HOW WELL DO WE UNDERSTAND QUASI-ELASTIC REACTIONS AT
ENERGIES CLOSE TO THE BARRIER

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In collisions between two heavy nuclei a wide spectrum of different reaction modes is observed covering the range from simple processes like elastic scattering to complicated multistep transfers and fusion. During the past few years it has become clear that these different reaction types are not separate processes but are strongly related. Because the strength of the various reaction modes varies with the mass of the projectile (e.g. for Coulomb excitation and for transfer reactions) experiments with medium mass projectiles allows us to investigate the interrelations of the various reaction modes and their dependence on bombarding energy, neutron and proton number in more detail. One of the most well known cases for an interference between two reaction types is the influence of inelastic scattering and transfer reactions on the strength of the fusion process at subbarrier energies¹. There are also several examples showing how inelastic scattering can influence the transfer reactions².

On the theoretical side heavy ion reactions are usually analyzed using models that were developed first for light ion induced reactions: the optical model for elastic scattering and the DWBA for more inelastic processes like transfer and inelastic scattering³. Some of the assumptions going into these approximations, however, are not valid for heavy ion induced reactions. Inelastic excitation, in particular, is sometimes so strong that it has to be included explicitly in a full coupled channel (CC) calculation with all its complexity. While this is rather straightforward for the case of inelastic scattering⁴, a similar calculation including transfer reactions is considerably more complicated. Generally it can be stated, however, that well established and successful models exist for reactions which get their main contributions from large partial waves and several examples will be given below. For reactions involving low partial waves various statistical model codes have been developed which usually give reliable predictions for the strength of compound nucleus formation at least at energies above the Coulomb barrier. The region between fusion and quasi-elastic reactions, is not well understood theoretically. This region is associated with deep inelastic collisions, which are complex multiparticle reactions involving transfer of several protons and neutrons. Some models in this region are extensions of a statistical treatment (diffusion type models)⁵, while other approaches start from a DWBA treatment⁶.

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In this contribution I want to discuss to what extent experiments in the field of quasi-elastic scattering are understood within the framework of various theoretical models and in what areas more work is needed. The experiments I want to discuss were performed with the Argonne Superconducting accelerator (ATLAS) and an Enge split pole magnetic spectrograph with its associated focal plane detectors for particle identification⁷. This setup provides good mass and Z information (up to the mass 100 region) at reasonable solid angles and, if one is willing to run with thin targets good energy resolution can also be obtained. An example for the energy resolution from the system $^{37}\text{Cl} + ^{208}\text{Pb}$ is given in Fig. 1a while data for the Z-separation

Fig. 1. Energy spectrum (top) for the reaction $^{37}\text{Cl} + ^{208}\text{Pb}$, and nuclear charge spectrum (bottom) for the system $^{80}\text{Se} + ^{60}\text{Ni}$, as measured with a split pole magnetic spectrograph and a position sensitive ionization chamber in the focal plane.

are shown in Fig. 1b obtained from the scattering of ^{80}Se ions on ^{60}Ni .

The area of elastic scattering has been discussed in several other contributions to this symposium⁸. It should be mentioned, however, that an extension of the work of Ref. 8 towards heavier masses is extremely difficult. The decreasing energy resolution for even heavier beams caused mainly by target effects puts a strong limitation on the choice of projectile and target nuclei. In particular at low energies, where most of the interesting effects occur, target effects become more and more severe. The heaviest system where pure elastic scattering has been measured so far is still the $^{86}\text{Kr} + ^{208}\text{Pb}$ system, measured about 10 years ago at GSI⁹.

For heavy ion induced inelastic scattering, the next more complex process, several studies have been performed with projectiles up to ^{86}Kr . As mentioned above the main difference to inelastic scattering induced by light ions is that in many cases several channels have to be treated coherently in a coupled channel calculation. An example of this effect is shown in Fig. 2 for the two systems

Fig. 2. Angular distributions for elastic and inelastic scattering for the systems ^{28}Si and ^{37}Cl on ^{208}Pb . The solid lines are the results of CC (^{28}Si) and DWBA (^{37}Cl) calculations.

^{28}Si , ^{37}Cl + ^{208}Pb . The ^{28}Si + ^{208}Pb system requires a full coupled channel treatment¹⁰ because the 2^+ state in ^{28}Si is strongly excited, while the ^{37}Cl + ^{208}Pb case can be calculated within the simple one-step DWBA¹¹. It should be mentioned that except for the optical potential and the size of the reorientation matrix element all other coupling parameters were taken from measured $B(e\lambda)$ -values and no adjustment to the absolute cross sections was made. With this in mind the agreement is rather impressive both for the strongly excited collective 2^+ state, but also for the single particle transition in ^{37}Cl . Similar observations have been made for other systems and one can state that for low-lying states CC and DWBA calculations give reliable absolute cross sections. It should be mentioned, however, that not everything is completely understood in this field. As can be seen from Fig. 2 for the ^{37}Cl + ^{208}Pb system the 3^- state in ^{208}Pb is poorly described in

particular at larger angles. Another example is given in Fig. 3 where the angular distributions for the 3^- state in ^{208}Pb are given for various

Fig. 3. Angular distributions for the excitation of the 3^- states in ^{208}Pb by ^{28}Si at different bombarding energies. The solid lines are the result of CC calculations.

bombarding energies¹². The solid lines are the result of CC calculations using the same potential which gives excellent agreement for elastic scattering and 2^+ excitation. There is a considerable overprediction of the cross section in the backward hemisphere for this presumably strongly collective 3^- state at the lowest bombarding energies. The reason for this discrepancy is not completely understood at the moment. Recently it was observed that for the excitation of the 3^- state in ^{208}Pb by ^{16}O at low bombarding energies an energy-dependent interaction potential had to be used¹³. It would be interesting to see if similar effects could explain the $^{28}\text{Si} + ^{208}\text{Pb}$ system.

While a reasonable amount of experimental data is available for inelastic scattering one-nucleon transfer reactions to resolved states involving medium mass projectiles ($A > 20$) have not been studied very extensively. As for inelastic scattering nuclei around closed shells had to be used for projectile and/or target in most cases. An example of an energy spectrum¹⁴ for the $^{40}\text{Ca}(^{28}\text{Si}, ^{29}\text{Si})^{39}\text{Ca}$ reaction is shown in Fig. 4.

Fig. 4. Energy spectrum for the one-neutron transfer reaction $^{40}\text{Ca}(^{28}\text{Si}, ^{29}\text{Si})^{39}\text{Ca}$ at $E_{\text{lab}} = 225$ MeV. The cross hatched area is a theoretical spectrum calculated within DWBA and spectroscopic factor from light ion reactions.

Good agreement with the low-lying energy spectrum is obtained with a DWBA treatment, indicated by the cross hatched area in Fig. 4 using spectroscopic factors taken from light ion reactions. Deviations are generally less than 50% which is of the same order of magnitude as the uncertainty of spectroscopic factors. For the higher excitation energy region spectroscopic factors are in many cases not available. Caused by the larger level density in heavier nuclei transitions to individual states can not be resolved experimentally. Therefore only the energy integrated strength in the low excitation energy range can be analyzed. Two examples for the reactions $^{28}\text{Si} + ^{208}\text{Pb}$ (Ref. 10) and $^{58}\text{Ni} + ^{208}\text{Pb}$ (Ref. 15), are shown in Fig. 5.

Fig. 5. Energy spectra for the one-neutron transfer reactions ($^{58}\text{Ni}, ^{59}\text{Ni}$) (left) and ($^{28}\text{Si}, ^{29}\text{Si}$) (right) on ^{208}Pb . The cross hatched area is explained in Fig. 4. Measured at $E_{\text{lab}} = 375$ MeV and $E_{\text{lab}} = 225$ MeV, respectively.

For the one-particle transfer reactions one can therefore summarize that deviations between theory and experiment by about factors of two are not uncommon.

Two-nucleon transfers are the next more complicated processes. While two-particle transfers played an important role in the study of pairing effects in light ion reactions similar experiments with projectiles heavier than mass 20 populating individual states have been carried out only recently¹⁶. These experiments are very difficult because the transfer strength to low-lying states is usually very small. In order to get a general idea about the problems which have been encountered I want to mention only a few results involving ^{16}O projectiles. In Fig. 6 the ratio between the measured cross section and the DWBA prediction (assuming a cluster transfer)

Fig. 6. Ratio of the experimental cross sections and the DWBA-predictions (assuming a cluster transfer) for the two-proton transfer reaction $^{90}\text{Zr}(^{16}\text{O}, ^{14}\text{C})^{92}\text{Mo}$ measured at different bombarding energies. The ($^{14}\text{C}, ^{16}\text{O}$) data are from Ref. 18.

is plotted for the two-proton transfer reaction $^{90}\text{Zr}(^{16}\text{O}, ^{14}\text{C})^{92}\text{Mo}(0^+)$ as function of the bombarding energy¹⁷. Some data for the $(^{14}\text{C}, ^{16}\text{C})$ reaction on lighter targets are also included¹⁸. The discrepancy between theory and experiment is about 700 for low energies and decreases at higher energies. The inclusion of 2-step processes¹⁹ reduces the discrepancy by about a factor of 4-5 and is therefore not able to explain the large experimental cross sections at low bombarding energies. Compared with the good agreement observed for simpler processes like inelastic scattering and one-nucleon transfer it is surprising to find that similar DWBA or CC calculations suddenly underpredict measured cross section by several orders of magnitude. This shows that our theoretical understanding of nucleon transfer changes dramatically between one and two-particle transfer reactions.

Similarly more complicated heavy ion induced transfer reactions can not be described within present models. The theory for these processes needs considerable improvements, in particular at low bombarding energies, where one would expect that the processes are usually easier to understand. Unfortunately not much development has been going on in that field during the last few years although there is a real need for new ideas. At this point I will leave the reactions involving transitions to individual nuclear states and discuss the behavior of more global quantities like energy-integrated transfer cross sections.

In the beginning I will discuss the one-neutron transfer reactions which for most cases show the largest energy-integrated cross sections. Fig. 7 shows

Fig. 7. Neutron transfer cross sections for reactions induced by various projectiles on ^{208}Pb at energies about 25% above the barrier. The solid line is the expectation for the mass dependence calculated within a single geometrical model and normalized to the case of ^{16}O .

energy and angle-integrated cross sections for various projectiles bombarding a ^{208}Pb target at energies about 25% above the Coulomb barrier. It is clear that the absolute strength of the cross sections increases dramatically going from the light particles like ^3He (Ref. 20), ^{12}C (Ref. 21) and ^{16}O (Ref. 22) to the heavier projectiles. In addition to the Q-values, which influence the transfer strength for these reactions, the number of single particle states which can be populated in the transfer is

another factor responsible for the strong increase in the energy and angle integrated transfer cross sections. With only these simple ingredients (phase space and Q-value) one already gets a quite good understanding of the absolute strength of the transfer cross sections. From simple matching conditions one expects that for neutron transfer processes states at excitation energies corresponding to Q-values around $Q=0$ should be strongly populated. If one considers a reaction with a positive Q_{gg} -value then a large number of excited states can be populated whereas a smaller integrated cross section is to be expected for a reaction with negative Q_{gg} -value. One therefore expects a cross section behavior as sketched schematically in Fig. 8. The experimental data for one-neutron transfer reactions induced by

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$$\sigma = \int_{-\infty}^{Q_{gg}} \sigma(Q) dQ$$

Fig. 8. Schematic for the expected Q_{gg} dependence of energy-integrated neutron-transfer cross sections. See text for details.

projectiles from ^{28}Si to ^{86}Kr and targets from ^{58}Ni to ^{208}Pb are shown in Fig. 9 (top). One clearly observes the exponential increase as function of Q_{gg} and if,

Fig. 9. top: One neutron transfer cross sections for various reactions induced by medium-mass projectiles on heavy targets ($A_t > 120$) plotted as function of the ground-state Q-value Q_{gg} . bottom: same as top, but corrected for binding energy effects (see Ref. 23).

in addition, effects of the binding energy are taken into account all data points follow a smooth behavior²³, as illustrated in the bottom part of Fig. 9.

The next question is the extent to which charged particle and multi-particle transfer reactions can be described within the same framework. Several theoretical calculations have shown that multi-particle transfer processes proceed mainly via sequential transfer routes^{2,24}. In Fig. 10 reduced (i.e. binding energy corrected)

Fig. 10. Binding energy corrected cross sections for one, two and three-neutron transfer reactions induced by medium mass projectiles on heavy targets. See text for details.

energy and angle-integrated two-neutron transfer cross sections are plotted as function of the groundstate Q -value for various systems. It is clear that their dependence on Q_{gg} is similar to the one observed for one-neutron transfer but the absolute strength is smaller by about a factor of 5. The only case of a three neutron transfer reaction is smaller yet by an additional factor of 5. The solid curves are obtained from the one-neutron transfer reactions scaled down by the appropriate factors of 5 and 25, respectively. The agreement is generally quite good.

Contrary to the observations for neutron transfer reactions, the optimum Q -value for proton transfer depends on the bombarding energy and the charge of projectile and target. Cross sections for charged particle transfer reactions are therefore expected to be energy, Q -value and projectile dependent. For these reasons a comparison of different systems is not feasible without introducing additional parameters. In order to compensate for the energy and charge dependence, Q -value corrected (along similar lines as in Ref. 23) cross section ratios for 2-neutron/1-neutron and 2-proton/1-proton transfer reactions are plotted in Fig. 11 as function of the charge of the projectile. The ratio for the neutron transfers is about 0.2, but about twice that value is observed for proton transfer reactions. It should be noted that proton pairing effects (i.e. populating states in even and odd- Z ejectiles) can not be solely responsible for this behavior, because the cross section

Fig. 11. Ratio of two-particle and one-particle - transfer cross sections for proton and neutron transfer, respectively. The solid lines serve to guide the eye.

ratio does not change in going from even Z projectiles (^{28}Si or ^{48}Ti) to an odd Z projectile ^{37}Cl . For the cases investigated so far it therefore seems that the 2-proton transfer reactions show more enhancement if compared to the corresponding neutron transfer reactions. Similar observations have been made recently for proton transfer studies in the system $^{88}\text{Sr} + ^{144}\text{Sm}$ (Ref. 25).

Let me mention two other topics in quasi-elastic reactions which have been discussed in the recent literature. One is the so-called 'slope anomaly' of neutron transfer reactions. The slope of the angular distribution for two-neutron transfer reactions at forward angles shows, if plotted vs. the distance of closest approach a slope similar to the one obtained from the angular distribution for one-neutron transfer. From binding energy arguments one would expect, however a difference by a factor of two. Heavier deformed nuclei, in particular, show large deviations from the expected behavior²⁶. An example of a case where the theoretically expected slopes are observed is the system $^{58}\text{Ni} + ^{208}\text{Pb}$ as shown in Fig. 12.

Fig. 12. top: Transfer probability for the one and two-neutron transfer reactions ($^{58}\text{Ni}, ^{59}\text{Ni}$) and $^{58}\text{Ni}, ^{60}\text{Ni}$) on ^{208}Pb , plotted as function of the distance of closest approach.

bottom: Wilczynski - plot for the one-neutron transfer reaction $^{208}\text{Pb}(^{48}\text{Ti}, ^{49}\text{Ti})^{207}\text{Pb}$.

The solid lines are obtained from calculated ground state binding energies and give a good description of the data. The deviation at the most forward angles is caused by the inclusion of deep inelastic processes as can be seen from a Wilczynski plot for the (^{48}Ti , ^{49}Ti) reaction shown in Fig. 12b. We have analyzed the slopes for one- and two-neutron transfer reactions for a large number of systems involving projectiles from ^{48}Ti up to ^{80}Se . The slopes of the one-neutron transfer reactions (open circles) together with the theoretical expectation (solid line) are plotted in Fig. 13 as function of the mass number of

Fig. 13. Slope parameter for 1n and 2n-transfer reactions induced by medium weight projectiles for various target nuclei. See text for details.

the target and good agreement is generally observed. A different picture evolves, however, for the two-neutron transfers (full squares in Fig 13). Only very few nuclei (in particular $^{58}\text{Ni} + ^{208}\text{Pb}$) are in agreement with the slope expected for a two-neutron reaction. Other projectiles (e.g. ^{48}Ti , ^{64}Ni) on the same target (^{208}Pb) show large deviations from the expected behavior. Reactions with ^{58}Ni on spherical and deformed Sm isotopes (mass 144, 149 and 154, respectively) show all similar deviations from the solid line. The largest discrepancy is found for the reaction $^{57}\text{Fe} + ^{197}\text{Au}$ where the two-neutron slope is the same as the slope for the one-neutron transfer reaction. From the data which were analyzed so far we can therefore conclude that the slopes of the angular distributions for a two-neutron transfer reaction induced by projectiles up to the mass 80 region is not particularly different for a spherical or for a deformed target. There seems to be, however, a strong nuclear structure dependence as seen e.g. from the results with the ^{208}Pb target and different projectiles.

The last question I want to address has to do with the influence of quasi-elastic transfer reactions on the strength of the fusion process. It has been shown that a coupling to inelastic scattering in many cases can explain the large subbarrier fusion enhancement observed particularly in systems involving medium mass projectiles¹. The variation of the enhancement within a given projectile-target combination involving different isotopes, however, is not easily understood by including inelastic

excitation alone. One example is the much discussed $^{58}\text{Ni} + ^{58,64}\text{Ni}$ system²⁷, but many others have been measured. The variations within such systems have been attributed generally to the influence of transfer reactions. Experimentally it has been observed that for heavier projectiles (Ti, Ni) neutron transfers are the most important channels whereas for lighter systems proton transfers can also be strong²⁸. Generally the strength of the quasi-elastic transfers scales with the observed fusion enhancement. One of the largest fusion enhancements measured so far involves the system $^{64}\text{Ni} + ^{100}\text{Mo}$ (Ref. 29). If the enhancement is measured by the energy shift necessary to bring the experimental excitation function in agreement with a one-dimensional barrier penetration calculation, then $^{64}\text{Ni} + ^{100}\text{Mo}$ requires a shift of about 8 MeV. Calculations for this system involving higher order effects²⁷ do not converge including first and second order effects³⁰. Coupling to inelastic channels requires β -values which are about 50% larger than the measured deformation parameters²⁹. From the systematics of transfer cross sections involving Si...Se projectiles on heavy targets (Sn...Pb) we would expect²³ neutron transfer cross sections which are of the order of 120 mb. We have recently measured transfer cross sections for the systems $^{58,64}\text{Ni} + ^{100}\text{Mo}$ at energies slightly below and above the Coulomb barrier by bombarding Ni targets with a ^{100}Mo beam. Surprisingly the measured (preliminary) cross sections are smaller than the values quoted above by about a factor of 5. Two-neutron transfer cross sections are even smaller by another factor of 4. In $^{64}\text{Ni} + ^{100}\text{Mo}$ we have therefore a system where so far all our theoretical attempts of coupled channel treatments at least up to second order are unsuccessful. The nuclei around mass 100 therefore seem to be a challenge, both in terms of their small transfer cross sections and in terms their large fusion enhancement.

From these few examples it is clear that our understanding of quasi-elastic reactions, i.e. processes where relatively small amounts of energy, mass and charge are exchanged during the nuclear interaction, is limited to the most simple processes, like elastic and inelastic scattering and one-nucleon transfer reactions. More complicated processes like two-particle transfers, which are important doorway states towards more complex reactions (deep inelastic scattering and fusion) are not well understood. Furthermore several nuclear structure effects are observed in these reactions which still have to be explained.

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