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Radioisotope Yields from 1.85-GeV Protons on Mo and 1.85- and 5.0-GeV Protons on Te

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Abstract

Radioisotope yields from 1.85-GeV proton interactions in a natural isotopic composition Mo target and those from 1.85- and 5.0-GeV protons in natural Te targets were measured at Lawrence Berkeley Laboratory's Bevatron. The radioisotope yields were determined by γ-counting the targets using a 100-cm^3 coaxial Ge detector following the irradiations. Cross sections were determined for the production of 31 radioactive nuclides, ranging from $Z = 35$, $A = 74$, to $Z = 43$, $A = 97$, from the Mo target and for 47 radioactive nuclides, ranging from $Z = 35$, $A = 75$, to $Z = 53$, $A = 130$ from the Te targets.

1 Introduction

Cross sections for high-energy proton-induced reactions on medium to heavy weight nuclei are important for the calculation of cosmic ray transport, the confinement time of cosmic rays in the Galaxy and for the calculation of cosmic-ray-induced reactions in meteorites, lunar surfaces, and in terrestrial materials. Among the most abundant elements above $Z = 40$ are molybdenum and tellurium. With the aim of providing cross sections which would be useful for calibrating and extending the range of semi-empirical calculations into the medium–heavy element range, we measured the radioisotope yields from 1.85-GeV proton interactions in a natural isotopic composition Mo target and those from 1.85- and 5.0-GeV protons in natural Te targets at Lawrence Berkeley Laboratory's Bevatron.

2 Experiment

The Mo and Te targets were disks of diameter 3.1 cm and each a thickness of 0.67 cm for the 1.85-GeV irradiation and the Te target was 5.1 cm ×5.1 cm with a thickness of 1.0 cm for the 5.0-GeV irradiation. The targets were bombarded with protons from the LBL Bevatron accelerator. The irradiation was performed with the targets in air, and with the Mo and Te slabs assembled in a stack, together with Polycast Acrylic sheets (polymethyl methacrylate, $[C_5O_2H_8]_n$). These plastic sheets served to monitor the integrated beam exposure, through the production of ^{11}C, from the C and O contents of the plastic [1, 2]. The bombardment times were approximately 1 h each, with integrated currents of 60 nC and 5 nC, respectively, for the 1.85-GeV and 5.0-GeV irradiations.

Following the irradiation, γ rays from each of the targets were counted (separately) with a 100 cm^3 coaxial HPGe detector inside a 5-cm thick lead shielding. Due to the widely different half-lives of the isotopes under study, we used three different lengths of time bins for counting: 5-min bins during the first two hours, 1-hour bins during the next 48 hours, and then a series of five 6-hours bins. A 1-h spectrum from the p+Mo irradiation is shown in Fig. 1.

3 Data Analysis and Results

The photo peak yields of characteristic γ-rays of each isotope were extracted using a peak fitting routine. At least two γ-ray lines were used for each isotope, when possible. After correcting for the detector efficiency, self absorption in the target, summing and dead-time effects, the time-dependent yields of each γ-ray line were fit to determine initial activities. In some cases the time yields could be fit with two time components, thus allowing the extraction of the contribution of a parent nuclide to a daughter. Effective cross sections for the production of each isotope were calculated from a knowledge of the deduced yields at the end of the irradiation, the average proton flux and the duration of the irradiation.

Table 1 shows the measured effective cross-sections for radioisotopes produced in the p+Te bombardment at 1.85 and 5.0 GeV, and Table 2 shows the cross sections for isotopes produced in p+Mo bombardment at 1.85 GeV. In those cases in which we determined the yield of a parent the direct production of the daughter isotope by spallation could be deduced. The cross section for such isotopes is marked as being direct in the Tables. A theoretical calculation

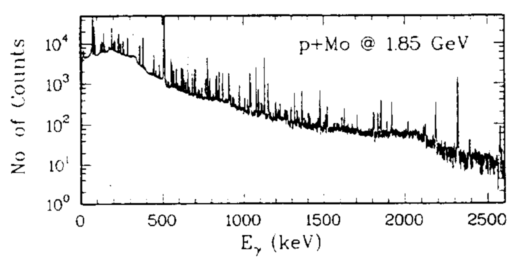

Fig 1: One-hour γ-ray spectrum from Mo target after one hour of irradiation with 1.85-GeV protons.

Table 1: Effective cross-sections for 1.85- and 5.0-GeV protons on natural Te

Isotope	1.85 GeV σ (mb)[a]	5.0 GeV σ (mb)[a]	Isotope	1.85 GeV σ (mb)[a]	5.0 GeV σ (mb)[a]
^{24}Na	0.91(4)	4.4(2)	^{111}Cd^m	5.5(2)	7.0(1)
^{75}Br	1.30(3)	2.12(16)	^{116}Sb^m	5.6(2)	6.2(6)
^{76}Br	2.8(2)	3.7(3)	^{117}Sb	30(2)[b]	38(2)[b]
^{77}Br	4.6(2)	7.2(3)	^{118}Sb	8.26(3)	12.2(4)
^{82}Rb^m	3.3(1)[b]	4.1(2)[b]	^{120}Sb^m	10.2(5)	15.7(5)
^{84}Rb^m	1.4(3)[b]	2.3(2)[b]	^{122}Sb	18.8(2)	32(2)
^{87}Sr^m	0.08(13)[b]	-	^{126}Sb	4.8(4)[b]	7.9(3)[b]
^{85}Y	0.9(5)	-	^{126}Sb^m	7.0(2)	10.4(2)
^{86}Y^m	5.2(1)[b]	6.1(1)[b]	^{127}Sb	11.8(4)	23(1)
^{86}Y	19(1)[b]	23(1)[b]	^{128}Sb	2.8(6)	3.7(2)
^{87}Y^m	3.0(13)[b]	2.2(37)[b]	^{128}Sb^m	3.1(2)	3.5(6)
^{87}Y	0.55(33)[b]	-	^{129}Sb	5.6(2)	8.8(8)
^{90}Y^m	0.78(3)	0.76(7)	^{123}Sn	1.65(7)	2.93(15)
^{86}Zr	2.1(1)	2.8(1)	^{117}Te	4.6(3)	5.5(3)
^{87}Zr	7.2(1)	10(2)	^{119}Te^m	9.2(7)	9.9(6)
^{90}Nb	8.8(4)	7.6(4)	^{119}Te	4.31(15)	6.1(5)
^{97}Ru	9.9(2)	9.7(3)	^{121}Te^m	14(4)[b]	22(2)[b]
^{100}Rh	6.8(5)	6.2(2)	^{121}Te	8.3(4)[b]	9.5(4)[b]
^{104}Ag	5.6(4)	4.2(4)	^{129}Te	25(1)[b]	52(3)[b]
^{104}Ag^m	4.7(2)	4.7(3)	^{121}I	3.7(1)[b]	6.2(2)[b]
^{107}In	2.6(4)	2.0(2)	^{123}I	9.0(2)[b]	11.7(3)[b]
^{108}In^m	3.2(1)	2.7(2)	^{124}I	9.4(3)[b]	15.2(5)[b]
^{108}In	1.2(1)	-	^{126}I	6.9(23)[b]	15.(6)[b]
^{109}In	9.1(1)	8.0(4)	^{128}I	5.7(4)[b]	10(2)[b]
^{110}In^m	4.1(2)	7.3(3)	^{130}I	3.0(1)[b]	4.6(9)[b]
^{110}In	5.7(2)	4.4(1)			
^{111}In	14.6(3)[b]	16.4(4)[b]			
^{116}In^m	4.3(3)	5.9(5)			

[a]Errors shown are statistical. There is an additional 10% error in the overall normalization of the cross-sections.
[b]Direct production cross-section.

of the effective cross sections was made using the semi-empirical formula given by Silberberg and Tsao [3], but these are not shown here due to lack of space. The median deviation from the experimental cross sections was about 60%.

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Table 2: Effective cross-sections for 1.85-GeV protons on natural Mo

Isotope	σ (mb)[a]	Isotope	σ (mb)[a]	Isotope	σ (mb)[a]
^{93}Tc	2.70(2)	^{86}Zr	8.1(2)	^{78}Rb	1.69(15)
^{95}Tc^{m}	2.0(5)[b]	^{89}Zr	14.7(1.7)[b]	^{79}Rb	5.1(6)
^{90}Mo	7.1(4)	^{95}Zr	2.0(2)[b]	^{81}Rb	15.9(7)[b]
^{93}Mo^{m}	2.8(1)[b]	^{97}Zr	2.10(5)[b]	^{82}Rb^{m}	9.6(3)[b]
^{88}Nb	3.9(2)	^{84}Y	7.2(2)	^{84}Rb^{m}	2.4(6)[b]
^{89}Nb^{m}	18(1)	^{85}Y	5.9(2)[b]	^{76}Kr	2.5(2)
^{90}Nb	26.2(8)[b]	^{86}Y	15.8(6)	^{77}Kr	4.58(15)
^{91}Nb^{m}	18(3)	^{87}Y	44(1)	^{79}Kr	12.4(7) [b]
^{92}Nb^{m}	13.6(5)[b]	^{90}Y^{m}	2.36(8)	^{74}Br^{m}	2.75(11)[b]
^{95}Nb	18.5(9)[b]	^{80}Sr	5.3(2)	^{75}Br	8.7(3)
^{95}Nb^{m}	5.0(4)[b]	^{81}Sr	3.8(2)	^{76}Br	10.1(9)[b]
^{96}Nb	11.2(5)[b]	^{83}Sr	18.6(6)	^{77}Br	4.17(13)
^{97}Nb	9.9(5)[b]				

[a]Errors shown are statistical. There is an additional 10% error in the overall normalization of the cross-sections.

[b]Direct production cross-section.

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