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(p,xn), (p, pxn), and (p, 2pxn) reactions for medium-mass nuclei at 12 GeV

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Cross sections for (p,xn), (p, pxn), and (p, 2pxn) reactions of Ti, Fe, Co, Ni, Cu, and Zn isotopes at 12 GeV were determined from spallation yield data measured with a Ge(Li) γ-ray spectrometer. Among the measured cross sections which include associated pion production the (p,n) reactions show a large target dependence. The cross sections for ^{57}Fe(p,n)^{57}Co, ^{65}Cu(p,n)^{65}Zn, ^{48}Ti(p,n)^{48}V, and ^{56}Fe(p,n)^{56}Co are 14.9 ± 2.4, 2.69 ± 0.20, 1.64 ± 0.26, and 0.58 ± 0.04 mb, respectively.

[NUCLEAR REACTIONS Ti, Fe, Co, Ni, Cu, Zn, (p,xn), (p,pxn), (p,2pxn), reaction cross sections, $E = 12$ GeV, activation, target dependence.]

Numerous investigations have been performed for nuclear spallation reactions using high energy protons and heavy ions. General characteristics of spallation reactions seem to be well described by the so-called two-stage model, i.e., knock-on and evaporation processes.[1] In the energy range above a few GeV per incident nucleon spallation cross sections for various target nuclei show a very small energy dependence and shapes of the mass-yield curves are nearly independent of projectiles.

Nuclear reactions in which a target nucleus loses only a few nucleons should be dominated by other processes such as peripheral collision processes. Only a small momentum is transferred to nucleons near the surface of the target nucleus and the nuclear-cascade process does not play an important role. Those reactions have been studied extensively at lower energies below 1 GeV,[2,3] and a few experiments were performed above 1 GeV.[4–8] At higher energies effects due to nuclear structures of the target nucleus are expected to be small for nuclear reactions in which a large fraction of the incident energy is absorbed by the target nucleus. The target dependence for those reactions is also expected to have a smooth variation with the target mass.

In the present report we describe some properties of measured cross sections of (p,xn), (p,pxn), and (p,2pxn) reactions for medium-mass targets at 12 GeV, where x is a small non-negative integer. Activation experiments of Ti, Fe, Co, Ni, Cu, and Zn targets were performed using the 12 GeV proton synchrotron at the National Laboratory for High Energy Physics, Japan (KEK). Exposures of the target stacks were made in two runs, two months apart. Table I gives the arrangements of the target stacks. A Ge(Li) detector was used for the γ-ray spectroscopy to measure yields of unstable product nuclides. Details of experimental procedure and general results of spallation reactions will be reported elsewhere.[9] The target samples used were not enriched and contained isotopes of natural abundance.

Table II lists measured cross sections used in the present analysis of target isotopes. Errors do not include the systematic uncertainty of the beam intensity calibration which is estimated to be approximately 10%.

The type of a reaction is defined by the conservation of the baryon numbers and charges between product and target nuclei. Therefore it should be noted that the reactions defined in the present analysis include all reactions associated with pion production if the baryon number and charge are consistent with those of the defined reactions. Hence the cross sections correspond to inclusive production of the product nuclides.

Contributions to yields from reactions in which the incident proton is captured by a target nucleus without any baryon emission are expected to be very small.

Cross sections of the (p,xn) reactions for various target

TABLE I. Arrangements of the target stacks and target thicknesses without including guard foils. The targets starting from the top row in the table were placed at the upstream side in this order. The thicknesses of the stacks are three times the total target thicknesses.

First run		Second run	
Target	Thickness (10^{-3} g/cm^2)	Target	Thickness (10^{-3} g/cm^2)
Al	5.20	Al	3.44
Fe	7.52	Ti	11.0
Co	8.36	Zr	16.6
Ni	17.4	Nb	21.1
Cu	9.06	Mo	14.8
Zn	58.1	Sn	15.2
Ag	12.1	Ta	41.2
Au	39.3	W	48.7
Total	157.0		172.0

TABLE II. Cross sections (mb) for natural targets used to determine the cross sections of (p,*x*n), (p,p*x*n), and (p,2p*x*n) reactions at 12 GeV.

Target	Ti	Fe	Co	Ni	Cu	Zn
Nuclide	^{46}Sc	^{54}Mn	^{55}Co	^{55}Co	^{61}Cu	^{65}Zn
Cross section (mb)	18.4 ± 0.9	27.5 ± 1.4	0.40 ± 0.03	4.43 ± 0.24	7.07 ± 0.36	20.3 ± 1.0
	^{47}Sc	^{55}Co	^{56}Co	^{56}Co	^{62}Zn	
	19.8 ± 3.0	0.15 ± 0.02	3.27 ± 0.18	18.8 ± 0.9	0.21 ± 0.02	
	^{48}Sc	^{56}Mn	^{56}Ni	^{56}Ni	^{65}Ni	
	1.59 ± 0.08	0.79 ± 0.05	< 0.04	1.19 ± 0.06	< 0.27	
	^{48}V	^{56}Co	^{57}Co	^{57}Co	^{65}Zn	
	1.21 ± 0.19	0.53 ± 0.04	17.0 ± 2.6	47.3 ± 7.1	0.83 ± 0.06	
		^{57}Co	^{57}Ni	^{57}Ni		
		0.32 ± 0.05	0.11 ± 0.01	16.6 ± 0.8		
			^{58}Co	^{58}Co		
			38.8 ± 1.9	12.0 ± 0.6		
			^{59}Fe			
			0.38 ± 0.03			

isotopes and the (p,p*x*n) reactions for ^{59}Co are given in Table III. The ^{51}V data are taken from Husain and Katcoff's results at 29 GeV.[10] Also given are cross sections of the (p,pπ^+) reactions for ^{59}Co and ^{65}Cu. The present Cu data are in good agreement with those by Cumming, Stoenner, and Haustein at 28 GeV.[11] It can be clearly seen that reactions in which target nuclei lose more neutrons (large *x*) are suppressed strongly for medium-mass targets used in the present work. Hence, after taking into account the isotope abundance of the nautral target, reactions such as ^{49}Ti(p, 2n)^{48}V and ^{65}Cu(p, 4n)^{62}Zn have been neglected compared with ^{48}Ti(p,n)^{48}V and ^{63}Cu(p, 2n)^{62}Zn, respectively. It is interesting to note that the ^{133}Cs(p,p*x*n) and (p,*x*n) cross sections measured by Molecke and Caretto[3] at 550 MeV show much weaker dependence on the number of neutrons *x*. As discussed above, cross sections for proton capture reactions such as ^{56}Fe(p capture)^{57}Co and ^{47}Ti(p capture)^{48}V should be very small in the present experiment.

The cross section for ^{57}Fe(p,n)^{57}Co is about 20 times larger than that for ^{56}Fe(p,n)^{56}Co. The purity of the iron target sample was 99.7% and manganese was the heaviest element among impurity materials. The iron sample was placed at the upstream side of the target stack behind only the aluminum sample (about 60 μm thick). Since the isotope abundance of ^{57}Fe is only 2.2%, contribution of ^{57}Co yield from other processes such as ^{56}Fe(p capture)^{57}Co by low energy background protons in the beam or secondary interactions in the target stack cannot completely be excluded in the present experiment. The target dependence among the (p,n) reactions given in Table II is very striking. Cumulative contributions from short-lived parent nuclides are essentially negligible since all the parent nuclides of interest decay with β^+ emission. Production of those nuclides should be strongly suppressed.

The present upper limit for the ^{65}Cu(p,pπ^+)^{65}Ni reaction is quite large compared with the cross section of about 0.1 mb estimated from Remsberg's excitation function.[6]

Table IV gives estimated cross sections for the (p, p*x*n) and (p,2p*x*n) reactions. In this case target isotopes were not determined uniquely. More than one target isotope can contribute to yields of product nuclides. The target isotopes given in Table III have the smallest *x* and are likely to have the largest cross sections for the product nuclides of interest. The difference between the two smallest *x* values is given by Δx. Smaller values given for the cross sections correspond to the case in which all the possible target isotopes were assumed to have the same cross section and larger values to the case in which only the target isotopes with the smallest *x* were assumed to contribute to the yields.

The (p,p2n) and (p,2p2n) reactions have much smaller cross sections. The difference between the cross sections for ^{58}Ni(p,p2n)^{56}Ni and ^{63}Cu(p,p2n)^{61}Cu may imply a target dependence of the (p,p2n) reactions. On the other hand, all the (p,pn), (p,2p), and (p,2pn) reactions measured have very similar cross sections of about 25 mb and they do not seem to have any appreciable target dependence. We note that the ^{142}Ce(p,pn) cross section is about three times larger than the ^{142}Ce(p,2p) cross section in the Meloni-Cumming experiment[5] in the same energy range. Jacob and Markowitz's ^{48}Ti(p,2p)^{47}Sc data[8] are consistent with the present result.

Some mass dependence of (p,n) and (p,2n) cross sections

TABLE III. Reaction cross sections (mb). The incident proton energy is 12 GeV. The ^{51}V data are from Huasin and Katcoff's results (Ref. 10) at 28 GeV.

Type	Reaction	Cross section (mb)
(p,n)	$^{48}Ti(p,n)^{48}V$	1.64 ± 0.26
	$^{51}V(p,n)^{51}Cr$	0.87
	$^{56}Fe(p,n)^{56}Co$	0.58 ± 0.04
	$^{57}Fe(p,n)^{57}Co$	14.9 ± 2.4
	$^{65}Cu(p,n)^{65}Zn$	2.69 ± 0.20
(p,2n)	$^{56}Fe(p,2n)^{55}Co$	0.17 ± 0.02
	$^{63}Cu(p,2n)^{62}Zn$	0.30 ± 0.03
(p,3n)	$^{59}Co(p,3n)^{57}Ni$	0.11 ± 0.01
	$^{51}V(p,3n)^{49}Cr$	0.34
(p,4n)	$^{59}Co(p,4n)^{56}Ni$	< 0.04
	$^{51}V(p,4n)^{48}Cr$	0.021
(p,p*x*n)	$^{59}Co(p,pn)^{58}Co$	38.8 ± 1.9
	$^{59}Co(p,p2n)^{57}Co$	17.0 ± 2.6
	$^{59}Co(p,p3n)^{56}Co$	3.27 ± 0.18
	$^{59}Co(p,p4n)^{55}Co$	0.40 ± 0.03
$(p,p\pi^+)$	$^{59}Co(p,p\pi^+)^{59}Fe$	0.38 ± 0.03
	$^{65}Cu(p,p\pi^+)^{65}Ni$	< 0.9

TABLE IV. Reaction cross sections (mb). The target isotope corresponds to the smallest x to produce the product nuclide. Δx is the difference between the two smallest x's for the product nuclide. The larger cross section corresponds to the case in which only the target isotope with the smallest x is assumed to contribute to the yield and the smaller cross section to the case in which all the possible target isotopes for the product nuclide are assumed to have a same cross section.

Type	Reaction	Δx	Cross section (mb)
(p,p*x*n)	$^{58}Ni(p,pn)^{57}Ni$	2	18 to 25
	$^{66}Zn(p,pn)^{65}Zn$	1	40 to 74
	$^{58}Ni(p,p2n)^{56}Ni$	2	1.3 to 1.8
	$^{63}Cu(p,p2n)^{61}Cu$	2	7.1 to 10
(p,2p*x*n)	$^{49}Ti(p,2p)^{48}Sc$	1	15 to 29
	$^{48}Ti(p,2p)^{47}Sc$	1	24 to 27
	$\left\{\begin{array}{l} ^{47}Ti(p,2p)^{46}Sc \\ ^{48}Ti(p,2pn)^{46}Sc \end{array}\right\}$	1	20 to 23
	$^{57}Fe(p,2p)^{56}Mn$	1	30 to 35
	$^{58}Ni(p,2p)^{57}Co$	2	47 to 69
	$^{56}Fe(p,2pn)^{54}Mn$	1	29 to 30
	$^{58}Ni(p,2pn)^{56}Co$	2	19 to 28
	$^{60}Ni(p,2pn)^{58}Co$	1	39 to 46
	$^{58}Ni(p,2p2n)^{55}Co$	2	4.4 to 6.5

was observed in the incident energy range near 100 MeV.[2] Small nuclear structure effects of about 20% were reported in (p,pn) reactions at 2.9 GeV.[4]

In conclusion, the measured cross sections of the (p,n) and possibly (p,p2n) reactions for medium-mass target isotopes at 12 GeV seem to show a large target dependence. Although it seems to be very unlikely, the possibility that the large cross section of $^{57}Fe(p,n)^{57}Co$ might be due to misidentification of ^{57}Co yield from other processes such as ^{56}Fe(p capture)^{57}Co by low energy background protons in the beam or secondary interactions in the target samples cannot completely be excluded. On the other hand, the (p,pn), (p,2p), and (p,2pn) reactions measured show essentially no appreciable target dependence. Reactions in which the target nucleus loses more neutrons tend to be suppressed and have much smaller cross sections for medium-mass targets. A plausible explanation for the target dependence of the (p,n) reactions is that an unpaired neutron of ^{57}Fe plays an important role in the charge exchange process of peripheral collisions even at 12 GeV. Further investigations using enriched isotope targets are being prepared.

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[1] For example, see *Spallation Nuclear Reactions and Their Applications*, edited by B. S. P. Shen (Reidel, Boston 1976).

[2] J. R. Grover and A. A. Caretto, Jr., Annu. Rev. Nucl. Sci. 14, 51 (1964).

[3] M. A. Molecke and A. A. Caretto, Jr., Phys. Rev. C 15, 719 (1977).

[4] N. T. Porile and S. Tanaka, Phys. Rev. 130, 1541 (1963).

[5] S. Meloni and J. B. Cumming, Phys. Rev. 136, B1359 (1964).

[6] L. P. Remsberg, Phys. Rev. 138, B572 (1965).

[7] P. L. Reeder, Phys. Rev. 178, 1795 (1969).

[8] N. P. Jacob, Jr. and S. S. Markowitz, Phys. Rev. C 11, 541 (1975).

[9] T. Asano *et al.*, Phys. Rev. C (in press).

[10] L. Husain and S. Katcoff, Phys. Rev. C 7, 2452 (1973).

[11] J. B. Cummings, R. W. Stoenner, and P. E. Haustein, Phys. Rev. C 14, 1554 (1976).