Nuclear Reactions of High Energy Deuterons with Medium Mass Targets

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Abstract

Formation cross sections of product nuclides in the nuclear reactions of medium mass targets by 10 GeV deuterons were measured with a gamma-ray spectroscopy. The measured data were compared with the cross sections of 12 GeV protons.

I. INTRODUCTION

At high energy accelerator facilities, various kinds of accelerator components are exposed to high energy primary and secondary particles during machine operation. As a result, they become radioactive. Especially the accelerator beam-line components such as target,slit, monitor,dump,etc.are highly activated. A spallation reaction is one of principal nuclear reactions leading to the formation of radionuclides in these accelerator hardwares.

Nuclear spallation reactions with high energy protons have been investigated both experimentally and theoretically. Some of the present authors have measured the formation cross sections of various spallation nuclides of medium mass with 12 GeV protons using γ -rayspectrometry[1]. The charge dispersion and target dependence of formation cross section were fairly explained by the two-step model,i.e.,the cascade-evaporation process originally reported by R.Serber[2].

These spallation date are very useful in understnding the problem associated with the residual radioactivities in various accelerator components. Recently, an experiment using 6 GeV deutron beams has started at the National Laboratiry for High Energy Physics(KEK). Although the deutron spallation data are indispensable to an quantitative estmation of residual radioativities, there are however only scattered data available. Kozma and Kliman[3] measured the cross sections for the reactions of 7.3 GeV deuterons and 8 GeV protons with a Ni target, and the ratio of cross sections for deuterons to protons was found to be 1.73. Their proton results were however inconsistent with our data[1] and also their recent data[4]. As they stated, it is very interesting to compare the proton data with those due to other high energy particles such as deuteron, heavy ions etc., in order to elucidate the mechanism of high energy spallation reactions.

A relative yield pattern for the reaction of 3.9 GeV ^{14}N ions with Cu was similar to that for high energy protons, except for the findings that the yields for light elements (^{3}H, ^{7}Be, ^{22}Na) are enhanced in the reaction of ^{14}N ions[5]. Similar results have been obtained in the radiochemical studies of 25 GeV ^{12}C ions[6] and 80 GeV ^{40}Ar ions[7] incident on Cu. These results indicate that the formation cross sections in nuclear reactions by high energy incident particles are nearly independent of the total energy above 3GeV. Factorization asserts that yield of target fragments may depend on the projectile only in a total cross section term [7].

In the present paper, we report the results of activation measurements of Fe,Co,Ni,and Cu targets with 10 GeV deuteron. The measured data were compared with the cross sections of 12 GeV protons to conform the above two-step model.

II. EXPERIMENTAL

A. Targets and Irradiation

The metal targets used in this experiment were Fe, Co, Ni and Cu. Each sample was sandwiched with same foils to minimize scattering-in and scattering-out effects. The total thickness of the target stacks was about 0.5 g/cm^2. Therefore, the effects due to secondaries was negligible at 10 GeV. Each target was bundled together and placed in order of target atomic weight. Thus a target with lighter mass was placed on the upstream side to proton beam. The target stack thus bundled was bombarded by 10 GeV deuterons in the external primary beam line of the KEK 12 GeV proton synchrotron. The beam intensity was continuously monitored by a SEC (secondary emission chamber), which was calibrated by the activation method using the $^{27}Al(d,3p2n)^{24}Na$ reaction. Its average intensity and irradiation time were 8.6 x10^{10} protons/sec and 31 min. respectively. The beam size was found to be about 2cm in diameter by a radiation sensitive film, which changes color from green to red as a result of the irradiation. The Al foil was placed at the front of the bundled target in order to monitor the total proton number irradiated on the targets.

After the bombardment, the irradiated part of each middle foil was punched out in a beam size and was sealed in an acrylic disc container.

B. radioactivity measurements

An Ge detector and a 4k-channel pulse-height analyzer system were used for the γ-rayspectroscopy. About 12 spectra were measured for each sample during 6 months. The measuring time was 15 min at the beginning of the measurements and several hours a few months later.

The total number of deuterons bombarded on the targets was calculated to be 1.56×10^{14} from the ^{24}Na yield in the Al target by using the cross section of 15±1.5 mb, which is the extrapolated value from 14.7±1.2mb for 7.3 GeV[3] and 15.25±1.5mb for 2.33 GeV deuteron[8] for the $^{27}Al(d,3p2n)\,^{24}Na$ reaction.

The cross sections were determined by the following sequences. First, a candidate nuclide was searched out by the photopeaks associated with its characteristics γ rays. Second, the obtained photopeak yields of several spectra were fitted with its decay time. When there are the nuclides, emitteing γ rays of an equal or nearly equal energy to that of the nuclide of interest, the fit was generally poor. In such a case, the least-squares fit for two or three nuclides with different decay times was performed to obtain a yield component for the nuclide of interest. For the nuclides emitting more than one γ ray, the cross section data for the individual γ rays showed a good agreement with each other in most cases. In general, the accurate values for detection efficiencies and photopeak yields are determined for higher energy γ rays. Thus, the cross section of the nuclide was determined by taking into account these counting conditions.

III. RESULTS AND DISCUSSION

Table 1 is the measured formation cross sections of individual nuclides from Fe to Cu irradiated by 10 GeV deuterons. The type of yield of each product nuclide is identified as being either independent (I), or cumulative(C-: β-decay, or C+: β+decay or electron capture) when at least one of the precursors is known, being determined from the decay scheme of Table of Isotopes (7th ed.)[9]. The quoted error includes the uncertainties of detection efficiencies of the γ rays (about 5%) and statistical errors for photopeak yields. Effects due to secondary interactions in the target stacks are estimated to be negligible.

The results for the 10 GeV deuteron reaction with Fe, Co, Ni and Cu were compared with those obtained for the reactions at roughly equivalent total kinetic-energy protons(12 GeV protons) with same targets.(figs.1-2) The dashed line indicates the ratios for total reaction cross sections. A systematic uncertainty for the absolute values of the ratios in Figs.1-2 is about 15 % due to the uncertainties in beam monitoring.

If the factorization hypothesis[7] were applied to these ratios, it would predict they should be constant and equal to the ratios for total cross sections. The total reaction cross sections for proton-nucleus and deuteron-nucleus were calculated by using the equations proposed by R.Silberberg and C.H.Tsao[10] and J.Jaros et al.[11], respectively. The estimated ratios, $\sigma(d)/\sigma(p)$for Fe, Co, Ni and Cu were calculated to be about 1.5.

Table 1 Cross sections (in mb) for Fe, Co, Ni and Cu targets in the nuclear spallation reactions with 10 GeV deuteron. The type of yield indicates independent(I) or cumulative (C-: β-decay, or C+: β+or electron capture).

Nuclide	Type of yield	Fe	Co	Ni	Cu
^{7}Be	I	21±1	18±1	33±2	21±1
^{22}Na	C+	3.8±0.3	3.7±0.3	14±1	3.3±0.2
^{24}Na	C-	5.0±0.3	5.4±0.3	4.7±0.3	6.2±0.3
^{28}Mg	C-	0.50±0.04	0.70±0.04	0.37±0.02	0.76±0.04
^{41}Ar	C-	0.58±0.03	0.82±0.05	0.20±0.02	0.69±0.04
^{42}K	I	3.5±0.2	4.0±0.2	2.0±0.1	3.2±0.18
^{43}K	C-	1.3±0.1	1.6±0.1	0.64±0.03	1.6±0.09
^{43}Sc	C+	2.4±0.15	1.7±0.13	2.1±0.18	2.0±0.11
^{44m}Sc	I	5.8±0.3	5.3±0.3	5.7±0.3	5.2±0.26
^{44}Sc	I	4.5±0.2	3.6±0.1	3.0±0.3	2.9±0.15
^{46}Sc	I	8.8±0.4	7.4±0.4	5.0±0.3	7.3±0.37
^{47}Sc	C-	3.8±0.6	4.0±0.6	-	3.6±0.54
^{48}Sc	I	0.55±0.03	0.82±0.05	0.14±0.01	0.65±0.04
^{48}V	C+	15±0.8	10.0±1.5	15±0.8	9.4±0.48
^{48}Cr	I	0.60±0.03	0.25±0.02	1.1±0.07	0.27±0.02
^{51}Cr	C+	45±2	25±1.3	38±2	23±1.2
^{52}Mn	I	8.4±0.4	5.5±0.3	10.5±0.5	5.8±0.3
^{52}Fe	I	0.35±0.06	0.15±0.02	1.0±0.15	0.14±0.02
^{54}Mn	I	49±2.5	26±1.3	19±1.0	15±0.7
^{55}Co	I	1.0±0.13	0.75±0.06	10±0.6	0.98±0.05
^{56}Mn	C-	2.3±0.14	5.7±0.3	0.50±0.03	2.6±0.14
^{56}Co	C+	1.7±0.13	5.8±0.3	33±2	6.5±0.35
^{56}Ni	C+	-	-	2.5±0.13	-
^{57}Co	C+	1.2±0.2	34±5	100±15	26±4
^{57}Ni	C+	-	-	25±1.2	0.81±0.07
^{58}Co	I	-	70±3	35±1.7	33±1.7
^{59}Fe	I	-	1.9±0.2	0.45±0.02	2.44±0.13
^{60}Co	I	-	-	-	22±0.06

The general picture emerging from the present studies of target fragmentation induced by deuterons shows a striking similarity to the reactions by 12 GeV protons. One of large differences from proton induced reactions appears for ^{7}Be which may be formed from central collisions of the ion with the target nucleus.

IV. REFERENCES

[1] T. Asano et al.,"Target dependence of charge dispersions in spallation reactions of medium-mass nuclei with 12 GeV protons"Phys.Rev.C28, pp.1718-1724, 1983.

[2] R. Serber,"Nuclear reactions at high energies", Phys.Rev.72,pp.1114-1115,1947.

[3] P.Kozma and J.Kliman, "Spallation of nickel by 9 GeV/c

protons and deuterons" J. Phys. G:Nucl. Part. Phys. 16,pp.45-53,1990.

[4] P.Kozma, V.I.Ilyushchenko, and V. Hnatovicz, "Spallation of nickel and copper isotopes by protons with energy 3.65 GeV", Sov. J. Nucl. Phys. 53, pp.451-457, 1991.

[5] J.B.Cumming et al., "Spallation of Cu by 3.9-GeV 14N ions and 3.9-GeV protons" Phys. Rev. C10, pp.739-755,1974.

[6] J.B.Cumming, R.W.Stoenner, and P.E. Haustein, "Spallation of copper by 25-GeV 12C ions and 28-GeV protons", Phys. Rev. C14, pp.1554-1563,1976.

[7] J.B. Cumming et al., "Spallation of copper by 80-GeV 40Ar Ions", Phys. Rev. C17,pp.1632-1641,1978.

[8] J.Banaigs et al.,"Determination de L'intensite d'un Faisceau de deutons experait d'un Synchrotron et Mesure des Sections Effecaces des Reactions 12C(d,p2n)11C et 27Al(d,3p2n)24Na a 2.33 GeV", Nucl. Instrum. Methods 95 pp.307-311, 1971.

[9] Table of isotopes, 7th ed., edited by C.M. Lederer and V. S. Shirley, New York, Wiley, 1978.

[10] R.Silberberg and C.H.Tsao,"Spallation processes and Nuclear Interaction Products of cosmic rays", Phys. Rep. 191,pp351-408,1990.

[11] J.Jaros et al.,"Nucleus-nucleus total cross sections for light nuclei at 1.55 and 2.89 GeV/c per nucleon", Phys. Rev. C18, pp.2273-2292, 1978.

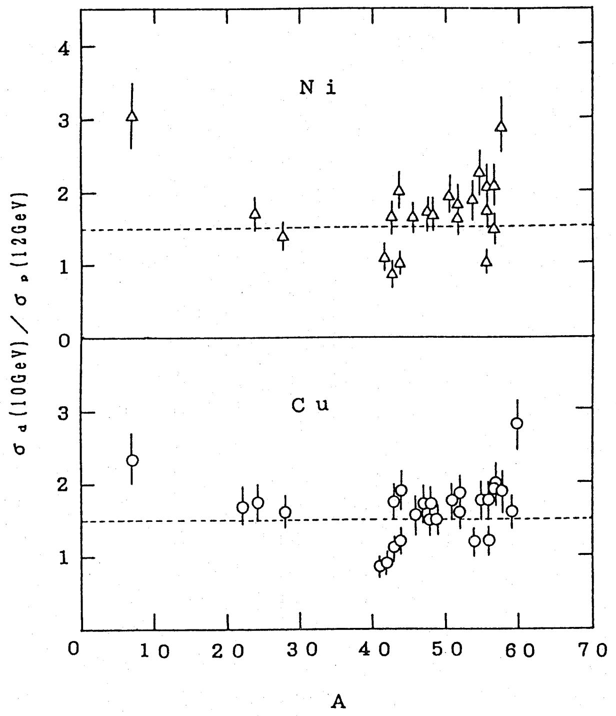

Fig.2 Ratios of cross sections for production of individual nuclides by 10 GeV deuteron to 12 GeV protons. The dased line indicates the ratios for total reaction cross sections.

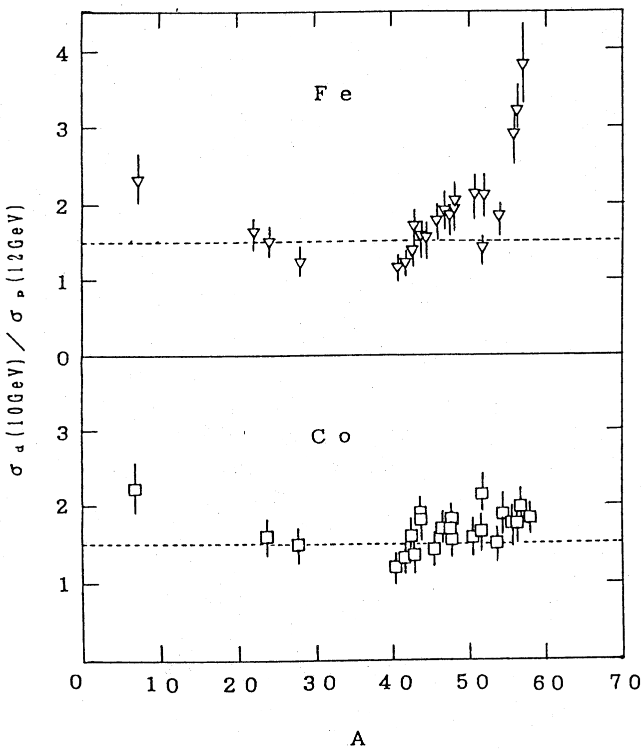

Fig.1 Ratios of cross sections for production of individual nuclides by 10 GeV deuteron to 12 GeV protons. The dased line indicates the ratios for total reaction cross sections.