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P.Kozma, J.Kliman

SPALLATION OF COPPER BY 9 GeV/c PROTONS AND DEUTERONS

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1. INTRODUCTION

The interaction of high-energy particles with complex nuclei has been the subject of many experimental studies in recent years. It has been observed a number of processes from which peripheral collisions such as the projectile fragmentation and spallation of target nuclei have been investigated extensively. Whereas the projectile fragmentation has been examined via kinematical properties of ^{24}Na and ^{28}Mg fragments from several target nuclei/1-3/, the spallation of target nuclei has been investigated from the Z and A distribution of residual nuclei resulting from the interaction. Most of previous experimental studies of this type were performed on copper/4-6/ and silver/7-10/ targets.

The spallation of copper by high-energy particles is also the subject of this paper. We report here on the distribution of residual nuclei resulting from the interaction of copper with 9 GeV/c deuterons $(T_d = 7.3$ GeV$)$ and 9 GeV/c protons $(T_p = 8.15$ GeV$)$. Our choice of 9 GeV/c protons and deuterons was simply motivated by their availability at the Dubna synchrophasotron. While proton data can be compared with previous results/5,6/, the spallation of copper with deuterons at GeV energies has not been reported up to now. The purpose of our study was to gain new experimental information and, by comparison with results obtained earlier by other authors, to contribute to the study of nuclear reactions induced by high-energy particles.

2. EXPERIMENTS

Two target stacks containing Cu, Al and Mylar foils were irradiated with 9 GeV/c protons and 9 GeV/c deuterons in an external beam of the Dubna synchrophasotron. The target discs were 3.8 cm in diameter and their thicknesses were as indicated in Table 1. The target stacks were positioned so that the beam passed through the centre from foil 1 to 11. Irradiation periods were chosen to achieve $\sim 10^{13}$ total flux particles in both experiments.

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Table 1

Properties of the target stacks

Foil	Material	Thickness (mg/cm^2) for proton beam	Thickness (mg/cm^2) for deuteron beam
1	Al	5.8	6.2
2	Al	20.3	19.8
3	Al	5.7	5.9
4	My	17.5	17.2
5	My	17.4	17.1
6	Cu	88.3	85.9
7	Cu	923.3	915.8
8	Cu	917.5	920.0
9	Cu	85.1	82.2
10	My	17.5	17.2
11	My	17.3	17.2

After irradiations, the target stacks were disassembled, and the individual foils were directly assayed with Ge(Li) gamma-ray spectrometers. High-resolution Ge(Li) detectors of 30 cm^3 and 50 cm^3 (ORTEC) were calibrated with mixed radionuclide gamma-ray standards. Series of separate measurements under identical geometry conditions were performed ranging in duration from 15 minutes to 12 hours. A portion of a typical gamma-ray spectrum, obtained 1.5 day after proton irradiations, is shown in Fig.1. The spectra were analyzed with computer programs which subtracted the background under the peaks and fitted the Gaussian peaks to the data points. Nuclidic assignments were made on the basis of gamma-ray energies, half-lives and fractional abundances taken from Gamma-Ray Catalog/11/. Pertinent decay characteristics of radionuclides carefully identified in both investigations are listed in Table 2.

3. RESULTS

3.1. Secondary effects

The contribution of secondary particle induced reactions to the measured cross sections can be estimated from the ratio of activities simultaneously measured with the thin and thick Cu-targets. Cumming et al./6/ have previously reported the secondary reaction contributions to the products from the reaction of 28 GeV protons and 25 GeV

Table 2

Decay properties of observed nuclides

Nuclide	Half-life	Energy (keV)	Fractional abundance
^{24}Na	15.02 h	1368.5	1.000
^{28}Mg	20.90 h	1778.8	1.000
^{42}K	12.36 h	1524.6	0.183
^{43}K	22.30 h	372.8 617.5	0.879 0.783
^{43}Sc	3.89 h	372.8	0.220
^{44}Sc	3.93 h	1157.0	0.999
^{44m}Sc	2.44 d	271.2 1157.0	0.778 0.999
^{46}Sc	83.80 d	889.2 1120.5	1.000 1.000
^{47}Sc	3.34 d	159.4	0.680
^{48}Sc	43.70 h	983.5 1037.5	1.000 0.975
^{48}V	15.97 d	983.5 1312.1	1.000 0.975
^{48}Cr	22.96 h	112.5 308.3	0.950 1.000
^{51}Cr	27.70 d	320.1	0.098
^{52}Mn	5.59 d	744.2 935.5 1434.1	0.900 0.945 1.000
^{54}Mn	312.50 d	834.8	1.000
^{56}Mn	2.58 h	846.8	0.989
^{52}Fe	8.27 h	168.7 1434.1	1.000 0.990
^{59}Fe	44.50 d	1099.3 1291.8	0.565 0.432
^{55}Co	17.54 h	477.2 931.5	0.203 0.705
^{56}Co	78.80 d	846.8 1238.8	1.000 0.670
^{57}Co	271.81 d	122.1 136.5	0.856 0.106
^{58}Co	70.92 d	810.8	0.994

Table 2 (continued)

Nuclide	Half-life	Energy (keV)	Fractional abundance
^{60}Co	5.27 y	1173.2 1332.5	1.000 1.000
^{56}Ni	6.10 d	158.4 811.9	0.988 0.860
^{57}Ni	36.10 h	1377.6	0.779

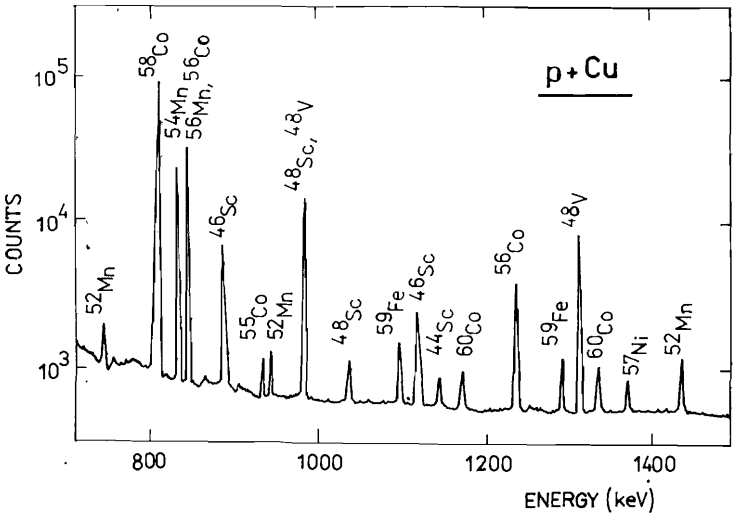

Fig.1. Portion of a gamma-ray spectrum of a copper target recorded 1.5 day after proton irradiation. Nuclidic assignments of identified gamma-rays are indicated.

^{12}C ions with copper. They have found that the secondary contributions to cross sections measured using two targets of total thickness 154 mg/cm^2 and 1158 mg/cm^2 differ by factor that ranges from no contribution to 23% with the proton projectiles with an average secondary correction of 1.3% per 100 mg/cm^2. Porile et al./10/ have reported a secondary contribution of 2.5-2.8% per 100 mg/cm^2 for the reaction of 25 GeV ^{12}C ions with silver.

The weighted average value of the thick/thin Cu-targets (see Table 1) activity ratios for products between A=24 and A=52 was found to be 1.04±0.03 and 1.03±0.02 for deuteron and proton irradiation, respectively. For products with A≥54 the secondary reaction contributions were found to be substantially larger. The maximum ratio obtained for A=55 is 1.24±0.12 and 1.29±0.13, respectively.

3.2. Monitor reactions

The central aluminium foils (No.2) in both target stacks were used as monitors of the beam flux by means of the $^{27}Al(p,3pn)^{24}Na$ and $^{27}Al(d,3p2n)^{24}Na$ reactions, respectively. The $^{27}Al(p,3pn)^{24}Na$ and $^{27}Al(d,3p2n)^{24}Na$ cross sections were determined on the basis of ^{24}Na induced activities in these foils measured as described above. The data have been also treated in the same manner. The weighted average cross sections corrected for the secondary effect (a 2% correction was applied for the production of ^{24}Na by secondary particles) were found to be 8.6±0.9 mb and 14.8±1.5 mb for $^{27}Al(p,3pn)^{24}Na$ at 8.15 GeV and $^{27}Al(d,3p2n)^{24}Na$ at 7.3 GeV, respectively.

3.3. Spallation reactions

The cross sections are listed in Table 3. For a nuclide emitting more than one assayed gamma-ray (see Table 2), the weighted average cross section is reported. An individual cross section is determined from counts in a series of gamma-ray measurements. The uncertainty of an individual cross section is based on our estimates of uncertainties from counting statistics, detector efficiencies, target thicknesses and so on. A systematic uncertainty of about 10% resulting from the beam flux monitor is not included in the tabulated values.

In the type of yield of Table 3, symbol I represents an independent yield. The cumulative yields C^+ and C^- represent the integrated isobaric cross section of neutron-deficient and neutron-excessive precursors, respectively.

Table 3

Cross sections for the production of radionuclides in the interaction of copper with 9 GeV/c protons and deuterons

Nuclide	Type of yield	Protons σ (mb)	Deuterons σ (mb)
^{24}Na	C^-	3.36 ± 0.31	21.14 ± 1.82
^{28}Mg	C^-	0.87 ± 0.11	2.09 ± 0.36
^{42}K	I	3.02 ± 0.85	10.62 ± 1.98
^{43}K	C^-	1.95 ± 0.22	2.38 ± 0.27
^{43}Sc	C^+	2.53 ± 0.37	4.27 ± 0.65
^{44}Sc	I	3.97 ± 0.22	5.31 ± 0.70
^{44m}Sc	I	5.44 ± 0.20	7.22 ± 0.81
^{46}Sc	I	6.22 ± 0.21	9.56 ± 0.83
^{47}Sc	I	2.07 ± 0.17	3.13 ± 0.25
^{48}Sc	I	0.60 ± 0.09	1.08 ± 0.17
^{48}V	C^+	13.11 ± 0.37	12.73 ± 0.41
^{48}Cr	I	0.33 ± 0.06	0.59 ± 0.09
^{51}Cr	I	18.02 ± 1.38	30.05 ± 2.57
^{52}Mn	I	5.78 ± 0.29	8.84 ± 0.61
^{54}Mn	I	13.36 ± 0.56	21.38 ± 1.39
^{56}Mn	C^-	3.05 ± 0.31	7.42 ± 0.88
^{52}Fe	I	0.16 ± 0.04	0.36 ± 0.09
^{59}Fe	C^-	1.23 ± 0.22	2.37 ± 0.44
^{55}Co	C^+	0.75 ± 0.16	1.17 ± 0.20
^{56}Co	C^+	7.12 ± 0.30	5.93 ± 0.22
^{57}Co	C^+	17.72 ± 1.64	21.34 ± 2.07
^{58}Co	I	23.53 ± 0.77	28.50 ± 1.04
^{60}Co	I	10.12 ± 0.53	14.68 ± 1.19
^{56}Ni	I	0.13 ± 0.04	0.18 ± 0.06
^{57}Ni	I	0.61 ± 0.11	1.06 ± 0.17

3.4. Parametrization of nuclidic cross sections

According to the previous treatments /12,13/, we have also parametrized the spallation cross sections $\sigma(A,Z)$ as a function of a product of mass A and atomic number Z as

$$\sigma(A,Z) = \sigma(A)\exp\{C(Z-Z_p(A))^2\} . \quad (1)$$

In this parametrization $\sigma(A)$ determines the distribution of isobaric yields (mass-yield curve), and the function of $\exp\{C(Z-Z_p(A))^2\}$ represents the charge-dispersion curve. The normalized charge-dispersion distribution is assumed to be independent of A when measured relative to the reference atomic number $Z_p(A)$ at each A. For spallation, it is convenient to consider $Z_p(A)$ to be the position of a maximum yield at the mass number.

We have adopted the approach of Cumming et al. /5/ and fitted our data with polynomial expansions in A of varying order. The best fit was obtained with the 6-parameter equation

$$\sigma(A,Z) = \exp\{\alpha_1 + \alpha_2 A + \alpha_3 A^2 + \alpha_4 (Z-Z_p)^2\} ,$$
$$Z_p = \alpha_5 A + \alpha_6 A^2 . \quad (2)$$

It should be noted that the first three parameters $\alpha_1 - \alpha_3$ determine the shape of the mass-yield distribution, α_4 the width of the charge-dispersion curve, which is symmetric about the most probable charge $Z_p(A)$, and the parameters α_5 and α_6 in Z_p the shape of the charge-dispersion curve. Eq. (2) was fitted to the experimental data (independent yields only) over a range of $42 \leq A \leq 60$. The results of the parametrization are summarized in Table 4 in which the values of $\alpha_1 - \alpha_6$ obtained for both the deuteron and proton experiments are tabulated. The appropriate reduced chi-square values χ^2_ν are also reported.

In order to obtain the charge-dispersion curves, we have calculated the fractional isobaric yields F_{exp} and F_{calc}, which are, respectively, the experimental and calculated cross sections $\sigma(A,Z)$ related to $\sigma(A)$. The isobaric yields $\sigma(A)$ are defined as

$$\sigma(A) = \sum_{Z=Z_{min}}^{Z=Z_{max}} \sigma(A,Z) , \quad (3)$$

where the values of Z_{min} and Z_{max} are 0 and 30, respectively, because the atomic number Z of spallation products from the interaction of

Table 4

Parameters obtained from the fit of Eq.(2) to the cross sections of independent yields from the spallation of copper by 9 GeV/c protons and deuterons

Parameter	Protons	Deuterons
α_1	2.06 ± 1.08	2.59 ± 1.23
α_2	$-(1.80 \pm 3.32) \times 10^{-2}$	$-(3.15 \pm 4.07) \times 10^{-2}$
α_3	$(4.54 \pm 3.19) \times 10^{-4}$	$(7.33 \pm 5.91) \times 10^{-4}$
α_4	-1.15 ± 0.13	-1.21 ± 0.19
α_5	$(4.90 \pm 0.03) \times 10^{-1}$	$(4.91 \pm 0.05) \times 10^{-1}$
α_6	$-(3.38 \pm 0.44) \times 10^{-4}$	$-(3.97 \pm 0.65) \times 10^{-4}$
	$\chi^2_\nu = 2.145$	$\chi^2_\nu = 2.918$

$_{29}Cu(p,X)$ and $_{29}Cu(d,X)$ should be less than or equal to 30. When replacing the sum of Eq.(3) by the integral between $+\infty$ and $-\infty$, the analytically calculated isobaric yields

$$\sigma_{anal}(A) = \exp\{\alpha_1 + \alpha_2 A + \alpha_3 A^2\} \int_{-\infty}^{+\infty} \exp\{\alpha_4 (Z-Z_p)^2\} dZ \qquad (4)$$

and the appropriate analytically calculated fractional yields

$$F_{anal}(A, Z-Z_p) = \sqrt{\frac{-\alpha_4}{\pi}} \cdot \exp\{\alpha_4 (Z-Z_p)^2\} \qquad (5)$$

can be determined. Including parameters α_4 from Table 4, we obtain

$$F_{anal}(A, Z-Z_p) = \begin{cases} 0.605 \exp\{\alpha_4 (Z-Z_p)^2\} & \text{for } _{29}Cu(p,X) \\ 0.620 \exp\{\alpha_4 (Z-Z_p)^2\} & \text{for } _{29}Cu(d,X) \end{cases} \qquad (6)$$

respectively. The fractional isobaric yields[10]

$$F(A, Z-Z_p) = F_{exp}(A, Z-Z_p) \left[\frac{F_{anal}(A, Z-Z_p)}{F_{calc}(A, Z-Z_p)}\right] \qquad (7)$$

are independent of mass number, and all the values of F lie on a single charge-dispersion curve.

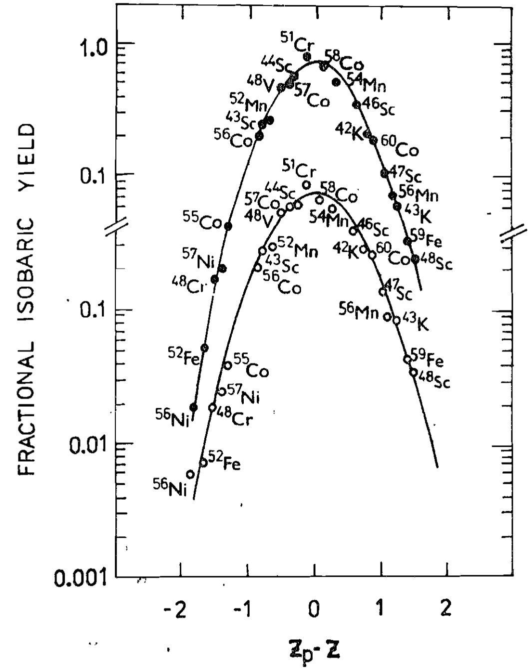

Fig.2. Charge-dispersion curves for products over a mass range of $42 \leq A \leq 60$ from the spallation of Cu by 9 GeV/c protons and 9 GeV/c deuterons. The lower curve and open points are for protons; the upper curve and filled points are for deuterons. The curves are displaced vertically by a factor of 10 for display purposes.

The charge-dispersion curves for the spallation of Cu by 9 GeV/c protons and deuterons, respectively, are displayed in Fig.2. Similarities between their shapes are implicit when comparing the α_5 and α_6 fitting parameter values (see Table 4).

The charge-dispersion parameters α_5 and α_6 obtained from the analysis of the present proton data are compared with those deduced for the spallation of copper by 3.9 GeV[5] and 28.0 GeV[6] protons in Table 5. The parameters deduced by Porile et al.[10] and Tominaka et al.[13] for the spallation of silver and niobium, respectively, by high-energy protons are also included. A good agreement of all charge-dispersion parameters is evident. From this agreement it can be concluded that products from the spallation of copper, niobium and silver by protons at GeV energies have very similar charge-dispersions.

The mass-yield distributions of spallation products over a range of $42 \leq A \leq 60$ from the p + Cu and d + Cu reactions at 9 GeV/c are shown in Fig.3. The points are the experimental cross sections corrected for the unmeasured portion of the isobaric yield by means of Eq. (2). The curves are the cross sections calculated by Eq.(4). The error bars incorporate a 20% uncertainty in the unmeasured contributions to the isobaric yields.

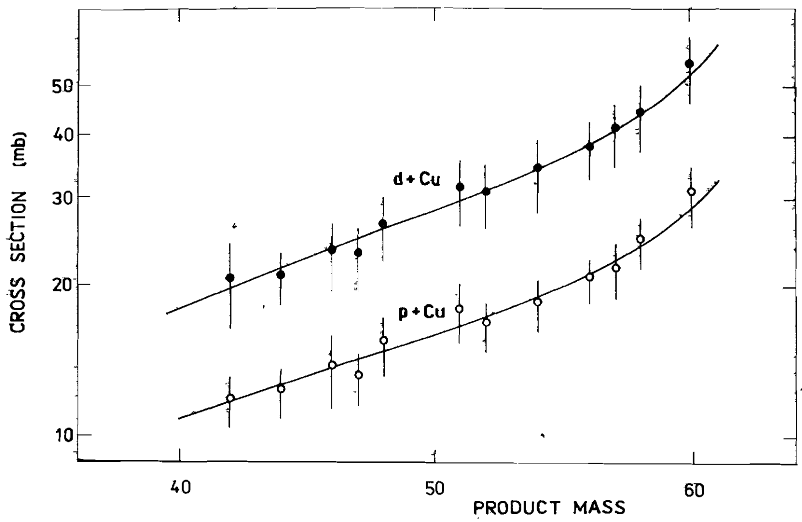

Fig.3. Mass-yield curves for products in a mass region of $42 \leq A \leq 60$ from the spallation of Cu by 9 GeV/c protons and deuterons. The points are the sums of experimentally determined yields with estimates of missing yields from the fitting procedure described in the text.

Table 5

Comparison of the parameters α_5 and α_6 in Z_p with other data

Ref.	Reaction	Energy	α_5	α_6
Cumming et al. /5/	p + Cu	3.9 GeV	0.457±0.002	
this work	p + Cu	8.15GeV	0.490±0.003	$-(3.38\pm0.44)\times10^{-4}$
Cumming et al. /6/	p + Cu	28.0 GeV	0.485±0.002	
Tominaka et al. /13/	p + Nb	12.0 GeV	0.488±0.004	$-(4.11\pm0.50)\times10^{-4}$
Porile et al. /10/	p + Ag	300.0 GeV	0.481±0.000	$-(2.92\pm0.03)\times10^{-4}$

3.5. Test of limiting fragmentation and factorization

The concepts of limiting fragmentation and factorization have been developed /14,15/ for the interpretation of the reaction induced by high-energy particles and nuclei. It was suggested that the cross sections of products which could be identified as fragments of the target (or projectile) are independent of energy for beam energies greater than 1-2 AGeV. Moreover, single particle inclusive spectra of target (or projectile) fragments were predicted to depend on the nature of projectile (or target) via the total reaction cross section. Consider a single particle inclusive reaction

$$P + T \rightarrow F + X \quad , \tag{8}$$

in which projectile particle P interacts with target T to produce fragment F, and X represents anything else. Following the hypothesis of factorization, the cross section for the product of target fragmentation (i.e. the product of spallation) F can be factorized to

$$\sigma^{F}_{T,P} = \sigma^{F}_{T}\gamma_{P} \quad , \tag{9}$$

where γ_P is dependent only on the projectile. To compare the present experimental data for deuterons to protons, we can write

$$\sigma^{F}(d+Cu)/\sigma^{F}(p+Cu) = \gamma_d/\gamma_p = \gamma \quad . \tag{10}$$

In this equation the ratio γ_d/γ_p is defined as a relative projectile factor γ. If the factorization hypothesis is valid, this factor should be equal to that of the total reaction cross sections $\sigma_R(d+Cu)/\sigma_R(p+Cu)$ /10,16/.

The total reaction cross section σ_R for the spallation process can be obtained from the parametrized values of $\sigma(A)$ (see Eqs.(3) and (4)) by appropriate summation of the isobaric yields. Our summation was performed from A=25 to A=60 because lighter products were assumed to have heavier partners and thus to have already been calculated. The results are $\sigma_R(d+Cu)$ = 935 mb and $\sigma_R(p+Cu)$ = 560 mb. The experimental ratios of the d+Cu and p+Cu spallation cross sections (see Table 3) give an average value of 1.68±0.26 for 23 measured radionuclides from ^{42}K to ^{60}Co, which is consistent with the relative projectile factor γ = 1.67. Another evidence for the factorization follows from the comparison of γ with the ratio of the total cross sections of monitoring reactions $^{27}Al(d,3p2n)^{24}Na$ and $^{27}Al(p,3pn)^{24}Na$ (see Sect.3.2) which is 1.72±0.36.

In order to test the concept of limiting fragmentation, we compare our proton results at 8.15 GeV with previous data[5,6] at 3.9 GeV and 28 GeV, respectively. The ratios $\sigma_{8.15}/\sigma_{3.9}$ and $\sigma_{8.15}/\sigma_{28.0}$ of measured 25 cross sections (Table 6) fluctuate about unity. The average values of the ratios are

$$\langle\sigma_{8.15}/\sigma_{3.9}\rangle = 1.05 \pm 0.14 \quad \text{and} \quad \langle\sigma_{8.15}/\sigma_{28.0}\rangle = 1.23 \pm 0.15 \; ,$$

respectively.

Table 6

Comparison of p+Cu cross sections at 8.15 GeV with previous data at 3.9 GeV[5] and 28.0 GeV[6]

Nuclide	$\sigma_{8.15}/\sigma_{3.9}$	$\sigma_{8.15}/\sigma_{28.0}$
^{24}Na	0.91±0.06	0.93±0.04
^{28}Mg	1.91±0.11	1.98±0.11
^{42}K	0.84±0.09	1.02±0.07
^{43}K	0.69±0.07	0.92±0.05
^{43}Sc	0.61±0.08	0.85±0.10
^{44m}Sc	1.04±0.06	1.27±0.09
^{44}Sc	0.90±0.07	1.18±0.06
^{46}Sc	0.98±0.06	1.20±0.05
^{47}Sc	0.87±0.09	1.10±0.08
^{48}Sc	0.92±0.18	1.20±0.22
^{48}V	1.44±0.13	1.70±0.14
^{48}Cr	1.06±0.22	1.38±0.27
^{51}Cr	0.94±0.05	1.22±0.04
^{52}Mn	0.95±0.04	1.25±0.06
^{54}Mn	0.97±0.03	1.15±0.05
^{56}Mn	1.18±0.15	1.45±0.17
^{52}Fe	0.89±0.33	1.60±0.50
^{59}Fe	0.92±0.34	1.05±0.19
^{56}Ni	0.93±0.81	0.72±0.77
^{57}Ni	0.92±0.26	1.33±0.26
^{55}Co	0.77±0.17	0.93±0.18
^{56}Co	1.25±0.07	1.59±0.04
^{57}Co	1.05±0.04	1.25±0.05
^{58}Co	1.14±0.03	1.33±0.03
^{60}Co	1.21±0.07	1.28±0.10

4. CONCLUSIONS

The spallation of copper by high-energy protons and deuterons has been investigated by the technique of gamma-ray Ge(Li) spectrometry. It was experimentally verified that the distribution of spallation products in both interactions was well characterized by the charge-dispersion and mass-yield curves derived from the general 6-parameter equation.

The principal result of our spallation experiments is the remarkable similarity of the mass-yield and charge-dispersion curves for both projectiles. In addition, no substantial difference in the shapes of the charge-dispersion curves for products from the spallation of copper, niobium and silver by high-energy protons was found. The evidence for factorization and limiting fragmentation has also been demonstrated.

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4.	Low energy theoretical physics
5.	Mathematics
6.	Nuclear spectroscopy and radiochemistry
7.	Heavy ion physics
8.	Cryogenics
9.	Accelerators
10.	Automatization of data processing
11.	Computing mathematics and technique
12.	Chemistry
13.	Experimental techniques and methods
14.	Solid state physics. Liquids
15.	Experimental physics of nuclear reactions at low energies
16.	Health physics. Shieldings
17.	Theory of condenced matter
18.	Applied researches
19.	Biophysics

Козма П., Климан Я. E1-86-606

Фрагментация ядер мишени Cu протонами и дейтронами с импульсом 9 ГэВ/с

В работе приведены результаты исследования процесса фрагментации ядер мишени Cu протонами и дейтронами с импульсом 9 ГэВ/с. Сечения образования радионуклидов в диапазоне массовых чисел $24 \leq A \leq 60$ определены по измерению гамма лучей с использованием Ge(Li)-спектрометра. Теоретический анализ полученных результатов проводился на основе 6-параметрической формулы, которая определяет зарядовые и массовые распределения образовавшихся ядер. Настоящие результаты, полученные на протонах, сравниваем с результатами раньше сделанных экспериментов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1986

Kozma P., Kliman J. E1-86-606

Spallation of Copper by 9 GeV/c Protons and Deuterons

The spallation of copper by 9 GeV/c protons and deuterons has been studied. Cross sections for the production of radionuclides with $24 \leq A \leq 60$ were determined from direct gamma-ray counting of irradiated targets with a Ge(Li)-spectrometer. The results were parametrized in terms of a 6-parameter equation which reproduces the measured charge-dispersion and mass-yield distributions. The proton results are compared with previous investigations.

The investigation has been performed at the Laboratory of High Energies, JINR.

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