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ISOSPIN TRANSPORT IN ^{84}Kr + ^{112,124}Sn COLLISIONS AT FERMI ENERGIES WITH THE FAZIA DETECTOR*

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Isotopically resolved fragments up to $Z \approx 20$ have been studied in a test experiment by the FAZIA Collaboration with a three-stage telescope. The reactions ^{84}Kr+^{112}Sn (n-poor) and ^{84}Kr+^{124}Sn (n-rich) at 35 MeV/nucleon were measured. The telescope was located near the grazing angle, so the detected fragments are mainly emitted from the phase-space region of the projectile. In the following, evidences for isospin diffusion and drift will be discussed.

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1. Introduction

The production of many fragments is one of the main features of heavy-ion reactions at bombarding energies higher than 15–20 MeV/nucleon. Various processes are responsible of fragment emission, spread over different time scales. Moreover, the de-excitation of the primary fragments may strongly alter their original identity. Therefore, the investigation of the isospin degree of freedom by means of the study of mass and charge distributions of the fragments produced in dissipative heavy ion collision is a challenging task. In recent years, many experimental and theoretical efforts (see [1–3] and references therein) have been devoted to the investigation of these problems, using reaction partners with different isospin content or by comparing data from reactions involving different isotopic combinations of the projectile and/or of the target [4–9]. From an experimental point of view, this kind of investigation requires detectors capable of good isotopic identification on an extended Z range. In view of this, the FAZIA Collaboration started an R&D program to improve the isotopic separation obtainable with Si–Si–CsI(Tl) telescopes. The study of the isospin content of fragments and light particles, gives clues on different processes of isospin transport: (a) isospin "diffusion", related to the isospin asymmetry between the reacting nuclei (*i.e.* projectile and target are chosen with different N/Z values) [2, 3, 6, 7, 10]; (b) isospin "drift" (or "migration"), related to the density gradient which develops between the interacting nuclei, associated to the formation of a diluted "neck" [10–13].

In the following, we show some results obtained bombarding with a ^{84}Kr beam at 35 MeV/nucleon two targets with different isospin: ^{112}Sn (n-poor system) and ^{124}Sn (n-rich).

2. The experiment and some results

The data analyzed in this paper are from a three-element telescope Si1–Si2–CsI(Tl) located at an angle of 5.4° and at 100 cm distance from the target. The silicon detectors (manufactured by FBK) were of the ion-implanted neutron transmutation doped (n-TD) type, with good doping uniformity (of the order of 3% FWHM measured with the method described in [14]). The silicon pads (20×20 mm^2) were obtained from "random" cut wafers (about 7° off the $\langle 100 \rangle$ axis) to minimize channeling effects [15] and feature very thin dead layers on both sides ($\sim$ 500–800 nm). The thickness of Si1 and Si2 were, respectively, 305 μm and 510 μm; the CsI(Tl) crystal (manufactured by Amcrys) was 10 cm thick, with a good doping uniformity (of the order of 5%) and the read-out is done by a custom designed photodiode.

The excellent performance of these detectors was due also to the custom-built high-quality electronics. More details are given elsewhere [14–17]. Here, we briefly remind that the charge and current signals produced in low-noise preamplifiers, mounted in vacuum next to the detectors, are sampled by fast digital boards purposely built by the FAZIA group. For each detector, the sampled signals are then stored for off-line analysis. Energy information was obtained by means of trapezoidal shaping of the digitized signals (see [16] for details). For energy calibration, the "punch-through energies" of light identified ions were used [16]. The acquisition rate was around 100 Hz.

In this work, we concentrate on identified fragments ($Z \geq 3$) stopped in the second silicon layer or in the CsI(Tl). The particles identification threshold corresponds to the energy needed to pass through 305 μm of silicon (for example, $\approx$ 130 MeV for ^{12}C). The kinetic energy of fragments stopped in Si2 is the sum of the two silicon energies $E_{\mathrm{sum}} = E_{\mathrm{Si1}} + E_{\mathrm{Si2}}$. When ions reach the CsI(Tl) crystal, their full kinetic energy is estimated from E_{sum} with the help of range-energy tables [18]. The particle identification has been obtained from the ridges in the two ΔE–E correlations, E_{si1}–E_{si2} or E_{sum}–CsI. The linearization of the ridges gives the Particle Identification (PI). The high quality of the detectors and of the dedicated electronics allows isotopic resolution up to $Z \approx 20$ (close to the limit reported in [16]). The telescope spanned the angular range from about 4.8° to 6°, just beyond the grazing angles of the two reactions (estimated to be about 4.1° and 4.0° for the n-poor and n-rich system, respectively). The position was well suited for a good sampling of a large variety of fragments, mainly originating from the quasi-projectile (QP) phase-space. From the large number of similar experiments performed in many years of investigation, we know that: (a) in peripheral and mid-central collisions, we mainly deal with binary dissipative collisions producing excited quasi-projectile (QP) and quasi-target (QT); (b) their decay is dominated by evaporation, in competition with fission-like processes, especially for massive nuclei or large excitations; (c) the most central collisions involve fusion-like phenomena, with the formation of a big transient system, which may then undergo a multifragmentation decay; (d) non-equilibrium phenomena are present, consisting in the rapid emission of light reaction products usually interpreted as neck emissions [19], or in the occurrence of fission-like processes retaining some memory of the preceding dynamics (fast oriented fission [20, 21]), with a possible continuous evolution into equilibrated fission [22]. The above described scenario can be observed in the correlation charge *vs.* laboratory velocity, commonly used (*e.g.*, [1]) to evidence the main reaction features. Figure 1 (left) shows such correlation for the data of the reaction ^{84}Kr+^{124}Sn. The laboratory velocity is deduced from the measured energy, using the identified mass (up to $Z \sim 20$) or the mass estimated from the Evaporation Attractor Line [23] for heavier elements.

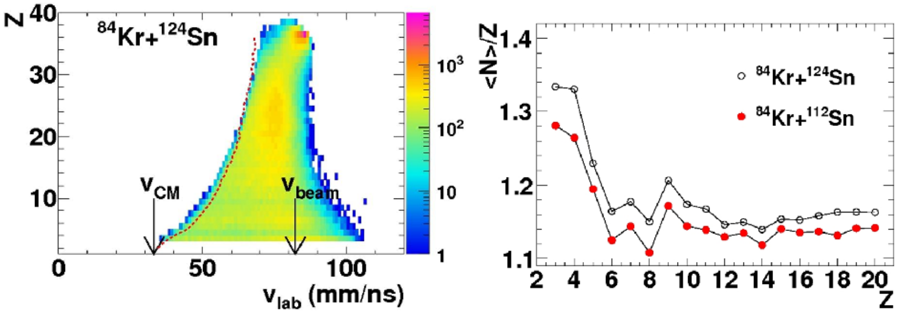

Fig. 1. Left panel: Charge *vs.* laboratory velocity for $Z \geq 3$ fragments passing through the first silicon detector for the reaction ^{84}Kr+^{124}Sn. Right panel: $\langle N\rangle/Z$ as a function of Z for the two reactions. Statistical errors are smaller than dot size.

The arrows in the left panel of Fig. 1 correspond to the velocities of the center of mass and of the beam (33.2 and 82.2 mm/ns, respectively): practically all measured fragments are forward-emitted in the center-of-mass system and the velocities of the heavier ones are not too different from that of the projectile. Therefore, one can infer that the fragments originate indeed from the QP, with almost no contamination from the QT (in the analysis we reject fragments with $v_{\mathrm{lab}} < 40$ mm/ns), and that there could be some contribution from the "neck region" (*i.e.* the phase space region corresponding to the contact zone of the colliding nuclei). The good isotopic resolution of the telescope allows to investigate the isotopic composition of the fragments in the n-rich and n-poor reaction. The average number of neutrons per charge unit $\langle N\rangle/Z$ as a function of Z is shown in the right panel of Fig. 1 for the two systems. In the n-rich system, this ratio is systematically higher than in the n-poor one, by an amount of about 0.03–0.05. Since, as said, most observed fragments belong to the QP region of the phase-space (see Fig. 1, left panel), the observed difference clearly demonstrates the action of an isospin diffusion mechanism: the isospin of fragments associated to the QP depends on the neutron content of the target with which the projectile has interacted.

One may wonder whether the isospin content of the fragments coming from the two reactions also depends on the phase-space region they belong to. For this purpose, Fig. 2 shows the evolution of $\langle N\rangle/Z$ for different elements (from $Z = 4$ up to $Z = 20$) as a function of the laboratory velocity of the fragments. The first evidence is that, as discussed before, the open circles (n-rich system) are always above the gray/red full dots (n-poor system) (related to isospin diffusion between the QP and the QT). The second clear observation is that for light ions $\langle N\rangle/Z$ rapidly decreases with increasing velocity, while it displays a rather flat behavior for heavier ions. The third point worth noting is that the highest values of $\langle N\rangle/Z$ of fragments with $Z = 4$ (and $Z = 3$) are reached at the smallest laboratory velocities (close to that of the center of mass). Considering the experiment geometry ($4.8^\circ \leq \theta_{\rm lab} \leq 6^\circ$), the fragments with large velocities (of the order of that of the beam) are likely to be emitted in forward direction from excited QP, while those with lower velocities focused in backward direction, with possible contributions from midvelocity- (or neck-) emissions [19]. In fact, at the Fermi energies, fragments may be produced also by the breakup of an elongated neck-like structure [24] formed between QP and QT. For the light products, the $\langle N\rangle/Z$ increases when going from QP decay (high velocity) to neck-emission (low velocity). This could be an indication of isospin drift, namely a neutron enrichment of the more diluted central region of the neck [10]. On the contrary, heavier fragments with $Z > 12$ have a low $\langle N\rangle/Z$ (around 1.15) with practically no dependence on the emission velocities. Qualitatively, these results are in nice agreement with many other published results which support a rather asy-stiff nuclear EOS, according to Stochastic Mean Field calculations. The FAZIA telescope allowed for the first time to extend such kind of study up to QP fragments in the region of the calcium. A complete and detailed discussion of the present data is shown in [25].

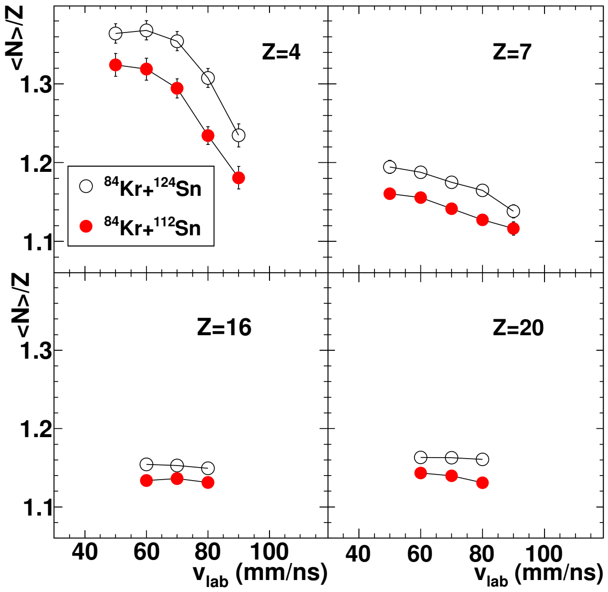

Fig. 2. $\langle N\rangle/Z$ as a function of the laboratory velocity for the reaction ^{84}Kr+^{124}Sn (open circles) and ^{84}Kr+^{112}Sn (gray/red full points) for different elements. Error bars combine statistical errors and uncertainties in the isotope identification.

3. Conclusion

The systems ^{84}Kr+^{112}Sn and ^{84}Kr+^{124}Sn at 35 MeV/nucleon have been studied by the FAZIA Collaboration. Isotopic resolution up to $Z = 20$ has been obtained using ΔE–E method. The angular geometry of the setup (near the grazing angles) allows us to detect products from the QP decay, with a contribution of light ions produced in the neck-zone. Evidences of isospin diffusion and drift have been found analyzing the $\langle N\rangle/Z$ of the fragments produced in the two reactions. The investigation of isospin transport and dynamics in future experiments also using unstable beams will certainly benefit of well performing modular arrays with high isotopic resolution, like the FAZIA detector.

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