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TARGET RESIDUES FROM THE REACTIONS OF 9 GeV/c PROTONS AND DEUTERONS WITH ^{181}Ta

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1. INTRODUCTION

The interaction of high-energy particles with heavy target nuclei leads to a variety of residues, the products of spallation and nuclear fission. A large number of heavy target residues forms a good statistical basis for obtaining their charge dispersions and mass yield distributions. In view of the basic concepts of high-energy nuclear physics /factorization, limiting fragmentation/ their analysis is desirable. Moreover, high-energy nuclear reaction models can be also tested by means of the isobaric /or mass/ yield distributions of residual nuclei resulting from the interaction.

In the present paper we are interested in the nuclear reactions of 9 GeV/c protons /T_p=8.1 GeV/ and 9 GeV/c deuterons /T_d=7.3 GeV/ with ^{181}Ta. The choice of these projectiles and energies, motivated by their availability at the Dubna synchrophasotron, allows us to make a comparison with earlier studies of tantalum target fragmentation by intermediate 0.34-0.66 GeV[1-3], 5.7 GeV[4] proton energies and 8 GeV ^{20}Ne-ions[5] as well as to gain new experimental information /to date the nuclear reactions of tantalum with high-energy deuterons have not been investigated/. Charge dispersions and isobaric yields of target residues in both investigations were obtained from nuclidic formation cross sections measured by the well-known activation technique.

2. EXPERIMENTS

Two target stacks containing mylar, aluminium and tantalum foils of high purity /99.9%/ were irradiated with 9 GeV/c protons and deuterons in an external beam of the Dubna synchrophasotron. The diameter of the target discs was 5 cm 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 8. The diameter of the beam spots in both irradiations was about 1 cm. The irradiation periods were equal to $\sim 10^{13}$ total flux particles in both irradiations. Aluminium foils No.2 in both target stacks were used as a beam flux monitor by measuring the induced ^{24}Na activity. The cross sections of the monitor reactions ^{27}Al/p,3pn/^{24}Na and ^{27}Al/d,3p2n/^{24}Na were taken to be 8.6 mb[6] and 14.8 mb[7], respectively.

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	6.0	6.0
2	Al	20.0	19.8
3	Al	6.2	6.1
4	My	17.5	17.7
5	Ta	62.1	61.8
6	Ta	154.0	154.2
7	Ta	61.6	62.2
8	My	17.6	17.5

The targets were gamma-ray counted on a Ge/Li/-spectrometer with a 4096-channel capacity. The resolution of two Ge/Li/ detectors /28 cm^3 and 45 cm^3/ was 2.8 keV and 2.3 keV at 1332.5 keV, respectively. They were calibrated against absolute efficiences with a variety of gamma-ray standards: based on the deviations of individual calibration points from a smooth curve, the absolute accuracy of the calculations was estimated to be about 5%. The spectra were analysed by means of a computer program which found all significant peaks and computed their areas and decay rates. The nuclides were unambiguously identified by their gamma-ray energies, half-lives and fractional abundances[8].

3. RESULTS AND DISCUSSION

The cross sections of target residues formed in the reactions induced by 9 GeV/c protons and deuterons on tantalum are listed in Table 2. The errors assigned to the cross section values are based on those of counting statistics, detector efficiences, target thicknesses and so on. A systematic error of about 10% corresponding to the beam flux monitor is not included. The calculation of the cross sections includes the correction for secondary effects. The contribution of a secondary particle induced reaction to the measured cross section was estimated from the ratio of the production cross sections simultaneously measured with "thin" /62 mg.cm^{-2}/ and "thick" /154 mg.cm^{-2}/ tantalum targets. Figure 1 shows the ratios obtained for these two targets in both experiments as a function of product mass number.

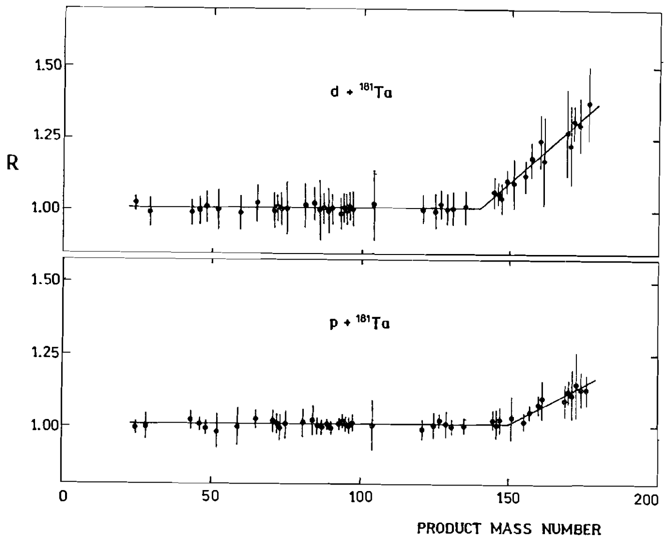

Fig.1. Thick to thin target cross section ratios $R = \sigma(154\text{mg.cm}^{-2}) / \sigma(62\text{mg.cm}^{-2})$ from the d+^{181}Ta and p+^{181}Ta reactions at 9 GeV/c, respectively.

As can be seen, the ratios for both reactions are independent of mass number for products with $A \lesssim 150$. The average value of the ratios of the cross sections, fluctuating about unity, indicates that secondary effects for these products are neglibile. However, the experimental ratios for products with $A \gtrsim 150$ increase with product mass number. This points to the occurrence of visible secondary effects for products close to the target. The measured cross sections in this mass region were corrected for the contribution of secondaries by linear extrapolation to zero target thickness.

Table 2

Production cross sections of target residues in the reactions of tantalum with 9 GeV/c protons and deuterons. Symbols I and C are used for independent and cumulative yields, respectively

Nuclide	Type of yield	Protons /mb/	Deuterons /mb/
^{24}Na	C	8.4±0.6	13.7±0.8
^{28}Mg	C	2.3±0.2	4.2±0.3
^{43}K	C	2.1±0.2	3.6±0.2
^{44}Sc^{m}	I	1.4±0.1	2.7±0.2
^{46}Sc	I	5.3±1.2	10.3±1.7
^{48}Sc	I	0.9±0.1	1.3±0.1
^{52}Mn	C	0.7±0.1	0.9±0.1
^{59}Fe	C	0.9±0.2	1.7±0.3
^{65}Zn	C	2.6±0.5	3.1±0.6
^{71}As	C	2.6±0.2	2.5±0.2
^{72}As	C	2.7±0.3	2.1±0.2
^{73}Se	C	0.9±0.1	1.9±0.2
^{75}Se	C	3.2±1.0	5.0±1.4
^{81}Rb	C	2.6±0.2	3.4±0.3
^{84}Rb	I	0.9±0.1	1.2±0.1
^{84}Rb^{m}	I	1.0±0.1	-------
^{86}Y	C	3.3±0.5	4.8±0.8
^{87}Y	C	2.9±0.2	3.5±0.3
^{87}Y^{m}	C	-------	3.6±0.3
^{86}Zr	C	1.5±0.1	1.6±0.2
^{89}Nb	C	2.1±0.2	2.0±0.4
^{90}Nb	C	2.5±0.3	3.4±0.4
^{93}Mo^{m}	I	-------	1.3±0.1

Table 2 /continued/

Nuclide	Type of yield	Protons /mb/	Deuterons /mb/
^{93}Tc	C	1.0±0.1	1.8±0.2
^{94}Tc	I	1.2±0.1	1.9±0.1
^{95}Tc	C	3.9±0.3	5.6±0.4
^{96}Tc	I	2.0±0.2	2.4±0.3
^{97}Ru	I	2.1±0.1	2.3±0.2
$^{101}Rh^{m}$	C	2.3±0.2	2.7±0.2
^{104}Ag	C	2.2±0.8	2.9±0.7
^{121}Te	C	5.4±0.5	8.4±0.9
^{125}Xe	C	4.9±0.6	7.2±0.8
^{127}Xe	C	4.2±0.4	6.0±0.5
^{129}Cs	C	6.3±0.5	9.9±0.6
^{131}La	C	4.4±0.3	5.8±0.4
^{135}Ce	C	5.7±0.3	6.2±0.5
^{145}Eu	C	11.9±1.1	16.7±2.1
^{146}Eu	C	9.7±0.9	14.2±1.0
^{147}Gd	C	11.0±1.2	11.1±1.7
^{149}Gd	C	--------	22.3±2.9
^{151}Tb	C	8.2±3.9	20.5±4.3
^{155}Dy	C	4.5±0.3	8.4±0.8
^{157}Dy	C	8.8±0.7	18.2±2.9
^{160}Er	C	8.7±1.0	9.2±1.5
^{161}Er	C	14.2±9.0	18.5±7.1
^{169}Yb	C	3.6±0.4	5.7±0.8
^{170}Hf	C	16.5±3.2	22.2±4.6
^{171}Hf	C	18.5±1.3	23.9±1.9
^{173}Hf	C	12.9±2.2	18.1±2.8
^{173}Ta	C	4.0±0.5	6.8±0.7

Table 2 /continued/

Nuclide	Type of yield	Protons /mb/	Deuterons /mb/
^{174}Ta	C	9.4±2.3	-------
^{176}Ta	C	20.9±1.3	39.8±4.9
$^{178}Ta^{m}$	I	11.8±0.9	-------

The nuclidic formation cross sections $\sigma(A,Z)$ can be parametrized by/9/

$$\sigma(A,Z) = \sigma(A)\left[2\pi C_Z(A)\right]^{-1/2} \exp\left[-\frac{(Z-Z_p(A))^2}{2C_Z^2(A)}\right] , \qquad /1/$$

where $\sigma(A)$ are isobaric yields, $C_Z(A)$ is the charge dispersion width parameter for mass number A and $Z_p(A)$ is the most probable atomic number for that A. Over small mass ranges, the width parameter was found to be independent of A, and the centre $Z_p(A)$ of charge distributions could be presented by

$$Z_p(A) = aA + bA^2 . \qquad /2/$$

Using this assumption as well as a further assumption that $\sigma(A)$ varies smoothly and slowly as a function of mass number, the measured cumulative cross section for precorsory β-decay can be iteratively corrected/5/.

In order to obtain charge dispersion parameters, the measured nuclidic formation cross sections $\sigma(A,Z)$ placed in eight groups according to mass number were fitted to an independent Gaussian-shaped yield /Eq./1//. It should be noted that no isomeric states were included in this fitting procedure. Nucliding groupings along with the width parameters C_Z and the coefficients a and b of the Z_p functions /Eq./2// for both investigations are listed in Table 3. The $p+^{181}Ta$ and $d+^{181}Ta$ charge dispersion curves are displayed in Figs.2 and 3, respectively, where, as usual, the calculated isotopic production cross sections σ_{IY} are plotted versus Z_p-Z. As can be seen, the charge dispersions of target residues are similar, the differencies being in the magnitude of yields.

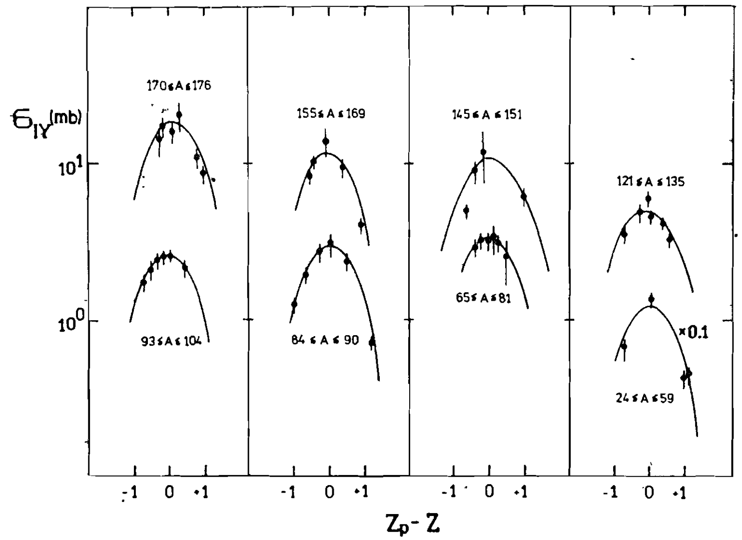

Fig.2. The charge dispersion curves from the reactions of 9 GeV/c protons with ^{181}Ta.

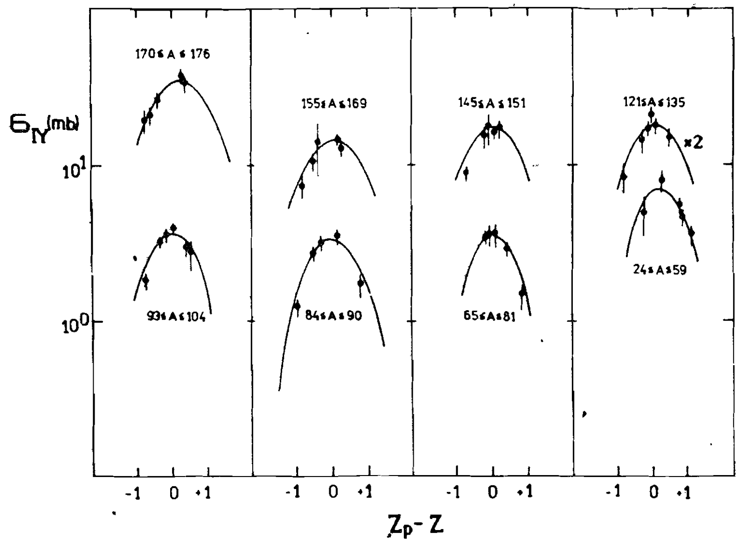

Fig.3. The charge dispersion curves from the reactions of 9 GeV/c deuterons with ^{181}Ta.

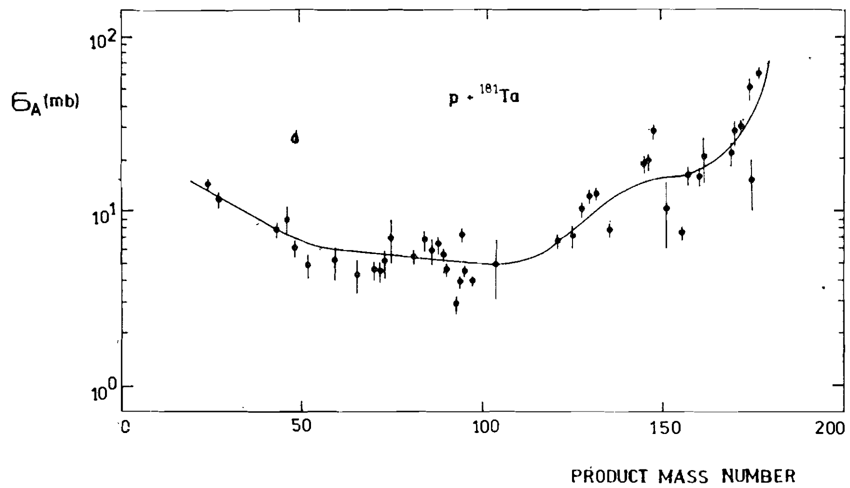

Fig.4. The mass yield distribution of target residues from the reactions of 9 GeV/c protons with ^{181}Ta.

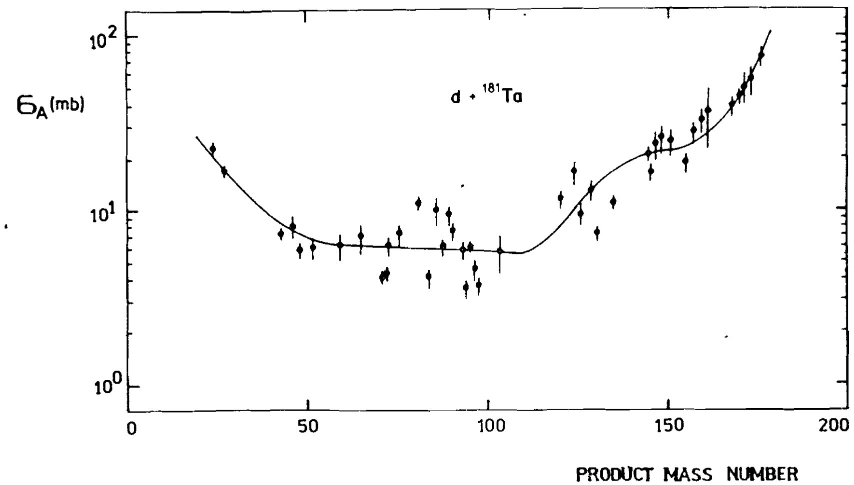

Fig.5. The mass yield distribution of target residues from the reactions of 9 GeV/c deuterons with ^{181}Ta.

Table 3
Charge dispersion parameters

Mass range	Protons C_z	Protons a	Protons b	Deuterons C_z	Deuterons a	Deuterons b
24- 59	0.65	0.47	-2.2×10^{-4}	0.60	0.48	-4.0×10^{-4}
65- 81	0.65	0.49	-3.9×10^{-4}	0.65	0.45	1.8×10^{-4}
84- 90	0.70	0.48	-3.1×10^{-4}	0.65	0.45	0.1×10^{-4}
93-104	0.75	0.52	-6.8×10^{-4}	0.625	0.49	-2.0×10^{-4}
121-135	0.55	0.43	0.3×10^{-4}	0.50	0.44	-1.4×10^{-4}
145-151	0.50	0.49	-4.0×10^{-4}	0.45	0.52	-5.9×10^{-4}
155-169	0.475	0.47	-3.0×10^{-4}	0.60	0.50	-4.8×10^{-4}
170-176	0.65	0.49	-4.2×10^{-4}	0.60	0.47	-3.1×10^{-4}

The mass yields σ_A have also been obtained on the assumption of Gaussian charge dispersions and the set of fitting parameters listed in Table 3. The p+^{181}Ta and d+^{181}Ta mass yield distributions are shown in Figs.4 and 5, respectively, where the values of $\sigma(A)$ are plotted versus product mass number A, and the solid curves are drawn to guide the eye. The error bars only incorporate measurement statistics and do not take into account the errors due to uncertainties in the beam flux or those induced by the analysis of the charge distributions. Due to the charge dispersion fitting process, the value of systematic uncertainties was estimated to be approximately 25%.

The p+^{181}Ta and d+^{181}Ta mass yield distributions display common features. First, the cross sections decrease slowly with increasing A and reach a minimum in the mass range of about $A \approx 100$. In this mass region a dominant contribution to the production of nuclides comes from nuclear fission. Next the cross sections increase sharply with increasing A, particularly in the vicinity of the target. In this mass region, spallation is a dominant mechanism. Integration of the mass yield distributions with respect to product mass number gives the production cross section of target residues, σ^{TR}. Our integration was performed over the interval from A=40 to the mass number of the target. A lower limit of 40 mass units was chosen for the same reasons as given in ref.[5]. The results of this integration along with those for the ^{20}Ne+^{181}Ta[5] investigation are summarized in Table 4. Here, the total reaction cross sections σ_R calculated as

$$\sigma_R = \pi r_0^2 \left(A_P^{1/3} + A_T^{1/3} - b_{PT}\right)^2 \qquad /3/$$

with the parameters r_o=1.37 fm and b_{PT}=0.51[10] are also included /as usual, the symbols P and T are used for particle and target, respectively/. The experimental cross sections of target residues represent ≈ 70% of σ_R ; the impact parameter b[11-13] can be estimated from the fraction of the total reaction cross section. As can be seen from Table 4, the calculated impact parameters $b < (R_P+R_T)$, where the appropriate radii are $R_P=r_oA_P^{1/3}$ and $R_T=r_oA_T^{1/3}$. Thus, the target residues from the p+^{181}Ta and d+^{181}Ta reactions are produced in collisions where the centre of the projectile lies inside the radius of the target nucleus.

Table 4
Comparison of the cross sections, radii and impact parameters of the nuclear reactions with ^{181}Ta induced by high-energy protons, deuterons and ^{20}Ne-ions[5]

Reaction	σ^{TR} /b/	σ_R /b/	R_P /fm/	R_T /fm/	b /fm/
p+^{181}Ta	1.46±0.25	2.11	1.37	7.75	6.31
d+^{181}Ta	1.67±0.31	2.30	1.73	7.75	6.88
^{20}Ne+^{181}Ta	2.6 ±0.4	3.64	3.72	7.75	8.18

The discussion of the results can be also presented in terms of the basic concepts of high-energy nuclear physics such as factorization and limiting fragmentation. The concept of factorization[14] of the nuclear cross section implies that the yield of a particular residue from the target due to nuclear interactions is independent of the projectile except from the geometric factor γ_P^T . Thus, the ratios

$$\frac{\sigma(^{181}\mathrm{Ta}/^{20}\mathrm{Ne},X/R_i)}{\sigma(^{181}\mathrm{Ta}/\ p,X/R_i)} \qquad /4/$$

and

$$\frac{\sigma(^{181}\mathrm{Ta}/d,X/R_i)}{\sigma(^{181}\mathrm{Ta}/p,X/R_i)} \qquad /5/$$

should have constant values of $\gamma^{Ta}_{Ne}/\gamma^{Ta}_{p}$ and $\gamma^{Ta}_{d}/\gamma^{Ta}_{p}$, respectively, for any target residue R_i. The experimentally determined ratios $Y_{Ne/p}$ /4/ and $Y_{d/p}$ /5/ for 8.0 GeV ^{20}Ne-ions/5/, 7.3 GeV deuterons and 8.1 GeV protons are displayed in Fig.6. The ratios of the cross sections were determined for 29 and 44 target residues in the mass region from ^{28}Mg and ^{176}Ta and from ^{24}Na to ^{176}Ta, respectively. The average values of the relative projectile factors $\gamma^{Ta}_{Ne}/\gamma^{Ta}_{p}$ = 2.48±0.45 and $\gamma^{Ta}_{d}/\gamma^{Ta}_{p}$ = 1.46±0.38. Another evidence for the factorization follows from the agreement of the p+^{181}Ta and d+^{181}Ta mass distributions at 9 GeV/c /see Figs.4 and 5/. The similarity of the mass distributions from the reactions of 8.0 GeV ^{20}Ne-ions /see Fig.7 in ref./5// and 8.1 GeV protons /Fig.4/ with ^{181}Ta, even though differing widely in projectile energy, can be also considered as giving support to the factorization hypothesis.

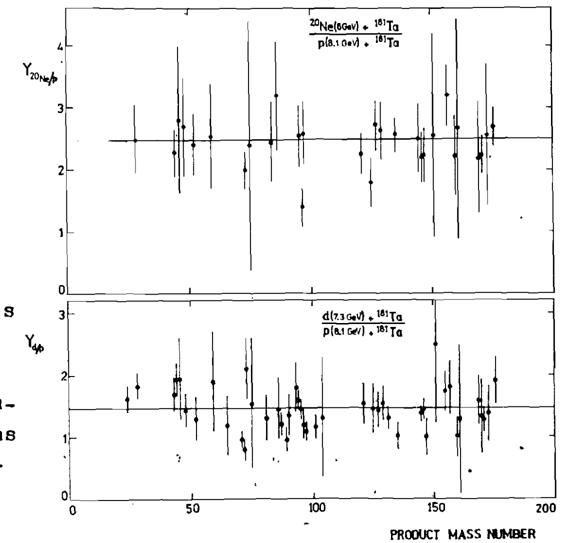

Fig.6.
The experimentally determined cross section ratios of target residues from the reactions of 8.0 GeV ^{20}Ne-ions/5/, 7.3 GeV deuterons and 8.1 GeV protons with ^{181}Ta. The solid horizontal lines indicate the appropriate average values.

The concept of limiting fragmentation/15/ implies that for sufficiently high projectile energies the production cross section of the residue R_i is independent of energy. In order to test this hypothesis, we compare our p+^{181}Ta results with previous proton data/1-4/. The shape of our p+^{181}Ta mass yield distribution /see Fig. 4/ was found to be similar to that resulting from the reaction of tantalum with 5.7 GeV protons /see Fig.6 in ref./4//, but very different from those resulting from the p+^{181}Ta reactions at 0.34 GeV/1/,

0.45 GeV/2/ and 0.66 GeV/3/ proton energies /see Fig.7 in ref./4/ and Fig.1 in ref./5//. The limiting fragmentation, as has been attempted, is not valid for intermediate proton energies. On the other hand, the similarity of the mass yield distributions of target residues from the p+^{181}Ta reactions at 8.1 GeV and 5.7 GeV manifests the validity of limiting fragmentation at these energies. The average value of the cross section ratios $\sigma_{8.1GeV}/\sigma_{5.7GeV}$ for 11 target residues in the mass region from ^{24}Na to ^{173}Hf /see Table 5/ is 0.97±0.13 .

Table 5
Comparison of the p+^{181}Ta cross sections at 8.1 GeV with previous data at 5.7 GeV/4/

Nuclide	$\sigma_{8.1}/\sigma_{5.7}$	Nuclide	$\sigma_{8.1}/\sigma_{5.7}$
^{24}Na	0.97±0.12	^{28}Mg	0.92±0.08
^{52}Mn	0.88±0.12	^{73}Se	0.61±0.08
^{121}Te	0.45±0.05	^{145}Eu	0.98±0.38
^{146}Eu	2.30±0.21	^{147}Gd	0.72±0.08
^{160}Er	0.35±0.04	^{171}Hf	1.42±0.10
^{173}Hf	0.96±0.17		

4. CONCLUSIONS

The charge dispersions and mass yield distributions of target residues from the reactions of 9 GeV/c protons and deuterons with tantalum have been determined. The charge dispersions in both investigations were found to be closely comparable. The similarity between the mass yield distributions of the target residues from the reactions p+^{181}Ta, d+^{181}Ta and ^{20}Ne+^{181}Ta/5/ for the projectiles of about the same kinetic energy may be viewed as an evidence for factorization in these reactions. The evidence of limiting fragmentation comes from the similarity of the p+^{181}Ta mass yields at 8.1 GeV and 5.7 GeV/4/ proton energies. The integration of these cross sections for target residues with A $\gtrsim$ 40 makes a $\approx$70% contribution to the total reaction cross section. The calculation of the "hard sphere" reaction cross section indicates that target residues from the reactions of 9 GeV/c protons and deuterons with ^{181}Ta are created in central collisions.

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Остаточные ядра в реакциях 9 ГэВ/с протонов и дейтронов с ядрами ^{181}Ta

Исследование образования радиоактивных нуклидов во взаимодействии 9 ГэВ/с протонов и дейтронов с ядрами ^{181}Ta проводились на синхрофазотроне ОИЯИ. Сечения образования остаточных ядер в диапазоне массовых чисел $24 \leq A \leq 178$ были определены методом "off-line" гамма-спектроскопии. На основе этих данных определены зарядовые и массовые распределения образовавшихся ядер. Обсуждение результатов проводилось в рамках основных представлений физики высоких энергий.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Target Residues from the Reactions of 9 GeV/c Protons and Deuterons with ^{181}Ta

The production of radioactive nuclides in the reactions of 9 GeV/c protons and deuterons with ^{181}Ta has been investigated at the Dubna synchrophasotron. The production cross section of target fragments with $24 \leq A \leq 178$ were determined by off-line gamma-ray spectroscopy. Charge dispersions and mass yields are deduced from these data. The results are discussed in terms of the concepts of high-energy nuclear physics.

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

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