Fusion-like processes near the Fermi energy

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Summary

The aim of this thesis was to determine what processes are responsible for the incomplete transfer of momentum in fusion-like reactions near the Fermi energy. This work involves a rather complete study of the $^{14}N + ^{232}Th$ reaction at 30 MeV/nucleon. The momentum transferred to the composite system was measured from the fission folding-angle by detecting the two fission fragments of the decaying system in coincidence. With the fission events acting as trigger almost all forward emitted fast particles were measured in coincidence in a plastic wall with a large angular coverage. By this method a decomposition of the fusion-like cross section into its various components was possible.

The energy calibration of the "phoswich" plastic scintillators forming the forward wall was obtained in a separate experiment. Since the forward wall does not cover the full forward hemisphere a novel method was introduced in this thesis to correct for those particles that escaped detection. These corrections were found, as expected, to be largest for those channels that involve multi-particle emission.

More than 40 different reaction channels involving pre-equilibrium emission as well as massive transfer of various combinations of charged particles were identified. Charged particle multiplicities up to $M = 5$, with charged particles ranging from protons up to nitrogen were observed. For each individual reaction channel the average value of the transferred linear momentum has been determined. The momentum transfer in the low multiplicity events, $M < 3$, more or less follows the trend expected for massive transfer reactions where the emitted fragment has approximately the beam velocity. For fixed total detected charge, Z_{det}, the charged particle multiplicity increases with increasing momentum transfer, indicating an increase in the violence in the reaction.

The average momentum transfer for the fusion-like reactions was $\langle \rho \rangle$ = 83 %, close to the values found for comparable systems. It was found that fusion-like reactions are associated with the emission of a small number of charged particles; the average charged-particle multiplicity $\langle M \rangle$ = 1.2. The main fusion-like channels were found to be associated with the emission of no charged particles (27.4 %) or single H (25.2 %) and He (7.2 %) isotopes. Other strong channels include the HHe (8.7 %) and 2H (13.4 %) channels. An abundance of complex particles (d, t, and He) was found in the fusion-like reaction.

For the peripheral reactions the average multiplicity $\langle M \rangle$ = 1.9, and the average momentum transfer, $\langle \rho \rangle$ = 10 %. Although on the average the peripheral channels were found to be non-binary, the strongest channels are associated with the emission of one single heavy fragment. (Thus indication that the peripheral cross section is distributed over a large number of reaction channels.) The energy spectra of these particles were found to be centered around the energy corresponding to the beam velocity.

The data set enabled to test the consistency of theoretical models by comparing different observables simultaneously. Five different pre-equilibrium models were used. Since these models do not include complex particle emission, we have compared the multiplicities extracted from the models to the total nucleon multiplicities (bound plus unbound nucleons) and not only to the unbound nucleon multiplicities. It was found that in general the models considered here overestimate the momentum transfer, while at the same time the total nucleon multiplicity is underestimated. These results indicate that the models are incomplete.

From the comparison with the models we conclude that there may be other processes that account for additional emission of particles and thus possibly also accounting for the difference in the momentum transfer. Taking this viewpoint, the contribution of pre-equilibrium complex-particles was estimated by applying the coalescence-mechanism relation to the hardest theoretical nucleon spectra and comparing the calculated spectra with the observed ones. This comparison showed that there is an additional component in the spectra corresponding to the emission of approximately beam-velocity particles. Therefore it was concluded that there are in fact two different processes that contribute to the fusion-like cross section. One associated with pre-equilibrium emission, as described by the theoretical models, and the other with massive transfer wherein a small part of the projectile escapes with approximately beam velocity.

7.1 Outlook

In this thesis several experimental techniques have been employed which are worth of being developed further. Furthermore, the experimental results suggest possible follow-up experiments that can lead to further insights into the fusion-like reactions. In this section several suggestions for future experiments and improvements of the experimental methods will be discussed.

Concerning the techniques for future experiments using the plastic wall, or equivalent detectors, several modifications of the detection system and the analysis procedure used in the $^{14}N + ^{232}Th$ experiment come to mind. As was shown in the calibration experiment, the lack of mass identification is the most important restriction to the energy calibration. Therefore, extending the experiment by using time-of-flight information would improve the energy calibration. Assuming a flight-path of 2 m the mass resolution would range from $1/35$ for 10 MeV/nucleon particles to $1/13$ for 100 MeV/nucleon. Here a time resolution of 0.5 ns was assumed and an energy resolution of 2 % was used. To identify the particles that are stopped in the first scintillator a shorter flight-path suffices, e.g. for hydrogen isotopes about 15 cm, taking into account the finite energy resolution of the detectors. Using the time information would therefore lower the energy thresholds for which particle identification becomes possible.

Misidentification of reaction channels due to the incomplete coverage of the forward hemisphere is another aspect that needs attention. In this thesis a novel method was developed to correct for these undetected particles. In this method use was made of the specific detector geometry in the present experiment for determining the detection efficiencies. A possible modification of this would be to use a more general extrapolation of the cross sections in determining the efficiencies. A candidate for this would be a moving-source parametrization with an azimuthal dependence. Another possible modification would be to introduce channel-dependent detection efficiencies. It should be realized, however, that this would complicate the correction method dramatically. Alternatively one might combine these two modifications by using a Monte-Carlo event simulation to determine channel dependent efficiencies. However, the simulation should then be iterated in order to fully reproduce the experimental results Of course the experimental setups should leave as little area uncovered as possible. Complete coverage, however, is not possible in principle. The system should also give sufficient angle information to make the extrapolation and interpolation of the data for applying the correction procedure reliable.

In the calculation of the momentum transfer two assumptions have been made which may not be necessary. The first assumption concerns the mass split between the fission fragments. Here it was assumed that the fissioning nucleus splits into two equal parts. Time-of-flight measurements of the fission fragments will allow for an event-by event determination of the mass ratio. Secondly, it was assumed that the recoil direction of the fissioning nucleus was parallel to the beam. Although it was shown in sect. 3.7 that this assumption only introduces small errors for the fusion-like reactions, the treatment of the recoil direction could be improved by reconstructing the momentum using the information obtained from the position and energy of the coincident fission fragments. Also the coplanarity angle gives information on the plane of the recoil direction. However, including these improvements is only useful if the measurement needs high accuracy on event by event basis (in contrast to high accuracy for the event average).

Suggestions for follow-up experiments originate from the model predictions or the experimental results. An interesting prediction from the Fermi-jetting models is that of low-energy backward-emitted pre-equilibrium particles for asymmetric systems (light projectile and heavy target). In fact these nucleons can have energies below the Coulomb barrier of the composite system. Observation of these sub-Coulomb pre-equilibrium particles would be a strong argument in favor of the Fermi-jetting process. This could be done by measuring the forward-backward asymmetry of low energy particles in the center-of-mass. This should show an enhancement of these particles at backward angles. Of course such an experiment would require a low-bias event trigger for fusion-like reactions, e.g. the neutron multiplicity or the folding-angle method.

Another possible experiment would be to investigate the correlation between the number of nucleon-nucleon collisions and the emitted particles. Intuitively one would expect that the number of collisions is smaller for a massive-transfer reaction in which an α-particle is emitted as compared to the emission of an α-particle emitted in a pre-equilibrium reaction. A possible probe for the number of proton-neutron collisions is the probability for emission of high-energy bremsstrahlung photons [Nif90, Wil91b].

A completely different question relating to the partition of the folding-angle distribution is: Does the minimum in the folding-angle distribution always occur for reactions where approximately half the projectile is captured by the target, as was found for the present experiment? To answer this question it would be interesting to obtain the partition of the fission cross section for systems with a heavier projectile, like Ne. If the minimum occurs for the transfer of half the beam momentum then the Li channel will be completely associated with fusion-like channels, comparable with the He channel in the present experiment. This may clarify the ambiguity between pre-equilibrium emission and massive transfer. While fission-fragment folding-angle distributions have been measured for other systems, to the best of my knowledge the partition of the cross section has not yet been obtained.

In the discussion of the results it was already noted that the time evolution of a reaction is important, i.e. low energy pre-equilibrium particles and equilibrium particles can be identified by means of the emission time. It is therefore important to measure an observable which can be used as a clock, starting early in the reaction and extending up to about 120 fm/c, after which pre-equilibrium emission has almost disappeared. Also, the clock should be accurate to very short times, since the two fusion-like mechanisms, pre-equilibrium and massive transfer, are expected to be separated very little in time. Neutron-neutron correlations were shown to be sensitive to the space-time extent of the emitting source [Avd92, Dün90, Jak91], and could be used to obtain the time evolution of the reaction.

Finally some words should be said about the theoretical models. Clearly there are a few ingredients that should be incorporated in any next generation model, e.g. complex particle emission should follow directly from the model. Furthermore, one would also like the pre-equilibrium stage of the reaction to change smoothly into equilibrium. Also, massive-transfer reactions should be incorporated. However, a major disadvantage of any complex model is that it is less transparent to see what mechanisms are important. In this respect simple models, only describing a small but well defined part of the cross section, will still be very useful in understanding the processes of the fusion-like reactions.

The follow-up experiments suggested above could conveniently be performed with the new accelerator and equipment that will be available at the KVI in a few years. The energy range of AGOR of 5–100 MeV/nucleon covers the Fermi-energy region ideally. The two-armed-photon spectrometer (TAPS) will be a convenient tool for the proton-neutron bremsstrahlung experiments. The multi-detector setup "Huygens" will allow to acquire detailed partitions of the cross section for different systems. The neutron detector setup EDEN is well suited for the low-energy neutron-correlation experiments.