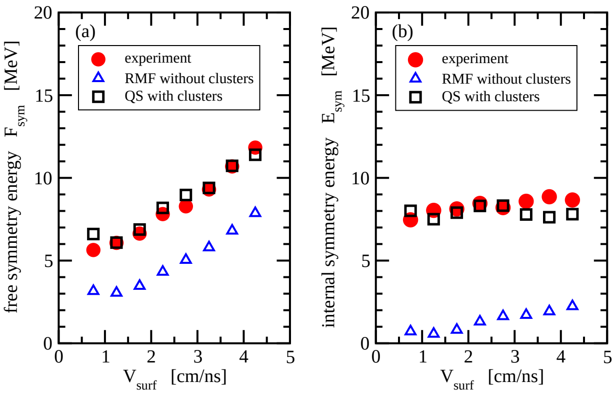


FIG. 1: (Color online) Free and internal symmetry energy as a function of the surface velocity. Experimental results are compared with results of theoretical calculations neglecting cluster formation (RMF) and including cluster formation (QS).

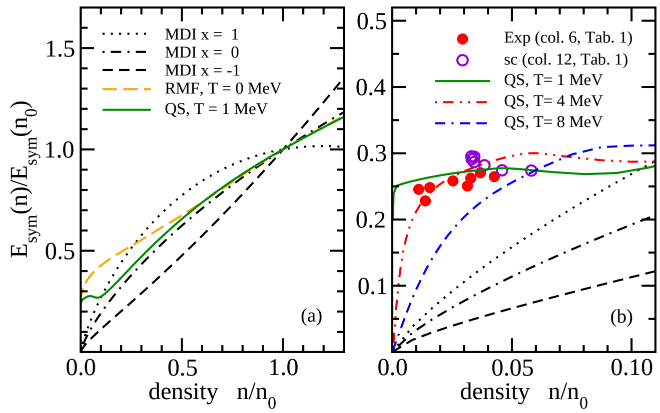


FIG. 2: (Color online) Comparisons of the scaled internal symmetry energy $E_{\rm sym}(n)/E_{\rm sym}(n_0)$ as a function of the scaled total density $n/n_0$ for different approaches and the experiment. Left panel: The symmetry energies for the commonly used MDI parametrization of Chen et al. [23] for $T = 0$ and different asy-stiffnesses, controlled by the parameter $x$ (dotted, dot-dashed and dashed (black) lines); for the QS model including light clusters for temperature $T = 1$ MeV (solid (green) line), and for the RMF model at $T = 0$ including heavy clusters (long-dashed (orange) line). Right panel: The internal scaled symmetry energy in an expanded low-density region. Shown are again the MDI curves and the QS results for $T = 1, 4,$ and 8 MeV compared to the experimental data with the NSE entropy (solid circles) and the results of the self-consistent calculation (open circles) from Tab. I

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from the measured yields, the internal symmetry energy can be calculated if the symmetry entropy is known. The values of the symmetry entropy $S_{\rm sym}^{\rm NSE}$ for given parameters of temperature and density within the NSE model are shown in Tab. I, column 5. They are calculated with the equivalent expression of Eq. (1) as the difference between the entropies of pure proton or neutron and symmetric nuclear matter. In contrast to the mixing entropy that leads to a larger entropy for uncorrelated symmetric matter in comparison with pure neutron matter, the formation of correlations, in particular clusters, will reduce the entropy in symmetric matter, see also Fig. 9 of Ref. [8]. For parameter values for which the yields of free nucleons in symmetric matter are small, the symmetry entropy may become positive, as seen in Tab. I for low temperatures. The fraction of nucleons bound in clusters can decrease, e.g. due to increasing temperature or the dissolution of bound states at high densities due to the Pauli blocking. Then, the symmetric matter recovers its larger entropy so that the symmetry entropy becomes negative, as seen in Tab. I also in the QS and self-consistent (sc, see below) calculations.

The results obtained in this way for the internal symmetry energy $E_{\rm sym} = F_{\rm sym} + TS_{\rm sym}^{\rm NSE}$ are shown in Tab. I, column 6. We note that in Ref. [20] the symmetry entropy was estimated using results of the virial expansion of Ref. [7] leading to different internal symmetry energies. However, this approximation is unreliable at the densities considered here.

In Tab. I, we also give results of the QS model [8] for the free and internal symmetry energies (columns 7 and 8) at given $T$ and $n$. In Fig. 1 (left panel) the experimentally obtained free symmetry energy is compared to the results of the RMF calculation without clusters and the QS model with clusters [8]. There are large discrepancies between the measured values and the results of calculations in the mean-field approximation when cluster formation is neglected. On the other hand, the QS model results correspond nicely to the experimental data. In the right panel of Fig. 1 we compare the internal symmetry energy derived from the experimental data with the RMF and QS results. Again, it is clearly seen that the quasiparticle mean-field approach (RMF without clusters) disagrees strongly with the experimentally deduced symmetry energy while the QS approach gives a rather good agreement with the experimental data.

In Fig. 2 we present results for different approaches to extracting the internal symmetry energy and compare with the experimental values. In the left panel of the figure we show theoretical results for $T$ at or close to zero. A widely used momentum-dependent parametrization of the symmetry energy (MDI) at temperature $T = 0$ MeV was given in Refs. [4, 23] and is shown for different assumed values of the stiffness parameter $x$. For these parametrizations the symmetry energy vanishes in the low-density limit. We compare this to the QS result at $T = 1$ MeV (at lower $T$ crystallization or Bose condensation may occur as discussed above). In this approach the symmetry energy is finite at low density. The $T = 1$ MeV curve will also approach zero at extremely low densities of the order of $10^{-5}$ fm$^{-3}$ because the temperature is finite. The RMF, $T = 0$ curve is discussed below. Also note