves on several samples. The value found was $\mu = 0.00626$ cm^2/mg.

In addition, the gamma-rays corresponding to the 190 kev isomeric transition of In^{114m} were counted in a gamma scintillation counter. The correction for electron conversion was 5.2 and the counting efficiency was 71.2%. The 190 kev transition occurs in 96.5% of the disintegrations. The disintegration rate computed from the gamma counting agreed satisfactorily in general with that from the beta counting, and an average was usually taken.

11. In^{115m}.

The gamma-rays corresponding to the 335 kev isomeric transition of In^{115m} (4.50 hr.) were counted in a gamma scintillation counter. The counting efficiency was 35%, and the correction for electron conversion was 1.98. The 335 kev transition occurs in 95% of the disintegrations. In^{109} also has a gamma-ray of this energy, but due to its low abundance, the correction is not large. It was estimated that 15 ± 10% of the 335 kev photopeak was due to In^{109}. The In^{115m} cross section found represents an independent yield.

IV. RESULTS AND DISCUSSION

The measured values of the cross sections are presented in Table I. Yields are given in millibarns and are based on the Al^{27} (p,3pn) Na^{24} cross section being equal to 10.5 mb. The table gives the cross section for each isotope as a function of proton energy and target thickness. The bombardments at 97 mg/cm^2 were made in duplicate. In order to show an estimate of the possible error of each value, they are classified by means of the following system:

class (a) ± 10% possible error
(b) ± 20% possible error
(c) ± 50% possible error

Table I

Cross Sections (in millibarns)

Proton Energy	6.2 Bev			4.1 Bev	2.0 Bev
Target Thickness	26 mg/cm^2	97 mg/cm^2	476 mg/cm^2	97 mg/cm^2	97 mg/cm^2
Isotope					
Be^7		14.4, 13.7 (a) (b)			
Cd^{107}		31, 26 (c)		27, 24 (c)	32 (c)
Cd^{109}		57, 46 (c)		46, 41 (c)	49, 53 (c)
Cd^{115}		0.075, 0.067 (b)		0.067, 0.065 (b)	0.051, 0.077 (b)
Cd^{115m}		0.153, 0.141 (a)		0.162, 0.132 (a)	0.145, 0.144 (a)
In^{109}					8.0 (b)
In^{110m}					17 (b)
In^{111}	17 (a)		26 (a)		21 (a)
In^{113m}					2.5 (c)
In^{114m}	57 (b)	69, 52 (b)	70 (b)	57, 57 (b)	50, 48 (b)
In^{115m}		4.7, 3.6 (b) (c)		5.0 (c)	3.5, 4.7 (c) (b)

where the error indicated is due to counting statistics, absolute beta counting factors, doubtful decay schemes, etc., but does not include any systematic error present in the Al^{27} (p,3pn) Na^{24} cross section. The internal consistency of a set of values for any one isotope may be better than that indicated, when the same error is constantly present.

In order to estimate how much of the yield was due to impurities in the target, one determination of the yield of Cd^{117} was made. Cd^{117} can be formed from In^{115} only by an extremely unlikely reaction, so that any found should be in indication of higher-Z impurities in the

indium. The Cd^{117} was determined by separating and counting the radiations from the In^{117} daughter. The yield of Cd^{117} obtained by this method corresponds to a cross section of 0.007 mb. Due to the low counting rate found (3 cpm) the possibility of contaminating activity is large, so that this cross section is more likely an upper limit for the yield from target impurities. The assumption is made that the yield of other isotopes would be similar. This yield is negligible except in the cases of Cd^{115} and Cd^{115m}, where it represents about 10% and 5%, respectively, of the measured yields.

The bombardment at 476 mg/cm^2 was on a target consisting of eight 3 mil indium foils. The front four indium foils and the back four indium foils were dissolved separately, and the cadmium and indium determinations made on each of the two groups. This was done to see if there was any change in yield in the front and back sections of the target due to secondary reactions. The yields of the (p,pn) reaction (In^{114m}) and also those of In^{111} in the two target sections agreed within experimental error.

1. In^{115} $(p,p\pi^+)$ Cd^{115}, Cd^{115m} Reaction.

The averaged yields at 2.0, 4.1, and 6.2 Bev for Cd^{115} are 0.064, 0.066, and 0.071 mb, and those for Cd^{115m} are 0.145, 0.147, and 0.147 mb, respectively. It can be seen that the yields of both isomers are essentially constant in this energy region, although the slight increase in the Cd^{115} cross section with energy may be real. The average total yield for both isomers is 0.21 mb. The preliminary values obtained by D. W. Barr and P. A. Benioff[6,7] for the $(p,p\pi^+)$ cross section on copper and aluminum at 6 Bev agree with this value, if allowance is made for an $A^{2/3}$ dependence.

Preliminary values for the yield of Cd^{115} with target thicknesses of 26 mg/cm^2 and 476 mg/cm^2 indicate that the yield may drop to 0.05--0.06 mb for the thinner target, and rise to about 0.13 mb for the thicker target. This implies that the yields measured with a target thickness of 97 mg/cm^2 are primarily from the $(p,p\pi^+)$ reaction, rather than from secondary reactions. By means of a simple linear extrapolation to zero target thickness, one can calculate that the Cd^{115} yield would be about 0.05 mb.

The spins of Cd^{115m} and Cd^{115} are 11/2 and 1/2, respectively. It is found that the yield of the higher-spin state is higher by a factor of 2.27 at 2.0 Bev and by 2.07 at 6.2 Bev. This difference is probably not significant. Many measurements of the ratio of the yields of Cd^{115m} to Cd^{115} have been made, but comparison is made difficult in many cases where independent yields are not available, as the beta decay of the parent, Ag^{115}, greatly favors the Cd^{115} ground state. For example, in the fission of uranium with 5.7 Bev protons,[1] a ratio of 0.34 was found.

The ratio of the yields of Cd^{115m} to Cd^{115} from the bombardment of iodine with slow negative pions has been measured by L. Winsberg[30] and found to be 2.6. Kruger and Sugarman[31] measured this ratio found from fission of gold, rhenium, tantalum, praseodymium, and iodine, and found an approximately constant value of 2.7. Lindner and Perlman[32] measured the cadmium ratio found in fission of antimony with deuterons and reported that it increased from 2.4 at 50 Mev to 4.5 at 190 Mev.

2. In^{115} (p,pn) In^{114m} Reaction.

The averaged yields of In^{114m} at 2.0, 4.1, and 6.2 Bev are 49, 57, and 63 mb. The measurements show a definite increase in yield as the energy is increased, similar to that found by S. Markowitz,[8] in the energy range 1 to 3 Bev. The yields are lower by about 20 mb than those found by Markowitz in this mass region. This may be due to that part of the (p,pn) reaction which leads to the ground state, In^{114}. The spin of In^{114} is 1, while that of In^{114m} is 5, so that the yield of the higher-spin state is expected to be higher.

The yields of In^{114m} at 6.2 Bev for target thicknesses of 26, 97, and 476 mg/cm^2 are 57, 61, and 70 mb. The contributions of secondary reactions to the (p,pn) and (p,pπ^+) reactions are probably of the same order of magnitude, but the contribution to the (p,pn) reaction is much less, proportionately, since it is small compared to the actual (p,pn) yield.

3. In^{115} (p,p') In^{115m} Reaction.

The averaged yields at 2.0, 4.1, and 6.2 Bev for In^{115m} are 4.1, 5.0, and 4.2 mb, so that the cross section is approximately constant over this energy range. The spins of In^{115} and In^{115m} are 9/2

and 1/2, respectively. One might expect therefore that the yield of In^{115} would be higher than that of In^{115m}, so that the total (p,p') yield is possibly much larger than that measured. One method of verifying this would be to measure the (p,p') yield of Rh^{103}. Rh^{103m} and Rh^{103} have spins of 7/2 and 1/2, respectively, so that one would expect the majority of the events to populate the Rh^{103m} level. It would then be possible to get a better estimate of the extent of low-energy nuclear excitation.

4. Overall yield of indium isotopes.

Very high energy nuclear reactions are characterized by a two step process; the incident particle initiating a nucleonic cascade predominantly in the forward direction, followed by an evaporation stage in which nucleons are emitted until the excitation energy is lowered sufficiently. The n/p ratio of the final nucleus is governed by the relative contributions of the two steps. In general it has been found that the isotopic yield curve will peak at a position a few neutrons short of stability. If one considers the (p,pxn) reactions, it is found that in low energy reactions a peak will occur in the isotopic distribution corresponding to that particular reaction which happens to be most energetically favored; whereas, in high energy reactions a monotonic distribution will be found, due to a continuous distribution in excitation energies. Particular reactions such as (p,p') and (p,pn) which can occur through different mechanisms may introduce singularities into the distribution.

The yields of the indium isotopes are shown in Fig. 2 as a function of mass number. They are designated either as partial isomeric yields, or as total isotopic yields. It is apparent that the yield of the isomer In^{110m} constitutes a major portion of the isotopic yield, whereas the yield of In^{113m} is probably much less than the total isotopic yield. In^{113m} is the low spin state, with I = 1/2, while the ground state, In^{113}, has I = 9/2. The spin assignment of the In^{110} isomers is not known, but on the basis of the yield measurements, one can predict that In^{110m} (5 hr.) probably has a higher spin than In^{110} (66 min.). The yields of the In^{114m} and In^{115m} isomers were discussed above in terns of spin values.

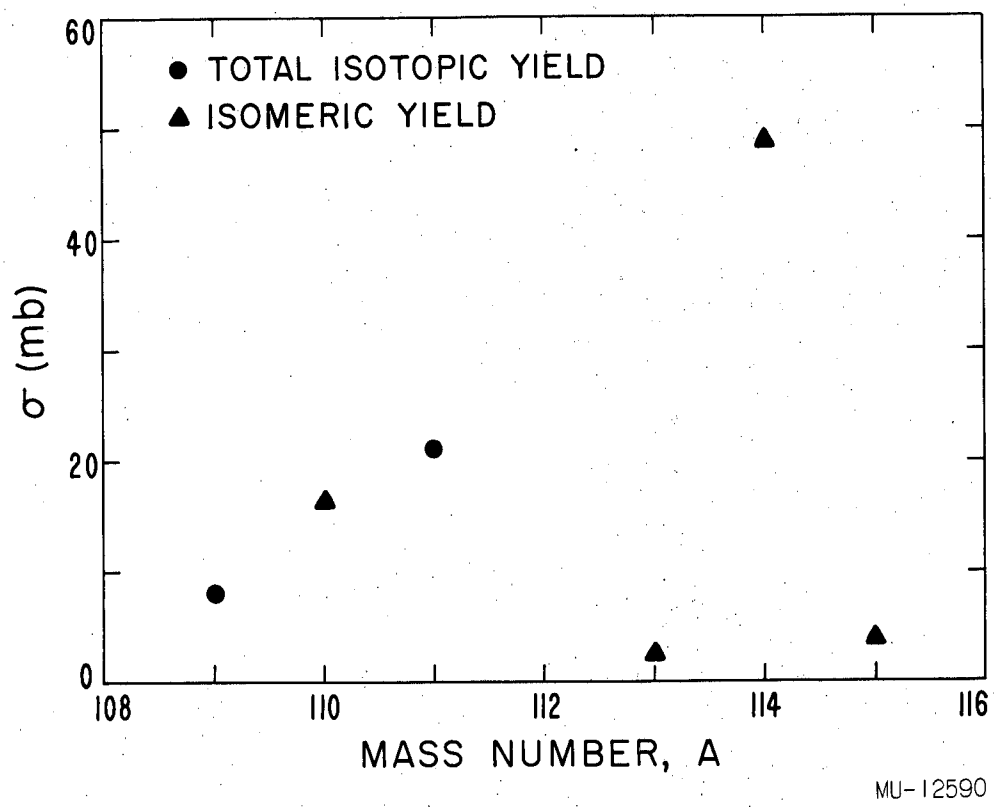

Figure 2. Yields of indium isotopes at 2.0 Bev (in millibarns)

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