Formation of Few-Body Clusters in Nuclear Matter

M. Beyer, FB Physik, Universität Rostock, 18051 Rostock, Germany

To describe the formation of clusters – in the general case a nonequilibrium process – in an interacting many-body system constitutes a new challenge for few-body methods. This may happen when the residual interaction between the quasi-particles leads to correlations. An example for such a system is nuclear matter. In the laboratory finite pieces of nuclear matter can be produced in heavy ion collisions. In astrophysics nuclear matter occurs e.g. during the supernova collapse and the formation of a neutron star.

A microscopic approach to treat the formation of clusters uses a generalized quantum Boltzmann equation. This coupled equation has been numerically solved for nucleon $f_N$, deuteron $f_d$, triton $f_t$, and helium-3 $f_{\text{h}}$ distributions utilizing the Boltzmann-Uehling-Uhlenbeck (BUU) approach [1]. The coupling between the different species is through the collision integrals $K[f_N, f_d, \ldots]$. For the deuteron loss $K_d^\text{out}(P, t)$, e.g., it is

$$K_d^\text{out}(P, t) = \int d^3k_1 \int d^3k_2 \int d^3k_3 |\langle k_1 k_2 k_3 | U_0 | k P \rangle|^2_{dN \rightarrow pnN} \times \bar{f}_N(k_1, t) \bar{f}_N(k_2, t) \bar{f}_N(k_3, t) f_N(k, t) + \ldots$$  \hspace{1cm} (1)

where $\bar{f}_N = (1 - f_N)$. The ellipsis denote further possible contributions, e.g. $dd \leftrightarrow tp$, $dd \leftrightarrow hp$ or processes like $\gamma d \leftrightarrow np$, etc. The quantity $U_0$ is the $Nd \rightarrow NNN$ break-up transition operator that in general depends on the medium. This dependence is neglected, if experimental cross sections are used to replace $U_0$ in Eq. (1) – a standard technique and in many cases very successful. To calculate $U_0$ including the self energy shift and the proper Pauli blocking and study the influence of the medium on different observables a generalized Alt-Grassberger-Sandhas (AGS) equation [2] has been derived earlier [3–8].

The effective few-body problem in matter arises in the Green function approach [9] along with a cluster mean-field expansion [10] or the a Dyson equation approach [11].

Using the effective equations derived elsewhere [3–8] we may study two important effects of the medium on the effective few-body-systems embedded in nuclear matter: (1) The change of binding energy, i.e. the self energy shift, (2) the changes in the reaction rates. Both effects are important and have consequences for the simulation of heavy ion collisions.

The change of binding energy eventually leads to the Mott effect (where $E_{\text{bound}} \rightarrow 0^-$). Not as dramatic as in Coulombic systems – here the Mott effect leads to the transition from isolating to conducting phase – it, however, influences the number of clusters and the energy spectrum produced in a heavy ion collision. The Mott density depends on the momentum of the cluster as for higher momenta blocking of the constituents of the cluster is less effective. The Mott momenta for deuteron and triton are shown in Fig. [11] for two different temperatures. Tritons are more stable than deuterons and at lower densities both clusters a more stable for higher temperatures.
For a typical temperature of the heavy ion collision (in the final stage) we have calculated the in-medium cross section. The result is shown in Fig. 2. The threshold shift is because of the change of the deuteron’s binding energy. A strong enhancement of the maximum of the cross section appears, however less change at higher energies.

As a consequence the reaction time scales become much faster, when *in-medium* rates are used in the calculation instead of *isolated* ones. Fig. 3 shown the deuteron break-up time $\tau_{bu}(P, n_N)$ evaluated in linear response, where the life time of deuteron fluctuations $\delta f_d(P, t)$ depends on the deuteron momentum $P$ and the nuclear density $n$. Similar, a chemical relaxation time $\tau_{rel}(n_N)$ can be defined, which results from a linearization of the respective rate equations [7]. The relaxation times are shown in Fig. 4.

Finally considering a specific heavy ion collision it is possible to calculate the total number of deuterons coming out of a central collision of $^{129}$Xe on $^{119}$Sn at 50 MeV/A [12].
Fig. 5 shows the integrated number of deuterons taking into account gain and loss terms induced by the reactions in the medium. The net effect is a significant enhancement of the number of deuterons. Fig. 6 shows the influence of using in-medium rates on the spectrum of the proton to deuteron ratio along with experimental data.

From the analysis it becomes clear that the medium modified elementary cross section and the proper self energy correction (binding energy shift, Mott effect) of the clusters should be included in the simulation of heavy ion collisions at that energies.

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REFERENCES

1. P. Danielewicz, G.F. Bertsch, Nucl. Phys. A 533 (1991) 712.
2. E.O. Alt, P. Grassberger, W. Sandhas, Nucl. Phys. B 2 (1967) 167.
3. M. Beyer, G. Röpke, and A. Sedrakian, Phys. Lett. B 376 (1996) 7.
4. M. Beyer and G. Röpke, Phys. Rev. C 56 (1997) 2636.
5. M. Beyer, Few Body Syst. Suppl. 10 (1999) 179.
6. M. Beyer, W. Schadow, C. Kuhrts, and G. Röpke, Phys. Rev. C 60 (1999) 034004.
7. C. Kuhrts, M. Beyer, and G. Röpke, Nucl. Phys. A688 (2000) 137.
8. M. Beyer, S. A. Sofianos, C. Kuhrts, G. Ropke and P. Schuck, nucl-th/0003071.
9. L.P. Kadanoff, G. Baym, Quantum Theory of Many-Particle Systems (Mc Graw-Hill, New York, 1962); A.L. Fetter, J.D. Walecka, Quantum Theory of Many-Particle Systems, (McGraw-Hill, New York, 1971).
10. G. Röpke, M. Schmidt, L. Mönchow, and H. Schulz, Nucl. Phys. A 399 (1983) 587.
11. J. Dukelsky, G. Röpke, and P. Schuck, Nucl. Phys. A628, 17 (1998).
12. INDRA collaboration, D. Gorio et al., Eur. Phys. J A 7 (2000) 245 and ref. therein.