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SPALLATION OF NICKEL BY 9 GeV/c PROTONS AND DEUTERONS

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In recent years considerable interest has been shown in investigations of nuclear spallation reactions induced by high-energy particles and nuclei. Most of them have been performed on copper targets /1-3/. The spallation of nickel at GeV energies has not been reported up to now. In this Letter we present results of a study of the distribution of radionuclides produced by the spallation of natural nickel by high-energy particles: 9 GeV/c protons (T_p = 8.15 GeV) and 9 GeV/c deuterons (T_d = 7.30 GeV).

Experiments were performed in an external beam of protons and deuterons of the Dubna synchrophasotron, The nickel target stacks consisted of three 31 mg/cm^2 thick foils. The outer foils were used for recoil loss compensation; the middle foil was analyzed. The target foils enclosed in Mylar catchers 17.5 mg/cm^2 in thickness were preceded on the upstream side by a 20 mg/cm^2 aluminium foil surrounded by 6 mg/cm^2 Al guard foils. The centre aluminium foil was used as a monitor of a beam flux by means of the induced ^{24}Na activity. The guard aluminium foils were used for recoil activities elimination. The target stacks, positioned so that the beam passed through the centre, were exposed to proton and deuteron beams with a total intensity of about 1.94 x 10^{13} and 1.76 x 10^{13}, respectively. The monitor, catcher and target foils from a given irradiation were assayed by off-line gamma counting under identical geometry on a high-resolution Ge(Li) detector. Detector signals were transferred to a 4096 channel pulse-height analyzer through conventional electronics.
Spectra were analyzed with a computer code SAMPO /4/. Radionuclides were identified on the basis of gamma-ray energies, half-times, and,

if necessary, fractional abundances taken from the Gamma-Ray Catalog[5].

The cross sections of radionuclides formed in the nuclear reactions induced by 9 GeV/c protons and deuterons are listed in Table 1. They are related to the cross sections of $^{27}Al(p, 3pn)^{24}Na$ and $^{27}Al(d, 3p2n)^{24}Na$ monitor reactions, the values of which, determined on the basis of ^{24}Na induced activities in appropriate aluminium foils, are equal to 8.6±0.9 mb and 14.8±1.5 mb, respectively. The errors assigned to the cross sections displayed in Table 1 are based on our estimates of errors from counting statistics, detector efficiency and so on. A systematic error of ~10% corresponding to the beam flux monitor is not included in the tabulated values. For numerous determinations, the weighted average cross sections and weighted errors are given. In the first column of Table 1 symbols I and C are used for independent and cumulative yields, respectively.

The spallation cross sections $\sigma(A,Z)$ can be parametrized by[6]

$$\ln\{\sigma(A,Z)\} = \sigma(A) + C(Z-Z_p(A)) , \qquad (1)$$

where $\sigma(A)$ are isobaric yields and the function $C(Z-Z_p(A))$ describes the distribution of yields at a given mass number with $\exp\{C(Z-Z_p)\}$ representing the charge-dispersion curve; Z_p is the most probable charge at a given A. Following the approach of Tominaka et al.[7], we have fitted our experimental data with the 6-parameter equation

$$\begin{aligned} \ln\{\sigma(A,Z)\} &= \alpha_1 + \alpha_2 A + \alpha_3 A^2 + \alpha_4 (Z-Z_p(A))^2 , \\ Z_p(A) &= \alpha_5 A + \alpha_6 A^2 , \end{aligned} \qquad (2)$$

in which the first three parameters $\alpha_1 - \alpha_3$ determine the shape of the isobaric-yield distribution $\sigma(A)$ (mass-yield curve), α_4 the width and α_5, α_6 the shape of the charge-dispersion curve.

Table 1

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

Nuclide	Type of yield	Protons σ(mb)	Deuterons σ(mb)
^{24}Na	C^-	3.17±0.18	19.19±1.04
^{28}Mg	C^-	0.38±0.06	1.96±0.18
^{42}K	I	1.88±0.12	5.27±0.54
^{43}K	C^-	2.04±0.24	4.24±0.43
^{43}Sc	C^+	2.27±0.17	4.21±0.51
^{44}Sc	I	5.13±0.31	7.28±0.67
^{46}Sc	I	8.46±0.65	9.75±1.13
^{47}Sc	I	3.95±0.33	3.91±0.64
^{48}Sc	I	0.56±0.08	1.39±0.32
^{48}V	C^+	9.31±0.42	8.96±0.55
^{48}Cr	I	0.22±0.05	0.20±0.08
^{51}Cr	I	16.94±0.57	28.42±1.36
^{52}Mn	I	7.53±0.41	11.75±1.09
^{54}Mn	I	16.88±0.35	28.60±1.12
^{56}Mn	C^-	4.00±0.49	10.04±0.87
^{52}Fe	C^-	0.83±0.11	1.21±0.21
^{55}Co	C^+	1.12±0.13	1.14±0.22
^{56}Co	C^+	4.36±0.33	6.86±0.71
^{57}Co	C^+	14.90±0.84	18.53±1.82
^{56}Ni	I	0.27±0.10	0.49±0.17
^{57}Ni	I	0.73±0.22	1.42±0.46

The deuteron and proton data over a $42 \leqq A \leqq 57$ mass range were separately fitted with Eq. (2) by using the least-squares code FEDEF[8]. Only independent yields (see Table 1) were taken into account. The results of the parametrization are displayed in Table 2 where the appropriate reduced chi-square values of χ^2_ν are also presented.

Table 2

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

Parameter	Protons	Deuterons
α_1	2.23 ± 0.96	2.66 ± 1.01
α_2	$-(1.26 \pm 1.97) \times 10^{-2}$	$-(2.59 \pm 3.71) \times 10^{-2}$
α_3	$(3.88 \pm 3.04) \times 10^{-4}$	$(5.91 \pm 3.54) \times 10^{-4}$
α_4	-1.25 ± 0.12	-1.09 ± 0.18
α_5	$(4.88 \pm 0.03) \times 10^{-1}$	$(4.83 \pm 0.05) \times 10^{-1}$
α_6	$-(4.12 \pm 0.57) \times 10^{-4}$	$-(3.39 \pm 0.62) \times 10^{-4}$
	$\chi^2_\nu = 1.747$	$\chi^2_\nu = 2.283$

The quality of the parametrization may be examined in comparison with the calculated charge-dispersion and mass-yield curves. In order to obtain the charge dispersion curves, we have calculated fractional isobaric yields F_{exp} and F_{calc}, which are, respectively, the experimental and calculated values of the cross sections related to $\sigma(A)$. The isobaric yields $\sigma(A)$ are defined as

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

where the values of Z_{min} and Z_{max} are 0 and 29, respectively, since

the atomic number Z of spallation products from the interaction of ${}^{nat}_{28}Ni(d,X)$ and ${}^{nat}_{28}Ni(p,X)$ should be less than or equal to 29. If the sum of Eq. (3) is replaced by the integral between $-\infty$ and $+\infty$,

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

and the appropriate analytically calculated fractional yields

$$F_{anal}(A,(Z-Z_p)) = \sqrt{\frac{-\alpha_4}{\pi}} \; e^{\alpha_4 (Z-Z_p)^2} \quad . \tag{5}$$

Including parameters α_4 from Table 2, we obtain

$$F_{anal}(A,(Z-Z_p)) = \begin{cases} 0.63 e^{-1.25 (Z-Z_p)^2} & \text{for } (p+Ni) \\ 0.59 e^{-1.09 (Z-Z_p)^2} & \text{for } (d+Ni) \end{cases} \quad , \tag{6}$$

respectively. The fractional isobaric yields

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

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

The charge dispersion curves for the spallation of natural nickel by 9 GeV/c protons and 9 GeV/c deuterons are displayed in Fig. 1. The mass-yield curves, based on Eq. (4), are shown in Fig. 2. The points are experimental cross sections corrected for an unmeasured portion of the isobaric yield by means of Eq. (2). The errors incorporate a 20% uncertainty in unmeasured contributions to the isobaric yields.

In summary, the 6-parameter equation, derived from the general expression, was found to be satisfactory to describe the distribution of radionuclides resulting from the spallation of nickel by high-energy protons and deuterons. Similarity of the mass-yield and charge distribution curves for both projectiles is remarkable.

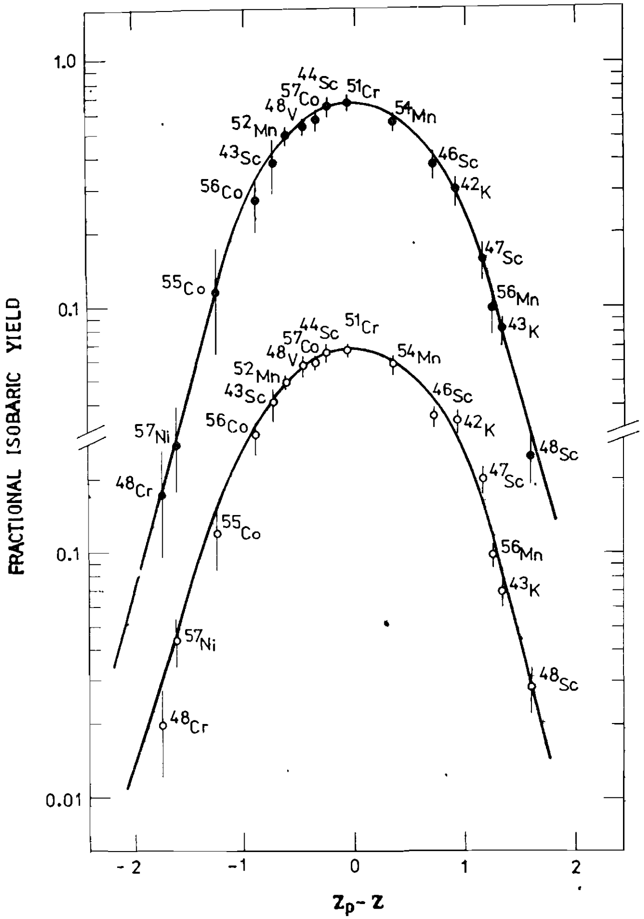

Fig.1. Charge-dispersion curves for products over a mass range of $42 \leqq A \leqq 57$ from the spallation of nickel by 9 GeV/c protons and deuterons. The upper curve and filled points are for deuterons, the lower curve and open points are for protons. Both curves are displayed vertically by a factor of 10 for display purposes.

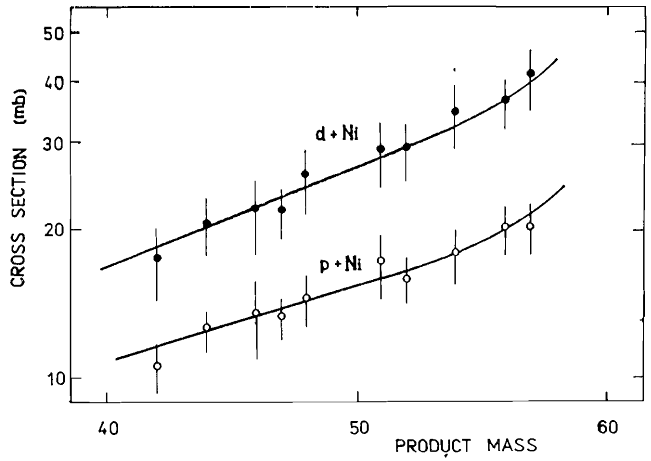

Fig.2. Mass-yield curves for products in a mass range of $42 \leqq A \leqq 57$ from the spallation of nickel by 9 GeV/c protons and deuterons.

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

Сечения образования радиоактивных нуклидов во взаимодействии с протонами и дейтронами с импульсом 9 ГэВ/с были получены посредством активационного метода. На основе этих данных определены и массовые распределения образовавшихся ядер.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Spallation of Nickel by 9 GeV/c Protons and Deuterons

Cross sections for the production of radionuclides in the interaction of nickel with 9 GeV/c protons and 9 GeV/c deuterons were determined by the activation technique. Charge-dispersion and mass-yield distributions were deduced from these data.

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

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