Excitation Functions of the $(p,2p6n)$ and $(p,3p5n)$ Reactions for 60-, 100-, 150-, and 240-Mev Protons on Enriched Zirconium-90†

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The cross sections of the $Zr^{90}(p,3p6n)Sr^{83}$ and $Zr^{90}(p,2p6n)Y^{83}$ reactions have been determined for proton energies of 60–240 Mev. The cross section for even-odd Sr^{83} production in the energy range 100–240 Mev is 1330–2140 times as large as that of odd-even Y^{83}, as contrasted with much smaller values for the production of odd-odd and even-even isobars in similar reactions.

INTRODUCTION

THE ratio of the yield of Mn^{52} to that of Fe^{52} from $(p,3p5n)$ and $(p,2p6n)$ reactions on Co^{59} for[1] 100–240- and[2] 370-Mev protons is of the order of 50 to 1 and 18 to 1, respectively. These same isobars are also produced in a ratio of 19 to 1 by reaction of 340-Mev protons on natural iron[3] and in a ratio of ~150 to 1 by reaction of As^{75} with 180–240 Mev protons.[4] A number of suggestions have been made to account for the much higher yields of Mn^{52}. Production of the isobar of lower atomic number would be favored by emission of alpha-particles from excited target nuclei and it is well known that alpha-particles are produced in spallation. That Fe^{52} is further removed from the valley of stability than is Mn^{52} has been emphasized.[3] This implies that consideration must be given to the influence of the "governor" factor[5,6,1] which reduces departure from the region of stable nuclei in the evaporation process.

Goshal[7] has observed that the yield of Cu^{62} is approximately four times that of Zn^{62} in the (α,pn) and $(\alpha,2n)$ reactions on Ni^{60} and in the (p,pn) and $(p,2n)$ reactions on Cu^{63}. He suggested that the greater level density of the odd-odd Cu^{62} as compared to that of the even-even Zn^{62} might be a factor. Belmont and Miller[2] have used this suggestion in their study of the spallation of cobalt. Similarly Miller, Friedlander, and Markowitz[8] state that their observed greater yield of Mn^{52} as compared to Fe^{52} produced by 33-Mev alpha-particles on Cr^{50} "indicates a level density of Mn^{52} substantially greater than that of Fe^{52} at a given excitation energy above the ground state." Pinijian and Halbert[9] also point out a qualitative relation between level densities and the yields of Fe^{52}, Mn^{52}, and Cr^{49} produced by the reaction on K^{39} of N^{14} ions of 23.5–27.5 Mev energy.

The yields of Y^{83} and Sr^{83} from $(p,2p6n)$ and $(p,3p5n)$ reactions, respectively, on Zr^{90} might be expected to be similar to the yields of Fe^{52} and Mn^{52} from these same reactions on Co^{59}, except for the difference in the odd and even character of the product nuclides. A determination of the cross sections for these reactions is therefore of some interest.

EXPERIMENTAL

Target

Zirconium oxide, enriched in Zr^{90}, was bombarded in the internal proton beam of the Rochester 130-in. synchrocyclotron at radii corresponding to energies of 60, 100, 150, and 240 Mev. The isotopic analysis of the zirconium was reported as Zr^{90} 98.66, Zr^{91} 0.768, Zr^{92} 0.344, Zr^{94} 0.183, and Zr^{96} 0.041%. The oxide powder, 10–25 mg, was bombarded in an aluminum envelope arranged as described earlier.[10] The proton beam was monitored by the $Al^{27}(p,3pn)Na^{24}$ reaction with use of the known cross sections for Na^{24} production.[11]

The 33-hr Sr^{83} was counted as such while 3.5-hr Y^{83} was allowed to decay to Sr^{83}, which was then counted. The decay scheme of Y^{83} is unknown but it was assumed that it decays completely to Sr^{83}.

Chemical Separations

1. Strontium

The ZrO_2 target was heated with HF in a Pt crucible. Holdback carriers of Nb, Rb, Br, Se, As (~10 mg each) and known quantities of Y and Sr were added. After allowing for exchange, the fluoride precipitate was centrifuged and washed twice with HF and once with water. The precipitate was dissolved with aqueous saturated boric acid and conc. HNO_3. Sr was precipitated as $Sr(NO_3)_2$ by addition of fuming HNO_3, the precipitate was separated, dissolved in water, reprecipi-

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tated with fuming HNO_3 and separated by centrifuging. The two supernatants, containing Y, were combined and processed as indicated under yttrium.

The $Sr(NO_3)$ precipitate was dissolved in water and scavenged twice by precipitation of $Fe(OH)_3$. For the determination of the chemical yield Sr was precipitated as the oxalate by addition of $(NH_4)_2C_2O_4$. The precipitate was filtered, washed with water, alcohol and ether, and dried and weighed as $SrC_2O_4 \cdot H_2O$.

2. Yttrium

To the fuming HNO_3 solution containing Y after separation of Sr as $Sr(NO_3)_2$, Sr scavenger was added to precipitate and separate $Sr(NO_3)_2$. The purified supernatant Y solution was evaporated, made up to known volume and allowed to stand for 15–18 hr. Sr formed by the decay of Y was separated from an aliquot as described above. The remainder of the solution was used to determine the chemical yield by precipitation of $Y_2(C_2O_4)_3 \cdot 10H_2O$, ignition to Y_2O_3 and weighing.

Counting

Final $Sr(NO_3)_2$ precipitates were filtered through a glass chimney onto a weighed filter paper disk which, after drying, was weighed and cemented to a stainless steel disk in the usual manner. Counting was done with a methane-flow β-proportional counter of the Los Alamos type. Corrections were made as follows for: (1) background, (2) air and window absorption, determined experimentally by back extrapolation of the observed aluminum absorption curve[12] and also calculated,[13] (3) backscattering from the sample support, determined experimentally by the method of Burtt,[12] (4) scattering and self-absorption in the sample itself by interpolation in the data of Nervik and Stevenson,[14] (5) geometry, calculated by the method of Burtt[12] and also determined experimentally with calibrated sources, (6) chemical yield. Air and housing scattering were negligible.

To obtain absolute cross sections the absolute disintegration rates were calculated to infinite bombardment time and compared with the corresponding disintegration rates of Na^{24} produced from the Al monitor, taking into account the weights of the target and monitor.

RESULTS

The cross sections for the production of Y^{83} and Sr^{83} from Zr^{90} by reaction of protons of 60–240 Mev energy are summarized in Table I. The ratio of the yield of Sr^{83} to that of Y^{83} at each energy is also given.

TABLE I. Cross sections for production of Y^{83} and Sr^{83} from Zr^{90}.

Proton energy (Mev)	Cross section in millibarns Y^{83}	Sr^{83}	$\sigma_{Sr^{83}}/\sigma_{Y^{83}}$
240	0.0085	18.2	2180
	0.0070	15.6	
150	0.0056	9.9	1700
	0.0076	12.6	
100	0.0085	11.8	1330
	0.0096	12.2	
60	0.0021	0.032	15

The absolute cross sections for Sr^{83} production from Zr^{90} at 100–240 Mev are approximately the same as observed for the corresponding reactions on V^{51} (10–20 mb),[15] Co^{59} (~34 mb),[1] As^{75} (~25 mb),[4,16] Y^{89} (7–40 mb),[17] I^{127} (4–10 mb),[18] Cs^{133} (2.4–5.0 mb)[19] and at 340 Mev on Fe^{56} (2.5 mb)[3]. Since this type of reaction, $(p,3p5n)$, exhibits low yields at low energies, few such measurements have been made. However, the cross section of 0.032 mb for Sr^{83} production at 60 Mev is of the same order of magnitude as the corresponding $(p,3p5n)$ reaction on V^{51} (0.08 mb)[15] and Cs^{133} (0.05 mb),[19] with reaction on Co^{59} and As^{75} larger at 1.4 and 3.4 mb, respectively.[1,4]

The cross sections of ~0.008 mb at 100–240 Mev for the $Zr^{90}(p,2p6n)Y^{83}$ reaction are considerably smaller than those for the corresponding $Co^{59}(p,2p6n)Fe^{52}$ and $As^{75}(p,2p6n)Ge^{68}$ reactions (~0.6 mb),[1,4] and $Y^{89}(p,2p6n)Sr^{82}$ reaction (2–11 mb).[17]

At 100–240 Mev the value of the ratio $\sigma_{Sr^{83}}/\sigma_{Y^{83}}$ from Zr^{90} is 40 to 1000 times as large as the ratio found for the other reactions of this type. Thus, the value of the ratio for Mn^{52} to Fe^{52} from Co^{59} varies from ~50 to 18, for Ga^{68} to Ge^{68} from As^{75} the value is ~2, and for Rb^{82} to Sr^{82} from Y^{89} ~4; in each case the odd-odd product isobar has a larger cross section than the even-even one. As pointed out previously, the $Y^{83}-Sr^{83}$ isobars however are odd-even and even-odd, respectively. Another obvious difference between the $Y^{83}-Sr^{83}$ pair and the other pairs is the much more highly neutron-deficient character of Y^{83} as compared to the other nuclides involved.

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