Study of the 14N+159Tb reaction between 6 and 22 MeV/u.

Balster, Gert Jan

Publication date:
1987

Chapter 9.

SUMMARY AND CONCLUSIONS

9.1. Introduction

The main aim of the research described in this thesis was to obtain a deeper insight into the evolution of the mechanism of light heavy-ion induced reactions from energies close to the Coulomb barrier to energies of several tens of MeV/u. Taking earlier studies performed at the KVI[1-3] as a starting point it was attempted to accomplish this goal by collecting a large set of data for one reaction, $^{14}N+^{159}Tb$, in order to systematically observe its behaviour as a function of energy.

Also including results earlier obtained at the KVI[1] inclusive data were obtained in the energy range of 6-22 MeV/u, from which the global reaction systematics could be observed. At 6.5 MeV/u inclusive measurements were also performed with a few other targets to study the reaction systematics at low energies. At higher energies the large variety of possible reaction channels and their complex nature required the additional use of a more elaborate experimental technique. Therefore the (KX-ray) method involving the measurement of coincidences between particles and KX-rays, which was initiated at the KVI[4], was further developed and applied to the $^{14}N+^{159}Tb$ reaction at energies from 8 to 22 MeV/u. A very large and unique data set was thus obtained for the $^{14}N+^{159}Tb$ reaction. In relation to the KX-ray method measurements were carried out to obtain more insight into the mechanism of KX-ray emission in heavy ion reactions. Some of these latter measurements have not been included in this thesis but have been published elsewhere[5].

In section 9.2 the results of the studies reported in this thesis are summarized. The main conclusions are presented in section 9.3. Section 9.4 contains an outlook on future developments.

9.2. Summary

Production cross sections of target KX-rays due to direct K-shell ionization by the projectile were measured for beams of ^{14}N at 92, 103, 115 and 180 MeV and ^{40}Ar at 180 and 300 MeV on targets with atomic numbers ranging from 40 to 90. It was found that these cross sections can be well reproduced with a plane wave Born calculation, provided that corrections for the Coulomb deflection of the projectile, the increased binding energy of the K-shell electron and relativistic effects of the K-shell wave function are taken properly into account.

Inclusive angle and energy integrated cross sections were obtained for projectile-like fragments (PLF's) with $Z \leq 6$ emitted in the reactions $^{14}N+^{60}Ni$, ^{112}Cd, ^{159}Tb and ^{197}Au at 92 MeV. The total cross section of PLF's with $Z \geq 3$ is little dependent on the target. These PLF's can be attributed to quasi-elastic peripheral collisions. The isotopic cross sections follow the Q_{gg}-systematics only in the case of projectile stripping leading to carbon and boron ejectiles. Of the cross sections of protons and α-particles part is due to sequential decay of PLF's and to evaporation from the target-like nucleus. The remaining part is strongly dependent on the target, which suggests that it can be associated with a non-peripheral process that is determined by the occurrence of an angular momentum limitation for fusion.

Inclusive angular distributions and energy spectra for isotopes with $Z \leq 9$ were measured for the $^{14}N+^{159}Tb$ reaction at 92, 236 and 309 MeV. For completeness data at 112, 140 and 168 MeV previously obtained at the KVI[1)] were included. Over the whole energy range PLF's with $Z \geq 3$ are mainly produced in a quasi-elastic process, i.e. they are emitted with approximately beam energy. At the higher energies a small fraction of the PLF's appear to originate from deep-inelastic reaction channels. The mass flow is almost exclusively in the direction of the target. The total angle integrated cross section for the formation of PLF's with $3 \leq Z \leq 6$ rises first and then stays rather constant as a function of bombarding energy. The cross sections for light particles with $Z \leq 2$ were separated into components due to evaporation and to non-evaporative processes, respectively. Both components increase in magnitude with increasing bombarding energy over the whole energy range.

Measurements of particle-KX-ray coincidences were performed for the $^{14}N+^{159}Tb$ reaction at 5 energies between 8 and 22 MeV/u with the charged particle detector placed near the grazing angle. With the KX-ray method partial cross sections $d\sigma/d\Omega(PLF, Z_{res})$ of PLF's as a function of the atomic number of the residual nucleus (Z_{res}) and thus the cross section balance were determined. It was found that the inclusive cross sections can be accounted for to within ~20% by the sum of the (exclusive) partial cross sections with the use of average KX-ray multiplicities. From the partial cross sections it was deduced that a large fraction of the inclusive PLF cross sections originates from "non-binary" reaction channels, in which additional charged particles are emitted. The evaporation of light charged particles from the target-like nucleus was observed to be only a minor source of these charge non-binary channels. At 115 and 168 MeV probabilities for sequential decay of primary fragments were obtained, which are in good agreement with results from particle-particle correlation experiments. The Q_{gg}-dependence does not give a satisfactory description of the cross sections for charge binary channels at the higher energies. The bulk of the reaction channels in which a PLF with Z≥3 is emitted were attributed to quasi-elastic peripheral collisions, in which a primary fragment is formed in a particle stable or unstable state. The quasi-elastic character of these channels was underlined by γ-ray multiplicities measured in the same experiments.

Employing the results from the inclusive and from the particle-KX-ray coincidence measurements for the $^{14}N+^{159}Tb$ reaction the cross sections of α-particles were decomposed into three components. These are (1) α-particles evaporated from the target-like nucleus, (2) α-particles emitted in coincidence with a PLF with Z≥3 which were ascribed to the sequential decay of excited primary fragments, and (3) α-particles from dissipative fragmentation-like (DFL) channels in which only (fast) light particles with Z≤2 are emitted. The average number of α-particles emitted per collision increases rapidly with beam energy for each of the three components, whereas the angle integrated total cross section of DFL channels tends to level off. The DFL channels were found to be the major source of the large cross sections of fast α-particles at forward angles. From γ-ray multiplicity data it was deduced that the DFL channels involve a significantly larger excitation of the heavy residual nucleus (inelasticity) than the (quasi-elastic) channels in which a PLF with Z≥3 is emitted. However, from the near beam velocities of the α-particles associated with the DFL channels it was concluded that they are emitted prior to the attainment of full energy damping.

The large set of data obtained for the $^{14}N+^{159}Tb$ reaction was further employed to obtain a detailed decomposition of the total reaction cross section and hence to observe the dependence of the various reaction channels on the bombarding energy. The reaction channels were divided into (1) quasi-elastic channels in which a primary fragment with Z⩾3 is emitted in a particle stable or unstable state, (2) DFL channels, and (3) channels leading to fusion. The cross sections of the primary fragments with Z⩾3 rise first and then become constant as a function of the bombarding energy. The fusion cross sections at 236 and 309 MeV, which could be deduced from the KX-ray data, constitute unlike those at the lowest energies only a minor fraction of the total reaction cross section. The cross sections of primary fragments and those of charge binary channels were compared with predictions of the sum-rule model of Wilczyński et al.[2]. No satisfactory agreement was found. The behaviour of the various cross sections as a function of the bombarding energy indicates that geometrical limitations related to the overlap of the colliding nuclei become important at the higher energies. However, no onset of basically different processes was observed in the energy range considered.

9.3. Conclusions

With respect to the method of measuring coincidences between particles and KX-rays (the KX-ray method) as applied to the $^{14}N+^{159}Tb$ reaction at energies up to 22 MeV/u, we conclude that it is a very powerful technique which offers the possibility of readily observing and identifying a large set of reaction channels at the same time. Combined with inclusive measurements the total reaction cross section can be decomposed.

One of the main results obtained with this technique for the $^{14}N+^{159}Tb$ reaction is the establishment of the fact that the very large cross sections of fast α-particles (and most likely also of fast protons) at forward angles are mainly due to the hitherto unidentified dissipative fragmentation-like channels. In these channels only light particles are emitted and the heavy nucleus is relatively strongly excited, but complete energy damping is not attained. It appears