Recoil studies in the reaction of $^{12}C$ ions with the enriched isotope $^{118}Sn$.

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Abstract

The recoil properties of the product nuclei from the interaction of 2.2 GeV/nucleon $^{12}C$ ions from Nuclotron of the Laboratory of High Energies (LHE), Joint Institute for Nuclear Research (JINR) at Dubna with a $^{118}Sn$ target have been studied using catcher foils. The experimental data were analyzed using the mathematical formalism of the standard two-step vector model. The results for $^{12}C$ ions are compared with those for deuterons and protons.

Three different Los Alamos versions of the Quark-Gluon String Model (LAQGSM) were used for comparison with our experimental data.

1 Introduction

Studies of the interactions of high-energy projectiles with complex nuclear targets lead to an overall picture of great complexity. The violent processes that are associated with a high multiplicity of emitted particles and lead to products a hundred or more masses, removed from the target are not well understood.

On the other hand, if one investigates less violent encounters, which can be classified under the generic term of target fragmentation some simplifications will be obtained. A target fragment is a major remnant of the portion of target nucleus which appears to have been the spectator to the region of projectile-target interaction. Linear momentum transfer between a projectile and a target fragment is expected to be low. For heavy-ion projectiles, an equivalent process in the moving system results in projectile fragments which have nearly the beam velocity. Many observations of target or projectile fragmentation appear consistent with two hypotheses originally associated with peripheral hadron-hadron interactions at high energies [1]. The hypothesis of limiting fragmentation predicts that both cross sections and energy spectra of fragments should become independent of bombarding energy at high energies. The second, factorization, asserts that these fragment projectiles can be written as a product of target and projectile factor. Both cross-sections of formation of residual nuclei and their recoil properties can be used for investigation of hypothesis mentioned above.

The recoil properties of nuclei are determined often via ”thick-target thick-catcher” experiment by using induced activation method. In such experiments, the thicknesses of the target...
and catcher foils are larger than the longest recoil range. The quantities measured are the fractions $F$ and $B$ of product nuclei that recoil out of the target foil into the forward and backward directions, respectively.

The results of the experiment are usually proceeded by the standard two-step vector representation [2]–[4].

The aim of our investigation is to obtain the kinematic characteristics of residuals in reactions of $^{12}C$ ions with enriched tin isotope $^{118}$Sn. Comparison of the results obtained in $^{12}C$ and proton and deuteron induced reactions will be used to examine the extent of the deviations from factorization exhibited by these properties.

2 Experimental setup and results

Targets of enriched tin isotope $^{118}$Sn were irradiated at the Nuclotron of the LHE, JINR by $^{12}C$ ion beams with energies of 2.2 GeV/nucleon. Irradiations were of 10 hours and had round form with a diameter of 2 cm. For beam monitoring, we used the reaction $^{27}$Al($^{12}$C, X)$^{24}$Na with cross sections of $14.2 \pm 0.2$ mb [5].

The target consisted of a high-purity target metal foil of size 20x20 mm$^2$ sandwiched exactly by one pair of Mylar foils of the same size, which collected the recoil nuclei in the forward or backward directions with respect to the beam. The enrichment of the target was 98.7 %, the thickness of each target foil was 66.7 mg/cm$^2$ and the number of target piles was 11. The whole stack, together with an Al beam-monitor foil was mounted on a target holder and irradiated in air.

After irradiation the target foils and all of the forward and backward catcher foils from one target pile were collected separately, and assayed for radioactivities nondestructively with high-purity Ge detectors at LNP, JINR for one year. The radioactive nuclei were identified by characteristic $\gamma$ lines and by their half-lives. The spectra were evaluated with the code package DEIMOS32 [6].

The kinematic characteristics of around twenty product nuclei were obtained. The relative quantities of the forward- and backward-emitted nuclei (relative to the beam direction) were calculated from relations:

$$F = N_F/(N_i + N_F + N_B); \quad B = N_B/(N_i + N_F + N_B)$$

(1)

where $N_F$, $N_B$, $N_i$ are the numbers of nuclei emitted in forward and backward catchers and formed in target foils, respectively. The recoil parameters obtained in these experiments are the forward-to-backward ratio, $F/B$, and the mean range, $2W(F + B)$. [The mean range of the recoils is somewhat smaller than $2W(F + B)$, but it is conventional to refer to the latter quantity as range]. The mathematical formalism of the standard two-step vector model [2]-[3] was used to proceed the experimental results.

The following assumptions are made in this model:

(1) In the first step, the incident particle interacts with the target nucleus to form an excited nucleus with velocity $v$, momentum $P$, and excitation energy $E^*$. 

(2) In the second step, the excited nucleus loses mass and excitation energy to form the final recoiling nucleus with an additional velocity $V$, which in general will have a distribution of values and directions.

The results of the recoil experiments depend on the range-energy relation of the recoiling nuclei. It is convenient to express this relation as [3]:

$$R = kV^n,$$

(2)
The parameters $k$ and $n$ in this formalism are obtained by fitting the range dependence on energy of accelerated ions within the region from 0.025 to 5 MeV/nucleon [8]. It is possible to calculate $\eta = v/V$ and $v$ in frame of two-step vector model [3], knowing the $F/B$ ratio of the experiment.

Our experimental results are shown in Tables 1. We note that uncertainties concerning definite quantities in our tables are not listed to keep the tables concise. These uncertainties are about 15–20%. As shown in Fig. 1, the ratios $F/B$ for $^{12}C$ ions induced reactions are of the order of $\sim 3 - 4$ for heavy product nuclei and decrease to about $\sim 1.5$ for light residuals. Such dependence could be explained by different mechanisms for the production of nuclei in different mass regions. Heavy nuclei are produced mainly via the spallation mechanism, with its products more in the forward direction, while light residual nuclei may be produced by multifragmentation or fission-like processes that lead to an isotropic distribution in the frame of excited residual nuclei. For understanding the mechanism of formation of residual nuclei a comparison with theoretical calculation was made.

Theoretical calculations by the LAQGSM03.01 [10], LAQGSM03.S1 [11], and LAQGSM03.G1 [11] models with our experimental results are compared. As can be seen from Fig. 1, there is some disagreement between experimental data and theoretical results by all three versions of LAQGSM considered here. Theoretical calculations well describe experimental ones only for the products in mass region $24 < A < 70$. It can be possible to explain it as follows: when making such a comparison, we first recognize that the experiment and the calculations differ in that: (i) the experimental data were extracted assuming the ”two-step vector model” [3, 4], while the LAQGSM calculations were done without the assumptions of this model; and (ii) the measurements were performed on foils (thick targets), while the calculations were done for interactions of $^{12}C$ and $^{118}Sn$ nuclei (thin targets).

LAQGSM03.01 [10] is the latest modification of the Los Alamos version of the Quark-Gluon String Model [12], which in its turn is an improvement of the Quark-Gluon String Model [16]. It describes reactions induced by both particles and nuclei as a three-stage process: IntraNuclear Cascade (INC), followed by preequilibrium emission of particles during the equilibration of the excited residual nuclei formed during the INC, followed by evaporation of particles from or fission of the compound nuclei.

LAQGSM03.S1 [11] is exactly the same as LAQGSM03.01, but considers also multifragmentation of excited nuclei produced after the preequilibrium stage of reactions, when their excitation energy is above $2A$ MeV, using the Statistical Multifragmentation Model (SMM) by Botvina et al. [13] (the “S” in the extension of LAQGSM03.S1 stands for SMM).

LAQGSM03.G1 [11] is exactly the same as LAQGSM03.01, but uses the fission-like binary-decay model GEMINI of Charity et al. [14], which considers evaporation of all possible fragments, instead of using the GEM2 model [15] (the “G” stands for GEMINI).

Many details and further references on LAQGSM03.01 and its 03.S1 and 03.G1 versions may be found in [17].

Fig. 2 shows the dependence of the fragment kinetic energy, $T_{kin}$, on the fractional mass loss $\Delta A/A$. The comparison with theoretical calculations by the LAQGSM03.01 [10], LAQGSM03.S1 [11], and LAQGSM03.G1 [11] models shows that for mass region of residuals $24 < A < 117$ the experimental results are described better by the LAQGSM03.G1 model. As one can see in article [18] formation of residual nuclei in mass region $A_t/3 < A < A_t/2$ can be explained by fragmentation as well as fission-like processes. In our previous publication [21] we described the formation of medium-weight nuclei ($7 < A < 60$) by multifragmentation mechanism while heavy residual nuclei were formed by evaporation mechanism. The fission-like binary decay model of
GEMINI used by LAQGSM03.G1 can be regarded somehow in the middle between multi-fragmentation and conventional evaporation, and it looks like it describes better the present experimental data in a wide mass region of the products. Owing to the proportionality between longitudinal momentum and excitation energy of the remnant in spallation regime \[19\] the mean velocity along the beam direction of the remnant \(v_{II}\) should increase linearly with \(\Delta A/A_t\) (\(\Delta A = A_{targ} - A_{res}\), where \(A_{targ}\) is the mass number of target and \(A_{res}\) is the mass number of product nuclei) in this regime. It is interesting to note that the measured forward velocity \(v_{II}\) increases practically linearly with the increase of \(\Delta A/A_t\), but remains approximately (roughly) constant at around \(\Delta A = 60\) (Fig. 3). In our past publications \[20, 21\] for proton- and deuteron-induced reactions we revealed that such behavior of dependence is conditioned by change of mechanism of production of residuals. The same picture was obtained for the production of the measured nuclei by \(^{12}\)C ions.

Fig. 4 shows the dependence of the mean ranges of fragments on the targets mass numbers. Our results for the target \(^{118}\)Sn conform well with the results for the targets in mass range from \(Cu\) to \(U\) at the \(^{12}\)C ions beam energy 18.5 GeV \[22\]. The ranges increase monotonically with target \(A_t\) and for a given target vary in an essentially inverse manner with product \(A\).

In our recent paper \[21\], we have investigate the recoil properties of the product nuclei on the enriched \(^{118}\)Sn target at the 3.65 GeV protons and 7.3 GeV deuterons beams. Therefore it is interesting to determine the applicability of factorization to the present data.

Fig. 5 shows a comparison of \(F/B\) ratios from 26.4 GeV \(^{12}\)C ions and 3.65 GeV protons bombardment of \(^{118}\)Sn and \(^{12}\)C ions and 7.3 GeV deuterons. For all three projectiles the behaviors of ratio \(F/B\) via \(\Delta A = A_{targ} - A_{res}\) are similar: decrease monotonically with increasing \(\Delta A\). The \(F/B\) ratios for \(^{12}\)C ions are slightly lower than those obtained with 3.65 GeV protons and the same average value than obtained with 7.3 GeV deuterons. The weighted average of the ratios of \(F/B\) for individual products are 0.77 ± 0.16 and 1.03 ± 0.20 respectively.

Fig. 6 shows the product mass dependence of ratios of \(v_{II}\) from 26.4 GeV \(^{12}\)C ions and 3.65 GeV protons bombardment of \(^{118}\)Sn and \(^{12}\)C ions and 7.3 GeV deuterons. The weighted average of the ratios of individual ranges being 0.84±0.25 for \(^{12}\)C and protons and 1.11±0.49 for \(^{12}\)C and deuterons. In general, our comparison of recoil properties and cross-sections (partially unpublished) of residual nuclei of the interaction of \(^{118}\)Sn with 26.4 GeV \(^{12}\)C ions with similar data for comparably energy (per nucleon) protons and deuterons indicates that the production cross-sections and recoil properties attain the regime of limiting fragmentation. The comparison of \(v_{II}\) for \(^{12}\)C ions and protons and deuterons support a factorization within errors for the energy of projectiles \(> 2\text{ GeV/nucleon}\).

3 Conclusion

The recoil properties of the product nuclei from the interaction of 2.2 GeV/nucleon \(^{12}\)C ions with a \(^{118}\)Sn target were obtained. The dependence of recoil properties via fractional mass loss shown the change of production mechanism for medium light residuals (\(A < 60\)). A comparison with the same properties for 3.65 GeV protons and 3.65 GeV/nucleon deuterons was made. Limiting fragmentation and factorization in this energy region were obtained.
Acknowledgments

The authors would like to express their gratitude to the operating personnel of the JINR Nuclotron and Synchrophasotron for providing good beam parameters. This work was supported partially by the US DOE.

Table 1. Kinematic characteristics of product nuclei on $^{12}$C ions induced reactions.

| Product | F/B | $\eta$ | $2W(F+B)$ | $T_{kin.}$ (MeV) | $\nu$ (MeV/amu)$^{1/2}$ |
|---------|-----|-------|-----------|-----------------|-----------------|
| $^{24}$Na | 1.40 | 0.084 | 4.82±1.02 | 20.24±4.29 | 0.1089 |
| $^{28}$Mg | 1.54 | 0.107 | 4.41±0.94 | 19.18±4.07 | 0.1255 |
| $^{43}$K | 1.55 | 0.108 | 2.86±0.61 | 15.11±3.20 | 0.0909 |
| $^{44}$Sc | 2.32 | 0.207 | 2.49±0.53 | 12.21±2.59 | 0.1543 |
| $^{52}$Mn | 1.88 | 0.157 | 3.27±0.69 | 21.51±4.56 | 0.1426 |
| $^{67}$Gd | 1.02 | 0.005 | 1.55±0.33 | 7.17±1.52 | 0.0024 |
| $^{74}$As | 2.48 | 0.223 | 1.50±0.32 | 7.12±1.51 | 0.1001 |
| $^{73}$Se | 3.33 | 0.292 | 1.51±0.32 | 7.33±1.55 | 0.1309 |
| $^{80m}$Y | 3.38 | 0.296 | 1.05±0.22 | 4.37±0.93 | 0.0943 |
| $^{77}$Br | 2.35 | 0.210 | 1.35±0.29 | 6.11±1.29 | 0.0837 |
| $^{89}$Zr | 2.87 | 0.258 | 0.73±0.15 | 2.45±0.52 | 0.0605 |
| $^{93}$Mo | 2.32 | 0.207 | 1.28±0.27 | 6.35±1.35 | 0.0778 |
| $^{90}$Nb | 3.49 | 0.303 | 1.01±0.21 | 4.08±0.86 | 0.0912 |
| $^{93m}$Mo | 4.33 | 0.351 | 0.92±0.19 | 3.69±0.78 | 0.0988 |
| $^{95}$Tc | 1.63 | 0.121 | 1.26±0.27 | 6.23±1.32 | 0.0445 |
| $^{97}$Tc | 3.14 | 0.278 | 0.98±0.21 | 4.21±0.89 | 0.0833 |
| $^{99}$Ru | 3.64 | 0.312 | 0.61±0.13 | 1.97±0.42 | 0.0635 |
| $^{99m}$Rh | 4.02 | 0.334 | 0.59±0.13 | 1.93±0.41 | 0.0667 |
| $^{103}$In | 3.16 | 0.280 | 0.50±0.11 | 1.48±0.31 | 0.0484 |
| $^{109}$In | 4.47 | 0.358 | 0.17±0.03 | 0.28±0.06 | 0.0256 |
| $^{110}$Sn | 2.35 | 0.211 | 0.039±0.008 | 0.029±0.006 | 0.0049 |
| $^{111}$In | 3.34 | 0.293 | 0.13±0.03 | 0.19±0.04 | 0.0169 |
| $^{117m}$Sn | 1.08 | 0.020 | 0.17±0.03 | 0.27±0.06 | 0.0014 |
Figure 1: $F/B$ versus the fractional mass losses $\Delta A/A_t$: line shows the calculation by LAQGSM.01, dash line shows the calculation by LAQGSM.S1, dot line shows the calculation by LAQGSM.G1.

Figure 2: Dependence of the kinetic energy of the product nuclei on the fractional mass losses $\Delta A/A_t$: dot line shows the calculation by LAQGSM.G1, line shows the calculation by LAQGSM.01, dash line shows the calculation by LAQGSM.S1.
Figure 3: Dependence of the forward velocity of excited nuclei on the fractional mass losses $\Delta A/A_t$:

Figure 4: Mean ranges of fragments emitted in the interaction of $^{12}C$ ions with targets of mass $A_T$: Basic data for 18.5 GeV $^{12}C$ ions were taken from [22]. Our data are only for $A_T=118$. The curves show the trends in the data.
Figure 5: Product mass dependence of ratios of F/B from 26.4 GeV $^{12}C$ ions and 3.65 GeV protons bombardment of $^{118}Sn$ and $^{12}C$ ions and 7.3 GeV deuterons.

Figure 6: Product mass dependence of ratios of $v_{II}$ from 26.4 GeV $^{12}C$ ions and 3.65 GeV protons bombardment of $^{118}Sn$ and $^{12}C$ ions and 7.3 GeV deuterons.
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