Pionic fusion in light-ion systems
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7. Discussion and outlook

In this work, we have compared two data sets for the pionic fusion reactions with well-defined initial and final state configurations. For the first time, we have measured almost the full pion angular distribution from pionic fusion reactions with a projectile heavier than $^1\text{H}$. We would like to mention with special emphasis that pionic fusion is a very rare process presenting a tiny fraction of the total pion production cross section. The observation of rather complete angular distributions of the extremely small cross sections of about $10^{-8}$ barn is remarkable. Figure 7.1 compares the results from the present experiment with the previous pionic fusion experimental results (that we found in the literature) in which the pion angular distributions have been measured. The presented angular distributions are sorted by the projectile mass from panels (a) to (j). Different symbols in every panel of the figure represent either a different beam kinetic energy or a different observed final state of the fusion product. The two lowest panels represent the KVI data. A number of remarks can be made:

(i) The measured angular distribution of different pion production experiments is anisotropic. Furthermore, from the inclusive experiments of the $^{12}\text{C}(^{12}\text{C},\pi^0)X$ [70] and $^{12}\text{C}(^{12}\text{C},\pi^+)X$ [71, 72] reactions, it has been observed that the anisotropy is getting more pronounced with increasing pion kinetic energy.

In fact, pion production from nucleus-nucleus collisions requires more and more “co-operative” interactions among nucleons in target and projectile the closer one gets to the coherent threshold. It has been observed that by increasing the energy the cross section increases. The cross section of the $^1\text{H}(^1\text{H},\pi^+)^2\text{H}$ reaction as the simplest pionic fusion reaction at $T_{\text{beam}}=560$ MeV is about 50 times larger than the one at $T_{\text{beam}}=295$ MeV. This is shown in Fig. 7.1-(a). The beam kinetic energies $T_{\text{beam}}=560$ and 295 MeV in the laboratory system are equivalent to available centre-of-mass energies $(T_{CM} - T_{\text{thr.CM}})$ of 123.1 and 3.5 MeV, respectively, in the centre-of-mass system. As is shown in Fig. 7.1-(c), the cross section of the $^3\text{He}(^1\text{H},\pi^+)^4\text{He}$ reaction increases by almost a factor of 2 when the beam kinetic energy changes from 178 MeV ($T_{CM} - T_{\text{thr.CM}}=10.9$ MeV) to 198 MeV ($T_{CM} - T_{\text{thr.CM}}=25.6$ MeV). In addition, it is shown in Table 1.1 that the cross section of the $^3\text{He}(^3\text{He},\pi^+)^6\text{Li}$ and $^4\text{He}(^3\text{He},\pi^+)^7\text{Li}$ reactions in the most forward angles increases when the beam kinetic energy increases.

It has been observed, however, that the increasing trend of the cross section will change when the beam kinetic energy is high enough compared to the coherent threshold energy. As an example, we again refer to the $^1\text{H}(^1\text{H},\pi^+)^2\text{H}$ reaction in Fig. 7.1-(a). By increasing the beam kinetic energy from 560 to 810 MeV (or the available centre-of-mass energy from 123.1 to 230.1 MeV), the total cross section decreases (the full squares). In case of the $^3\text{He}(^1\text{H},\pi^+)^4\text{He}$ reaction at 800 MeV beam kinetic energy (equivalent to $T_{CM} - T_{\text{thr.CM}}=437.9$ MeV) the cross section is considerably lower than the one obtained at 198 MeV ($T_{CM} - T_{\text{thr.CM}}=25.6$ MeV). Furthermore, the observations of the $^4\text{He}(^3\text{He},\pi^+)^7\text{Li}$ reaction indicate that the cross section decreases when the beam kinetic energy increases from 266 ($T_{CM} - T_{\text{thr.CM}}=12.8$ MeV) to 348 MeV ($T_{CM} - T_{\text{thr.CM}}=58.4$ MeV) (Fig. 7.1-(h)). It is depicted in Table 1.1 that for the $^6\text{Li}(^2\text{H},\pi^-)^8\text{B}$ reaction by increasing the
The measured pion angular distributions in the pionic fusion experiments, which were found in the literature, in comparison with the results of the KVI experiments. The results of the KVI experiments are shown in the lowest row of the figure. \( T_{\text{beam}} \) indicates the beam kinetic energy (in MeV) and the numbers inside the bracket are the available energies in the centre-of-mass system (in MeV). The used references are [46, 63, 64, 65, 66, 67, 68, 13, 49, 69, 14].
beam kinetic energy from 300 to 600 MeV \((T_{CM} - T_{thr,CM}=86.21\) to 301.51 MeV) the cross section in the most forward angles decreases by a factor of 6. One can draw the conclusion that by increasing the available centre-of-mass energy to a value higher than about 300 MeV which is the required energy to form the \(\Delta\)-resonance, more exit channels are available and therefore, the chance of pion production by pionic fusion decreases.

(ii) Due to the symmetric target-projectile combination in the \(^1\text{H}(^{1}\text{H},\pi^+)\text{H}\) reaction, the \(\pi^+\) angular distribution is forward-backward symmetric. It has also been shown that in the inclusive reaction of \(^{12}\text{C}(^{12}\text{C},\pi^0)\times\) \([70]\) the distribution is forward-backward symmetric since the target and projectile are the same. In the existing experimental results of the pionic fusion reaction with the same projectile and target, \(^{12}\text{C}(^{12}\text{C},\pi)\)\(^6\text{Li}\) and \(^{12}\text{C}(^{12}\text{C},\pi)\)\(^7\text{Li}\) reactions, either only the total cross section or a small part of the angular distributions are reported. Therefore, no conclusion about the possible symmetric behaviour of the pion angular distribution can be drawn. It can be noticed from Fig. 7.1 that in pionic fusion reactions with different target and projectile, the pion angular distribution is forward-backward asymmetric in the nucleus-nucleus centre-of-mass system and is dominantly forward peaked. The asymmetric behaviour increases mainly with increasing mass difference of target and projectile. The graphs (b), (c) and (d) in Fig. 7.1 show the asymmetric and forward peaked angular distributions for the \(^2\text{H}(^{1}\text{H},\pi^+)\text{H}\), \(^{3}\text{He}(^{1}\text{H},\pi^+)\text{He}\) and \(^{4}\text{He}(^{1}\text{H},\pi^+)\text{He}\) reactions, respectively.

One possible explanation for the forward peaked behaviour of the angular distribution depicted in graphs (a)-(d) in Fig. 7.1 is that pion production is dominated by \(\Delta\)-excitation in the proton which is moving to the forward direction. The empty and full markers in graph (e) are the results of the \(^3\text{He}(^{1}\text{H},\pi^+)\text{He}\) measurements from ORSAY \([69]\) and Indiana-Texas groups \([66, 67]\), respectively. The two groups have used almost the same beam kinetic energies (180 and 190 MeV by the ORSAY group and 178 and 198 MeV by the Indiana and Texas groups), however, their results are not consistent. The angular distributions obtained by the ORSAY group (empty markers) seem to be flat compared with the one measured by the other groups. Furthermore, the \(\pi^+\) angular distribution from the two reactions, \(^{91}\text{Zr}(^{1}\text{H},\pi^+)\text{Zr}\) and \(^{209}\text{Pb}(^{1}\text{H},\pi^+)\text{Pb}\) depicted in graphs (e) and (f) are anisotropic but not forward peaked. Therefore, these two distributions are not consistent with our explanations about the forward peaked behaviour of the distribution.

By moving to the pionic fusion reactions with a projectile heavier than proton, the \(\pi\) angular distribution is still forward peaked as can be seen in the measured results of the \(^3\text{He}(^{3}\text{He},\pi^+)\text{He}\) reaction (graphs (g) in Fig. 7.1). The possible explanation would be similar to the one for the reactions with \(^1\text{H}\) projectiles. Here, the pion can be produced from the \(^3\text{He}\) which moves to the forward (backward) direction causing a forward (backward) peaked angular distribution. The \(\pi^+\) and \(\pi^0\) angular distributions from the \(^4\text{He}(^{3}\text{He},\pi^+)\text{He}\) (graph (h)) and \(^4\text{He}(^{3}\text{He},\pi^0)\text{Be}\) (graph (i)) experiments are not consistent in the forward direction since the latter is not forward peaked. In case of the \(^4\text{He}(^{3}\text{He},\pi^0)\text{Be}\) experiment, where the target and projectile are almost the same, the angular distribution is nearly symmetric around 90° (Fig. 7.1-(i)). We observed that the forward-backward asymmetric behaviour is stronger in case of the \(^6\text{Li}(^{4}\text{He},\pi^0)\text{He}\) reaction compared to the \(^4\text{He}(^{3}\text{He},\pi^0)\text{Be}\) reaction, which corresponds to the larger projectile-target mass difference of the former reaction.

(iii) The distributions exhibit a minimum at around 90°. According to the Microscopic reaction model, which is described in Chapter 2, the angle of this minimum depends on
how much target and projectile contribute to the pion production process. The conclusion of this model for the \( ^3\text{He}(^3\text{He},\pi^+)^6\text{Li} \) reaction is depicted in Fig. 2.7. In case of target contribution, the minimum of the angular distribution is found at \( \theta_{c.m.} < 90^\circ \). Following this description, \( \pi^0 \) in the \( ^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^* \) reaction may dominantly be emitted from the \(^6\text{Li} \) target side.

(iv) By increasing the target plus projectile mass, in general the total cross section decreases. It should be mentioned that different experiments used different centre-of-mass energy above the coherent pionic fusion threshold. Therefore, it is difficult on basis of the different experimental results to formulate the behaviour of the cross section in terms of the available number of nucleons. From the theoretical point of view, the Sudden Overlap model and the model based on clustering correlations predict that the overall trend is a decreasing cross section with increasing mass. According to the Sudden Overlap model, by increasing the momentum of the participating nucleon in the reaction, the calculated total cross section increases sharply. For a given available energy, by increasing the number of available nucleons the amount of the available energy per nucleon decreases, therefore the cross section decreases (Fig. 2.4). Results of the model based on the clustering correlations show that for the shell model wave functions the cross section decreases gradually as the mass of the final nucleus becomes larger up to the end of each shell. The cross section decreases as well when the cluster model wave function is used, but the slope is much steeper than for the shell model results (full circles in Fig. 2.12).

We observe that, up to now, the model based on strong clustering correlations has been the most successful one in describing the magnitude of the cross section together with the behaviour of the angular distributions for the \( ^4\text{He}(^3\text{He},\pi^+)^7\text{Li} \) and \( ^4\text{He}(^3\text{He},\pi^0)^7\text{Be} \) reactions. Furthermore, we concluded that the clustering correlations are important for the \( ^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^* \) reaction (see Chapter 6). Here we will discuss the next possible steps of future theoretical work that is required to understand the pionic fusion reaction of \( ^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^* \) based on the model with clustering correlations.

Different experiments have shown that the \(^6\text{Li} \) nucleus exhibits an \( \alpha\text{d} \) cluster structure \([73]\). In addition, different studies show that in case of the \(^6\text{Li} \) nucleus, the cluster model works better than the shell model \([74, 75]\). Therefore, in the simplest picture, the entrance and exit channels can be seen as an \( \alpha\alpha\text{d} \) cluster system. The \( \alpha\)-deuteron cluster structure of the ground state of \(^6\text{Li} \) has been investigated \([76]\) by solving the coupled Schrödinger equation for the relative motion between the clusters. The equation has been derived by using the Resonating Group Method and taking into account the \( D \)-state contribution in the deuteron cluster. This method can successfully describe experimental data like \( \alpha\alpha \) scattering \([77]\). In this approach of modelling the many-nucleon system, an effective inter-nucleon force has been used. In the \( ^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^* \) reaction in addition to the NN interaction, the cluster subsystems interact with each other as a whole. The pion production operator will then depend much on the relative movement of the clusters as has been investigated by the models based on clustering correlations \([8]\).

The proposed pionic fusion processes for the \( ^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^* \) reaction are schematically shown in Fig. 7.2. The first possible process for pion production is that the pion is emitted from the deuteron which is transformed into a “quasi deuteron” with \( I=1 \) and \( J=0 \) as has been suggested for the modelling of the \( ^2\text{H}(^4\text{He},^6\text{Li}^*)\pi^0 \) reaction \([12]\). The pion may be re-scattered on one (or both) of the \( \alpha \) particle(s) which retains its identity (Fig. 7.2-(a)). The second and the third possibilities are that the pion is emitted from one of the \( \alpha \)
Figure 7.2: Schematic representation of the possible reaction mechanisms for the $^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^*$ reaction, taking the strong clustering correlations into account. The dashed square represents the pion production operator ($H_{int}$) and "C" denotes the clustering correlations. The graph (a) ((b)) represents pion production from the target emission when the deuteron (α) particle as a target sub-cluster produces the pion. After the pion is emitted, it can be re-scattered by the projectile or another sub-cluster of the target. (c) depicts pion production from the projectile side and pion re-scattering from the target side.

The differential cross section of the $^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^*$ reaction should be exhausted by the type (a) reaction mechanism, because of the isospin $I=1$ of the quasi-deuteron. This is in fact consistent with the explanation of the target emission and the related measured minimum of the angular distribution which occurs at angles lower than 90°. On the other hand, the $\pi^0$ angular distribution is expected to be mainly backward peaked since in the entrance channel the deuteron moves to the backward direction. However, as was shown by the polynomial fits to the $^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^*$ angular distribution and the comparison with the fits to the calculated results of the $^4\text{He}(^3\text{He},\pi^0)^7\text{Be}^*$ reaction (Chapter 6, Section 6.6), the measured $\pi^0$ angular distribution from the $^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^*$ reaction is forward peaked (see dotted curve in Fig. 6.8). One possible explanation could be that still the second and the third reaction mechanisms contribute and effectively change the angular distributions from the backward to a forward peaked distribution. Using the calculation based on clustering correlations for the $^4\text{He}(^3\text{He},\pi^+)\cdot^7\text{Li}$ reaction, it was found that the $^4\text{He}$ contribution in the $\pi^+$ production is negligible (Fig. 2.11). However, our results imply a larger probability of the $^4\text{He}$ contributions to the pion production.

In order to formulate the reaction mechanisms shown in Fig. 7.2, the entrance and exit channel wave functions together with the pion production operator need to be specified.
Following the method involving strong clustering correlations, Eq. 2.32 can be written as

\[
\langle \zeta_\alpha \zeta_\alpha \zeta_d r | k_f; J_f M_f \rangle = \left[ \frac{4!4!2!}{10!} \right]^{1/2} S_{aad}[\Phi_\alpha(\zeta_\alpha)\Phi_\alpha(\zeta_\alpha)\Phi_d(\zeta_d)]
\otimes \delta Y^L(\hat{r})|_M \chi_{JL}(r),
\]

(7.1)

where \(S_{aad}\) is the antisymmetrizer of nucleons and \(\Phi_\alpha(\zeta_\alpha)\) and \(\Phi_d(\zeta_d)\) are the internal wave functions of \(\alpha\) and deuteron, respectively. They can be assumed to have the highest spatial symmetries \((0s)^4\ [71]\) and \((0s)^2\), for \(\alpha\) and deuteron, respectively, with Gaussian radial dependence. The internal wave functions for the deuteron and \(\alpha\) particles using harmonic oscillator momentum-space wave functions can be written as

\[
\Phi(\vec{p}_1, \vec{p}_2, ..., \vec{p}_A) = \prod_{i=1}^{A} (\beta \sqrt{\pi})^{-3/2} e^{\frac{1}{2\beta^2}(\vec{p}_i - \vec{p}_A)^2}.
\]

(7.2)

\(\vec{p}_i\) and \(\vec{p}\) are the nucleon and nucleus momentum, respectively, and \(A\) is 2 in case of deuteron and 4 in case of \(\alpha\) particle. \(\beta\) is the oscillator parameter which should be adopted for \(\alpha\) and deuteron separately. This parameter should satisfy the variational stability conditions. The observed charge radii and binding energies need to be reproduced well with the obtained wave function. The inter-cluster relative wave function \(\chi_{JL}(r)\) needs to be determined variationally by solving the RGM equation of motion Eq. 2.33. The many-body pion production Hamiltonian can be written as

\[
H = \sum_{i=1}^{10} t_i - T_G + \sum_{k<l} v_{kl} + iW_D(r),
\]

(7.3)

where \(t_i\) and \(T_G\) represent the kinetic energy of the \(i\)th nucleon and the centre-of-mass energy, respectively. The two-body interaction \(v_{kl}\) may consist of three different parts: the central part, the spin-orbit nuclear force and the Coulomb force. Hasegawa [76] showed that in the ground state of \(^6\text{Li}\), realistic two-nucleon potentials need to be employed in order to be able to properly reproduce the large intrinsic energy of an \(\alpha\) cluster and to obtain the reasonable values of the total and the relative binding energies. In case of the central part of the nuclear force, different approaches, e.g., the Volkov force [78], the modified Hasegawa-Nagata force, the modified Brink-Boeker force [79], and modified Wildermuth-Tang force [80] need to be examined.

The local imaginary potential \(iW_D(r)\) takes care of the mutual interaction between the three clusters. The model based on clustering correlations [8] shows that the local imaginary potential changes the pion angular distribution in the backward angles. Therefore, the anisotropy of the angular distribution can be also dependent on this potential. In addition, the total cross section is influenced by this interaction. The initial scattering wave can be constructed by superposition of the cluster wave functions from Eq. 7.1 as was reported for Eq. 2.34, since the clustering representations of \(^6\text{Li}\) indicate that the clustering correlations exist already before the interaction. Furthermore, the model based on clustering correlations has successfully employed the cluster interactions in the entrance channel which gives confidence in pionic fusion cross sections calculated using these clustering correlations.
To even better guide the theory and to obtain a systematic study of the anisotropic behaviour of the $\pi$ angular distribution, more pionic fusion experiments \cite{81,82} need to be performed. A systematic study of the target-projectile combinations in different mass regions is essential. The reaction $^6\text{Li}(^6\text{Li},\pi^0)^{12}\text{C}^*$, i.e. a measurement of the pion, the fused nucleus and its photon decay was already proposed earlier \cite{81} but could not be carried out because of difficulties in producing the $^6\text{Li}$ beam at that time. In this reaction the target-projectile combination is symmetric and the same clusters as those in the $^6\text{Li}(^4\text{He},\pi^0)^{10}\text{B}^*$ ($\alpha$ and $d$) and $^4\text{He}(^3\text{He},\pi^0)^7\text{Be}$ experiments are involved in the pionic fusion process but the cluster structure is more complicated ($\alpha\alpha dd$) and, therefore, the analysis would be even more decisive for the underlying reaction dynamics.

The $^6\text{Li}(^6\text{Li},\pi^0)^{12}\text{C}^*$ reaction should lead from the $I=0$ ground state to the 15.1 MeV $I=1$ excited state, which is well separated from the ground state. In fact, the excited state of $^{12}\text{C}$ can be detected by the $M1\gamma$ decay to the ground state. In order to measure the pion, the fused nucleus and its photon decay, a combination with an excellent photon detector is required. The proposed experimental setup in Ref. \cite{81} for this reaction offers ideal conditions for the detection of all final state particles. By choosing a beam energy of about 260 MeV, the available energy above the coherent threshold in the centre-of-mass frame will be about 7 MeV. This choice would produce pion momenta $k_\pi \approx 40$ MeV/c and would allow a comparison with the $^{12}\text{C}(^{12}\text{C},^{24}\text{Mg})\pi^0$ data from reference \cite{17}.