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RECOIL PROPERTIES OF DEEP SPALLATION AND FRAGMENTATION PRODUCTS IN THE INTERACTION OF TANTALUM WITH 3.65 AGeV ^{12}C-IONS AND PROTONS

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1. INTRODUCTION

The interaction of high-energy particles and light nuclei with heavy target nuclei has been the subject of many experimental studies in recent years. The formation of deep spallation (mass loss $\Delta A \gtrsim 30$) and fragmentation ($A \lesssim 1/3A_{target}$) products in three reactions has been investigated particularly from the Z and A distributions of these products measured by the well-known activation technique and gamma-ray spectroscopy. Moreover, the investigations can be also performed by measurements of the recoil properties of the radionuclides formed in the interactions. The thick-target, thick-catcher technique, in which both target and catcher are thick compared to the range of the products of interest, has been studied extensively [1-6]. The experimental results are expressed as the ratios of the forward-to-backward emission ranges of F/B and the mean ranges of products in the target material, 2W(F+B): F and B are the fractional numbers of product recoiling into the forward and backward catcher, respectively, W (in mg/cm^2) is the target thickness.

By using this technique we have measured recoil properties of deep spallation and fragmentation products of the interaction of tantalum with 3.65 AGeV ^{12}C-ions and protons. The experiment has been performed in conjunction with the cross sections determination reported in our previous work [7]. In the present work our attention is focused on recoil properties of products: the systematics of the appropriate kinematic parameters and their dependence on product mass and fractional mass loss will be examined. Moreover, comparison of the results obtained in ^{12}C-ion and proton induced reaction at the same energy per nucleon will be used to test the validity of factorization hypothesis. The results are treated within the theoretical framework of the two-step velocity vector model.

2. EXPERIMENTAL

As has been pointed out in the introduction, the experiment was performed in conjuction with the target cross section determination reported in [7] which describes the experimental procedure in detail. Briefly, the irradiations were performed with 3.65 AGeV ^{12}C-ions and 3.65 GeV protons at the external beam of the Dubna synchrophasotron. The target stacks consisted of 62 mg/cm^2 thick tantalum foil of high purity (99.9%) surrounded by 17.5 mg/cm^2 thick Mylar catcher foils.

After irradiations, the target stacks were disassembled and appropriate forward, F, and backward, B, catcher foils were gamma-ray counted on Ge(Li) spectrometer with 4096 channel capacity. The spectra were analyzed with codes SAMPO [8] and GSAP [9]. The nuclides were unambiguously identified by their gamma-ray energies, half-lives and fractional abundances [10].

3. RESULTS AND ANALYSIS

The experimental values of the mean ranges, 2W(F+B), and the ratios of forward-to-backward emission, F/B, of products formed in both interactions are given in Table 1 and displayed graphically in Figs.1 and 2. Figure 1 shows the variation of the forward-to-backward ratios with product mass in both $p + {}^{181}Ta$ and ${}^{12}C + {}^{181}Ta$ reactions and Fig.2 exhibits the behaviour of the experimental ranges. The similarity is observed for both projectiles: while the ranges decrease with increasing product mass, the F/B values initially decrease slowly with increasing A in order to reach a minimum in the mass range of about $A \approx 40$-50 and then increase sharply at higher mass numbers.

The trends of recoil properties can be evaluated more directly in terms of the kinematic parameters obtainable from the experimental F/B and 2W(F+B) data by means of the two-step vector velocity model [11]. The analysis within the framework of this model is based on the following assumptions. The observed velocity of a recoil product $\vec{v}_r$ can be divided into two components $\vec{v}$ and $\vec{V}$ corresponding to the cascade and breakup stage of the interaction, respectively. The range of a recoil product in the target is given by

$$R = k(|\vec{v} + \vec{V}|)^N , \qquad (1)$$

k and N being constants. By using the notation

$$\eta_{||} = v_{||} / V \qquad (2)$$

($v_{||}$ is the component of $\vec{v}$ parallel to the beam direction, the perpendicular component of the cascade velocity $v_{\perp}$ is assumed to be zero) and

Table 1

Recoil properties of deep spallation and fragmentation products of the interaction of ^{181}Ta with 3.65 AGeV ^{12}C-ions and 3.65 GeV protons

Product	p + ^{181}Ta 2W(F+B) [mg/cm²]	F/B	^{12}C + ^{181}Ta 2W(F+B) [mg/cm²]	F/B
^{24}Na	10.56±1.45	2.01±0.11	12.88±1.67	2.32±0.14
^{28}Mg	12.48±1.50	1.86±0.12	14.23±1.73	2.20±0.14
^{44}Sc^{m}	5.31±0.43	1.66±0.10	6.21±0.50	1.80±0.12
^{46}Sc	5.40±0.45	1.70±0.10	5.30±0.45	1.78±0.13
^{48}Sc	5.77±0.48	1.71±0.10	5.85±0.49	1.71±0.11
^{52}Mn	4.10±0.37	1.66±0.07	3.77±0.36	1.65±0.10
^{59}Fe	4.58±0.42	1.69±0.07	4.35±0.40	1.65±0.10
^{65}Zn	4.25±0.35	1.75±0.07	4.89±0.42	1.70±0.10
^{74}As	3.45±0.28	1.84±0.06	3.70±0.33	1.82±0.11
^{81}Rb	3.03±0.25	2.05±0.08	2.67±0.23	2.00±0.13
^{84}Rb	3.23±0.28	1.96±0.10	2.94±0.26	2.03±0.15
^{87}Y	---- ---	--------	3.56±0.29	2.37±0.20
^{88}Zu	2.52±0.32	2.38±0.22	3.00±0.41	2.35±0.28
^{89}Nb	3.26±0.29	2.15±0.14	3.00±0.38	2.40±0.28
^{90}Nb	2.19±0.17	2.20±0.14	2.42±0.20	2.27±0.18
^{96}Tc	2.07±0.15	2.32±0.14	2.05±0.17	2.29±0.19
^{101}Rh^{m}	2.12±0.15	2.50±0.16	1.80±0.14	2.48±0.21
^{105}Ag	2.00±0.16	2.33±0.15	-------	--------
^{111}In	1.54±0.12	3.00±0.18	1.82±0.14	2.95±0.23
^{125}Sn	1.25±0.10	3.15±0.20	1.50±0.13	3.24±0.25
^{131}Ia	0.93±0.13	3.68±0.21	1.14±0.17	3.77±0.33
^{145}Eu	0.60±0.08	4.02±0.27	0.75±0.10	4.15±0.34

$$R_0 = kV^N \tag{3}$$

(R_0 is the mean range in the target material, corresponding to the recoil speed V), the following relationships can be derived [11]:

$$\frac{F}{B} = \frac{1 + 2/3\,\eta_{||}\,(N+2) + [\,\eta_{||}\,(N+1)/2\,]^2}{1 - 2/3\,\eta_{||}\,(N+2) + [\,\eta_{||}\,(N+1)/2\,]^2} \tag{4}$$

$$2W(F+B) = R_0[\,1 + 1/4\,\eta_{||}^2\,(N+1)^2\,]. \tag{5}$$

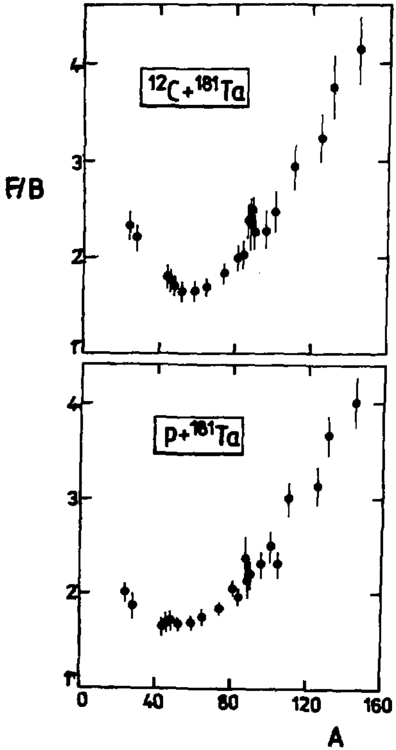

Fig.1. Product mass dependence of the forward-to-backward emission ranges of deep spallation and fragmentation products of the interaction of tantalum with 3.65 AGeV ^{12}C-ions and 3.65 GeV protons.

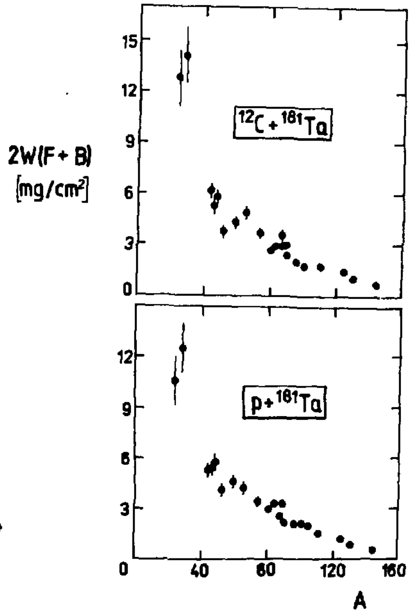

Fig.2. Product mass dependence of the ranges of deep spallation and fragmentation products of the interaction of tantalum with 3.65 AGeV ^{12}C-ions and 3.65 GeV protons.

The kinematic parameters of interest are the fragment kinetic energy

$$T = 1/2AV^2 \qquad (6)$$

and the velocity imparted to the fragment

$$\beta_{||} = v_{||}/c = \eta_{||}/c\sqrt{2T/A}\ . \qquad (7)$$

These parameters were obtained from recoil properties data using Eqs.(4) and (5), the range-energy tables of Northcliffe and Schilling [12] and relationships derived by Winsberg [13] from the experimental stopping powers.

4. DISCUSSION

We start the discussion of the above results with a consideration of the fragment kinetic energies of deep spallation and fragmentation products in both reactions. Figure 3 shows the dependence of the fragment kinetic energy, T, on the fractional mass loss, $\Delta A/A$, ΔA being the mass difference between target and product. Cumming and Bachmann [14] and Winsberg [15] have systemized the kinetic energies of spallation products on the basis of assumptions related to the random nature of individual deexcitation steps. They have shown that kinetic energies should increase linearly with $\Delta A/A$. As can be seen from Fig.3, the expected dependence in both interactions is valid up to a fractional mass loss of some 0.8. Large deviations from the observed trend are seen for the lightest fragments ^{24}Na and ^{28}Mg, respectively. Moreover, a sharp increase of T in $\Delta A/A$ region from 0.6 to 0.8 is also evident. In Fig.3, the appropriate lines in both $\Delta A/A$ regions represent a least squares fit of T values on fractional mass loss. Results of the derived parametrizations are summarized in Table 2.

The lines through the points in both $\Delta A/A$ regions indicate an average energy dissipation of approximately 25 MeV per

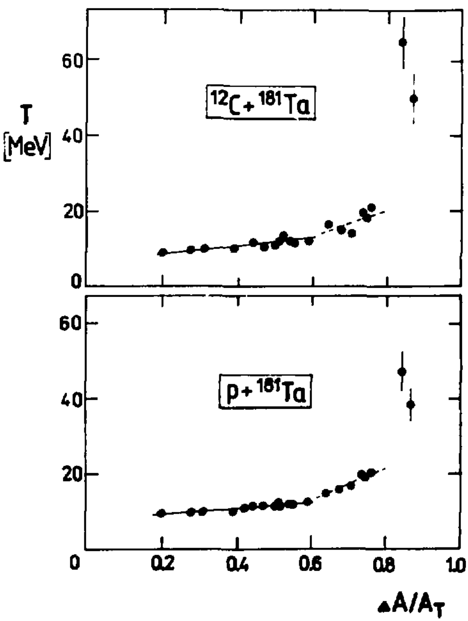

Fig.3. Dependence of product kinetic energy T on fractional mass loss, $\Delta A/A_T$. The straight line is a least squares fit for $0.2 \lesssim \Delta A/A_T \lesssim 0.6$. The dot-dashed line is the same fit for $0.6 \lesssim \Delta A/A_T \lesssim 0.8$.

Table 2

Product kinetic energy T as a function of fractional mass loss, $\Delta A/A_T$

Reaction	Range of $\Delta A/A_T$	T [MeV]
$p + {}^{181}Ta$	0.2-0.6	$7.43 + 9.04\Delta A/A_T$
	0.6-0.8	$-7.79 + 34.80\Delta A/A_T$
${}^{12}C + {}^{181}Ta$	0.2-0.6	$6.42 + 10.58\Delta A/A_T$
	0.6-0.8	$-6.45 + 33.06\Delta A/A_T$

emitted particle, which corresponds to a temperature of approximately 15 MeV /16/. This result is in accordance with those obtained previously by Wang and Porile /6/ and Winsberg /7/, as well. It should be noted that deviations from the observed trends in dependences of product kinetic energy on fractional mass loss for intermediate and particularly light fragments indicate a change in reaction mechanism. One of possible mechanisms can be connected with a clustering of nucleons into fragments in the vicinity of a liquid-gas transition point /18,19/.

Now, we turn to the velocities $\beta_{||}$ and appropriate forward moments of remnants $\beta_{||}A_T$, as well. The values of $\beta_{||}$ for proton and ^{12}C-ion induced reactions are displayed in Fig.4. These values are based on the kinetic energies shown in Fig.3 and the $\eta_{||}$ values derived from the two-step model assumptions. According

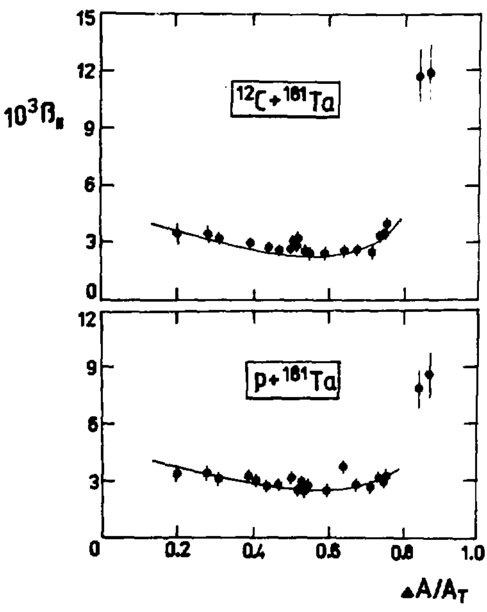

Fig.4 Dependences of the velocity $\beta_{||}$ on fractional mass loss, $\Delta A/A_T$. The curves show the trends in the values.

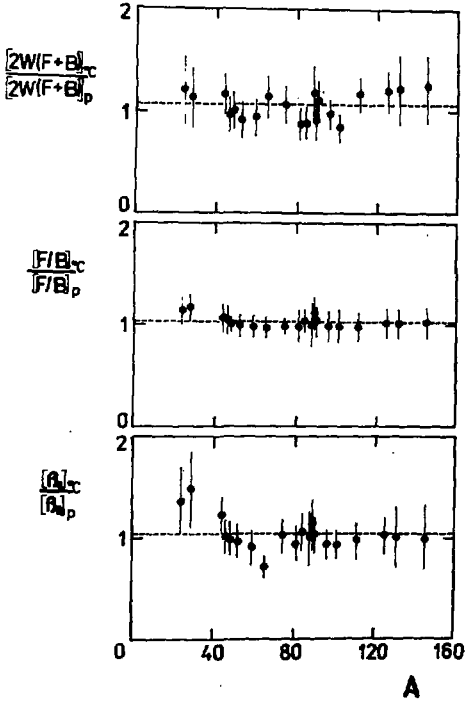

Fig.5. Ratios of the ranges, forward-to-backward emission ranges and deduced velocities of deep spallation and fragmentation products of the interaction of tantalum with 3.65 AGeV ^{12}C-ions and 3.65 GeV protons. The dashed horizontal lines indicate the appropriate average values.

to this model, the momentum $\beta_{||}A_T$ must be proportional to the excitation energy of the remnant and, consequently, to the mass loss. Thus, $\beta_{||}$ should increase with $\Delta A/A_T$. However, no increase in the velocities is seen. The values of $\beta_{||}$ vary slowly with fractional mass loss without any discernible systematic trends in the whole region. It seems that $\Delta A/A_T$ is not a good scaling variable in this case. Moreover, large values of $\beta_{||}$ associated with the formation of the lightest products, ^{24}Na and ^{28}Mg were found to be several times greater than the expected ones. The shift of these fragments cannot be described in terms of a two-step model.

Finally, we can examine the validity of factorization [20] by comparison of the results obtained in ^{12}C-ion and proton induced reactions. If the hypothesis of factorization is valid, the ratios of recoil and kinematic parameters of products emitted in both reactions should vary about unity. Ratios of the mean ranges, forward-to-backward emission ranges and velocities of deep spallation and fragmentation products of the interaction of 3.65 AGeV ^{12}C-ions and protons with tantalum are displayed in Fig.5. The appropriate average values of 1.07±0.22, 1.03±0.13 and 1.04±0.21, respectively, found in the present experiment, support factorization.

5. CONCLUSIONS

The recoil properties of a number of deep spallation and fragmentation products emitted in the interaction of tantalum with 3.65 AGeV ^{12}C ions and protons have been measured. The analysis of the results by means of the two-step vector velocity model yielded kinematic properties, such as the mean fragment kinetic energies and velocities of the appropriate remnants. While the kinetic energies T can be scaled with the fractional mass loss and increase linearly with $\Delta A/A_T$ up to a value of about 0.8, the velocities $\beta_{||}$ do not scale with $\Delta A/A_T$ in contradiction to the model predictions. Large deviations of T and $\beta_{||}$ values for the lightest fragments ^{24}Na and ^{28}Mg found in both interactions indicate that the formation of these fragments is connected with another type of mechanism and cannot be treated within the framework of a two-step model. The similarity between the appropriate mean ranges, forward-to-backward emission ratios and velocities of products in the reactions p + ^{181}Ta and ^{12}C + ^{181}Ta at the same bombarding energy per nucleon may be viewed as an evidence for factorization.

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