Pionic Fusion in Nucleus-Nucleus Collisions

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A microscopic model is presented for the complete fusion of two nuclei with the total excess energy being transferred to the pion field. The meson exchange between two nucleons, each of them belonging to one of the colliding fragments, leads naturally to a coupling of the initial relative motion to the final pion field. With use of this reaction mechanism an adequate description can be achieved for the process $^3He(^3He, \pi^+)^6Li$ around 280 MeV.

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During the last decade[1] the coherent production of pions in proton-induced reactions on nuclei has been studied extensively. A similar process is possible also in nucleus-nucleus collisions[2]:

$$A_1 + A_2 \rightarrow B(J) + \pi, \tag{1}$$

where the projectile (A_1) and target (A_2) form a united nucleus B in some bound state $|J\rangle$. This fusion of two nuclei to a specific bound state of the final nucleus—sometimes referred to as coherent[2,3] or doubly coherent[4] pion production—clearly requires the coherent action of all the nucleons since the kinetic energy of the entrance channel is completely converted into one pion. This energy transfer between two well-defined degrees of freedom excludes a fully developed thermalization process. Consequently, a statistical approach is inadequate for such an exclusive process; obviously for this kind of reaction all the nucleons have to contribute cooperatively.

It is the purpose of this paper to derive a corresponding many-body mechanism which, starting from a microscopic ($NN \rightarrow NN\pi$) interaction, leads to a genuine coupling of the pion field to the relative motion of the two fragments. This model is then applied to the specific reaction

$$^3He + {}^3He \rightarrow {}^6Li(J) + \pi^+ \tag{2}$$

which has recently been studied experimentally by Bimbot *et al.*[5] and analyzed by Germond and Wilkin[6] in a simplistic cluster model based on the triangle diagram.

To describe the process (1) we start from the general expression

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{c.m.}} = \frac{1}{8\pi^2}\frac{k\pi}{\kappa}\frac{E_1E_2E_B}{E_{\text{c.m.}}^2}\sum_f\overline{\sum_i}|T_{fi}|^2, \tag{3a}$$

where κ and k_π denote the relative momenta in the entrance and exit channels, respectively. With the notation of Eq. (1) the transition amplitude is given by

$$T_{fi} = \langle \vec{k}_\pi, B(J)|H_{\text{int}}|A_1, A_2; \vec{\kappa}\rangle. \tag{3b}$$

Following Ref. 3 we construct a model for H_{int} on the basis of an elementary $NN \rightarrow NN\pi$ vertex[7] [Figs. 1(a)–1(c)]. For the interaction of two nucleons belonging to *different* fragments A_1 and A_2, respectively, the corresponding c.m. coordinates, R_1 and R_2, of the colliding nuclei are naturally affected; this then leads to a direct coupling of the relative coordinate, $\vec{R}_{12} = \vec{R}_1 - \vec{R}_2$, of the entrance channel to the pion field. This obviously is the essential mechanism which allows for the occurrence of such a highly cooperative reaction as Eq. (1). For the resonant pion exchange contribution of Fig. 1(a), this is schematically represented in Fig. 1(d); the corresponding formal development will be briefly outlined in the following.

Accordingly we obtain

$$H_{\text{int}} = \Lambda G W = \sum_{m=1}^{B}\Lambda(m)(E_{\text{c.m.}} - H)^{-1}\sum_{i\in A_1}\sum_{k\in A_2}W(i,k), \tag{4}$$

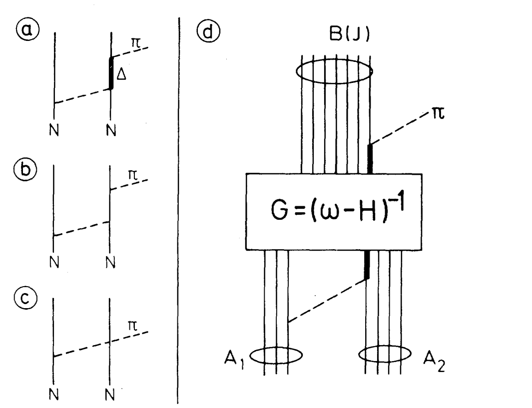

FIG. 1. Elementary $NN \rightarrow NN\pi$ transition: (a) s wave; (b) nonresonant p wave; (c) resonant p wave (Δ excitation); (d) pionic fusion via the intermediate Δ excitation.

where H is the generalized nuclear Hamiltonian[8] which consistently treats nucleons and Δ's on the same footing while $E_{\mathrm{c.m.}}$ denotes the total energy in the c.m. system. The elementary $(NN \to N\Delta)$ interaction is expressed by

$$W(i,k) = (2\pi)^{-3}(ff^*/m_\pi^2)\int d^3q\, F_1(q)v(q)F_2(q)\exp[i\vec{q}\cdot(\vec{r}_k - \vec{r}_i)]\,(\vec{\sigma}_i\cdot\vec{q})(\vec{S}_k^{\dagger}\cdot\vec{q})(\vec{\tau}_i\cdot\vec{T}_k^{\dagger}), \tag{5a}$$

with $v(q)$ denoting the pion propagator, $F_1(q)$ and $F_2(q)$ the form factors[9] of the πNN and $\pi N\Delta$ vertices, respectively, and with otherwise standard notations. Similarly the $\Delta \to N\pi$ decay vertex is given by[10]

$$\Lambda(m) = (2\pi)^{-3/2}(f^*/m_\pi)\int d^3k'\, F_3(k')\exp[-i\vec{k}'\cdot(\vec{r}_m - \vec{r}_\pi)](\vec{S}_m^{\dagger}\cdot\vec{k}')(\vec{T}_m^{\dagger}\cdot\hat{\varphi}_\pi). \tag{5b}$$

Introducing the biorthogonal set of eigenmodes, $|B_\mu{}^*\rangle$, of H we can rewrite Eq. (4):

$$T_{fi} = \sum_\mu \langle f|\Lambda|B_\mu{}^*\rangle(E_{\mathrm{c.m.}} - \mathcal{E}_\mu)^{-1}\langle \tilde{B}_\mu{}^*|W|i\rangle, \tag{6}$$

with the corresponding complex eigenenergies $\mathcal{E}_\mu$. Equation (6) describes (i) the storage of the incoming energy in the internal nuclear Δ degree of freedom and (ii) its subsequent coupling to the outgoing pion field. In order to work out more transparently the structure of Eq. (6) we introduce the closure approximation as in the phenomenological isobar doorway model[11]: $E_{\mathrm{c.m.}} - \mathcal{E}_\mu \approx E_{\mathrm{c.m.}} - \bar{\mathcal{E}}$. Then

$$T_{fi} = (E_{\mathrm{c.m.}} - \bar{\mathcal{E}})^{-1}\langle f|\Lambda W|i\rangle. \tag{7}$$

For the following discussion Eq. (7) is used rather than Eq. (6) to demonstrate explicitly the dependence of the interaction Hamiltonian on the various degrees of freedom.

For the sake of translational invariance we transform the single-nucleon coordinates of Eqs. 5(a) and 5(b) to a Jacobian representation (by standard techniques[12]) to obtain

$$\begin{aligned}\Lambda W = c\int d^3q\, v(q)\int d^3k'\, F(q,k')\exp(i\vec{k}'\cdot\vec{\rho}_\pi)C(\vec{q},\vec{k}',\vec{R}_{12})\\ \times\sum_{\alpha,\gamma} d(\alpha,\gamma)\sum_{i\in A_1}\exp(-i\vec{q}\cdot\vec{v}_i)\sum_{k\in A_2}\exp[i(\vec{q}-\vec{k}')\cdot\vec{v}_k]\\ \times\{[\sigma_i\times\sigma_k{}^\gamma]^\alpha\times[q\times(k\times q)^\gamma]^\alpha\}^0\sum_\beta c_\beta[(\tau_i\times\tau_k{}^\beta)^1\times\hat{\varphi}_\pi]^0.\end{aligned} \tag{8}$$

Here $\vec{\rho}_\pi$ denotes the pion coordinate with respect to the overall c.m.; $\vec{v}_i$ and $\vec{v}_k$ depend linearly on the internal coordinates of the fragments, A_1 and A_2, respectively; $d(\alpha,\gamma)$ and c_β are coefficients which arise from spin and isospin recoupling, whereas c is an overall constant. Finally $F(q,k')$ is the product of the form factors in Eqs. 5(a) and 5(b). However, most importantly Eq. (8) exhibits explicitly the coupling of the pionic degree of freedom to the relative coordinate $\vec{R}_{12}$ by the operator C:

$$C(\vec{q},\vec{k}',\vec{R}_{12}) = \exp\{-i[(b_1 - b_2)\vec{q} + b_2\vec{k}']\cdot\vec{R}_{12}\}, \tag{9}$$

where the coefficients b_i depend on the particular target and projectile combination. It should be stressed that this specific property of H_{int} depends neither on the canonical choice of Jacobian coordinates nor on the specific form of the $(NN \to NN\pi)$ vertex.

To elucidate the physical content of this mechanism we apply it to the reaction $^3\mathrm{He}(^3\mathrm{He},\pi^+)^6\mathrm{Li}(J)$ where experimental data are available from Orsay (Ref. 5) at laboratory energies of 268.5 and 282 MeV, respectively. In view of the inherent complexity the actual calculation should be considered as a first attempt to explore the dynamics of those highly coherent processes. For this purpose we describe the structure of the low-lying states of ^{6}Li in a cluster representation assuming a $^3\mathrm{He}\times{}^3\mathrm{H}$ fragmentation; for the relative motion we take harmonic oscillator functions adjusted to the ^{6}Li form factor.[13] The transition operator H_{int} is treated in the closure limit of Eq. (7) with a resonance shift of about 50 MeV to account phenomenologically for the medium corrections to the nuclear Δ excitation.[8] We expect that with this choice of the closure energy the dominant effects of pion distortion in the resonant πN channel are included to a good approximation, particularly for the present threshold situation ($T_\pi \approx 15$ MeV). For the coupling constants and cutoff masses in the form factors we take conventional values[9,10]: $f^2/4\pi = 0.08$, $f^{*2}/4\pi = 0.35$, $\Lambda_1 = \Lambda_2 = 1$ GeV, and $\Lambda_3 = 0.5$ GeV. Finally, we neglect the distortion in the entrance channel, but account properly for the identity of target and projectile.

The results of those calculations are shown in Fig. 2 for the production of the three lowest states

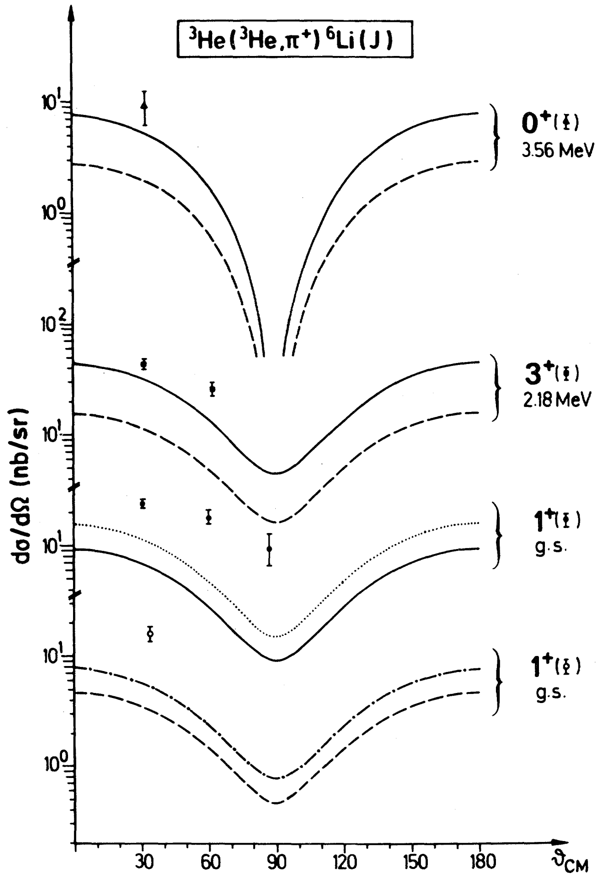

FIG. 2. Differential cross sections for various final states. Solid (dashed) curve for $T_{\text{lab}} = 282$ (268.5) MeV; dotted (dash-dotted) curve is the results for a 10% D state in the ground state for 282 (268.5) MeV. Experimental data from Orsay (Ref. 5).

of ^{6}Li at both energies mentioned above. The agreement seems fair in view of the complexity of the reaction. Estimates of the effects of the nonresonant terms [Figs. 1(b) and 1(c)] and of the closure approximation indicate an uncertainty of a factor of about 2, which is similarly expected for the off-shell continuation and the initial state interactions. We emphasize, however, that the structure of the final nuclear state plays a crucial role. As an example we mention a realistic description of the relative cluster wave function like the D-wave admixture in the ground state of ^{6}Li; the effect of a 10% D-state probability is demonstrated in Fig. 2. A detailed quantitative analysis of those uncertainties is presently under way.

Summarizing the preceding discussion we conclude that the proposed reaction mechanism allows a microscopic approach to the fusion process: The meson exchange between two nucleons belonging to different fragments leads naturally to a conversion of the kinetic energy of the relative motion to the pion field. This direct coupling between two quite different degrees of freedom avoids the thermalization and allows the occurrence of highly cooperative reactions. It should be kept in mind, however, that a number of theoretical uncertainties still await a detailed investigation; they concern both the structure of the final nucleus and the elementary production process. It is clear that a detailed understanding is a prerequisite for the application of those cooperative reactions as a new tool to investigate the physics of complex nuclei.

Specific applications could be exploration of the cluster structure of nuclei as well as the role of intermediate nuclear N^* excitations in nucleus-nucleus collisions. Finally, as a result of the unique signal, such fusion processes may develop into a method to produce and to investigate new isotopes, even far off the valley of stability.

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