What is the physics behind the $^3$He–$^4$He anomaly?

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Received:

We show that coalescence of nucleons emitted prior to thermalization in highly excited nuclei can explain the anomaly of kinetic energies of helium clusters. A new coalescence algorithm has been included in the statistical approach to nuclear reactions formerly used to describe intermediate mass fragment production.

25.70.-z, 25.70.Pq

Introduction

In this paper we address a phenomenon which seems to be important for understanding mechanisms which favour light cluster production in intermediate energy reactions. It concerns the so-called $^3$He–$^4$He "puzzle", i.e. the anomalous behaviour of their kinetic energies. Usually, thermal models (e.g. meckjian) or approaches which consider a possible radial expansion (flow) apply to describe the kinetic energies of light charged particles (LCP). In the thermal scenario we expect \( (E_{\text{kin}}(^3\text{He})) \approx (E_{\text{kin}}(^4\text{He})) \) whereas radial flow delivers \( (E_{\text{kin}}(^3\text{He})) < (E_{\text{kin}}(^4\text{He})) \). However, in many reactions quite an opposite behaviour has been observed. The corresponding data are summarized in table 1. For example, there is evidence of the "puzzle" in the inclusive kinetic energy spectra of He isotopes obtained from p + Ag Vol74 and p+C And98 reactions at 1 GeV, in 7.5 GeV/c proton collisions with $^{12}$C, $^{112,124}$Sn, $^{197}$Au Bog80 and in Ne+U reactions at 250 and 400 A-MeV gutbrod. The anomaly was also observed in antiproton reactions 202 MeV/c p + $^{12}$C, $^{40}$Ca, $^{63}$Cu, $^{92,96}$Mo and $^{238}$U Mar88. Precise measurements of 55 MeV $^3$He+Ag collisions at $\Theta_{\text{lab}}=147.5^\circ$ also show the anomalous behaviour of $^3$He and $^4$He (ref.Vio98). The following trends have been observed in heavy-ion collisions: (i) the difference \( \Delta E = (E_{\text{kin}}(^3\text{He}))- (E_{\text{kin}}(^4\text{He})) \) is positive and increases with the particle multiplicity in Au + Au reactions at 250 A-MeV Dos87, (ii) the "puzzle" is pronounced in central event samples of Au + Au Pog93, 95 A-MeV Ar + Ni Bor96, 50 A-MeV Xe+Sn Bou99 but weaker in Ar + Ca Moh96 collisions, (iii) positive values \( \Delta E \) are observed in the incident energy range from about 50 A-MeV to 300 A-MeV but the anomaly vanishes at \( \approx 1 \) GeV Lis95. The existing data indicate that the larger the number of nucleons of the colliding system the larger the deviation of the kinetic energies of $^3$He and $^4$He.

Table Experimental data concerning the $^3$He–$^4$He anomaly. The temperatures \( T \) of the helium isotopes were obtained by Maxwell-Boltzmann fits to the kinetic energy distributions, in case of *) an exponential fit to the data at $\Theta_{\text{lab}}=90^\circ$ was applied.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Incident energy</th>
<th>T($^3$He)</th>
<th>T($^4$He)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au + Au</td>
<td>250 A-MeV</td>
<td>Dos87</td>
<td></td>
</tr>
<tr>
<td>Au + Au</td>
<td>95 A-MeV</td>
<td>Pog93</td>
<td></td>
</tr>
<tr>
<td>Ar + Ni</td>
<td>50 A-MeV</td>
<td>Bor96</td>
<td></td>
</tr>
<tr>
<td>Xe + Sn</td>
<td>202 MeV/c p</td>
<td>Gutbrod</td>
<td></td>
</tr>
</tbody>
</table>

An appropriate way to describe processes involving many particles is the statistical approach. The system characterized in the initial stage by nonequilibrium distribution functions evolves towards equilibration as a result of interaction between particles. In this process the system runs through different states. The first one can be considered as equilibration of the one-particle degrees of freedom. In the following the evolution toward total thermalization can be considered as progressive involving of higher order particle correlations. For finite expanding systems one cannot predict in advance what kind of equilibration should be considered.

It is usually accepted that Intermediate Mass Fragments (IMF) observed in multifragmentation processes are mainly produced in a state close to thermalization. This assumption is supported by the success of statistical multifragmentation models, e.g. SMM bondorf and MMC gross. However, this conclusion may not be true for composite particles like $^3$He and $^4$He.

We guess that their unexpected behaviour results from an interplay of different production mechanisms.

Production of composite particles by coalescence

First we point at an alternative way to form clusters. We start from a distribution of nucleons in the phase space at some "freeze-out" time obtained after a dynamical evolution. Generally, non-uniform distributions are conceivable. But in some experiments, e.g. central nucleus–nucleus collisions Rei97, it is possible to select events which are nearly isotropic in space and look like thermal ones. Therefore, in such cases, we can simply assume that the nucleons populate the available many-body phase space uniformly, i.e. there is equilibration in one-particle degrees of freedom, that gives rise to a thermal distribution for individual nucleons in thermodynamical limit.
A composite particle can be formed from two or more nucleons if they are close to each other in the phase space. This simple prescription is known as coalescence model and it reflects the properties of the nucleon–nucleon interaction. Here we use the coalescence in momentum space only. The basic assumption is that the dynamical process which leads to a momentum redistribution is very fast (nearly instantaneous) so that the coordinates of nucleons are just defined by their momenta. It is also justified taking into account quantum properties of the system since the wave functions of nucleons are rather broad. This type of coalescence model has proven successful in reproducing experimental data (see e.g. BU63, Ton83, CS86).

In the standard formulation of the model it is assumed that the fragment density in momentum space is proportional to the nucleon density times the probability of finding nucleons within a small sphere of the coalescence radius $p_0$. From this hypothesis an analytical expression can be derived for differential yields of coalescent clusters.

We developed an alternative formulation of the coalescence model which is suitable for computer simulations. Nucleons can produce a cluster with mass number $A$ if their momenta relative to the center-of-mass momentum of the cluster is less than $p_0$. Accordingly we take $|\vec{p}_i - \vec{p}_{cm}| < p_0$ for all $i = 1, ..., A$, where $\vec{p}_{cm} = \frac{1}{A} \sum_{i=1}^{A} \vec{p}_i$. This is performed by comparing the momenta of all nucleons. In the following examples the value $p_0 \approx 94 \text{ MeV}/c$ has been adopted corresponding to relative velocities $v_{rel}=0.1c$ in agreement with previous analyses Ton83.

We note a problem which is sometimes disregarded in these simulations. Some nucleons may have such momenta that they can belong to different coalescent clusters according to the coalescence criterion. In these cases the final decision depends on the sequence of nucleons within the algorithm. To avoid this uncertainty we developed an iterative coalescence procedure. $M$ steps are calculated in the coalescence routine with the radius $p_{0j}$ which is increased at each step $j$: $p_{0j} = (j/M) \cdot p_0$ ($j = 1, ..., M$). Clusters produced at earlier steps participate as a whole in the following steps. In this case the final clusters not only meet the coalescence criterion but also the nucleons have the minimum distance in the momentum space. Mathematically exact, this procedure gives correct results in the limit $M \rightarrow \infty$ but we found that in practical calculations it is sufficient to confine the steps to $M = 5$.

To demonstrate how fragments are produced by coalescence we take as an example a nuclear system with mass number $A_0 = 200$ and charge $Z_0 = 80$ at various excitation energies $E^\ast=10, 20, 30$ and 100 $\text{A}\cdot\text{MeV}$. We disintegrate the system into nucleons by taking away about 7 $\text{A}\cdot\text{MeV}$ (binding energy). The rest of the energy turns into the kinetic energies of nucleons which populate the whole available many-body momentum phase space uniformly. We use the procedure developed in Kopylov to generate momenta. Figure center file=anomfig1.eps, width = 8.6cm