Low Density In-Medium Effects on Light Clusters from Heavy-Ion Data

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The modification of the ground state properties of light atomic nuclei in the nuclear and stellar medium is addressed, using chemical equilibrium constants evaluated from a new analysis of the intermediate energy heavy-ion (Xe + Sn) collision data measured by the INDRA Collaboration. Three different reactions are considered, mainly differing by the isotopic content of the emission source. The thermodynamic conditions of the data samples are extracted from the measured multiplicities allowing for a parametrization of the in-medium modification, determined with the single hypothesis that the different nuclear species in a given sample correspond to a unique common value for the density of the expanding source. We show that this correction, which was not considered in previous analyses of chemical constants from heavy-ion collisions, is necessary, since the observables of the analyzed systems show strong deviations from the expected results for an ideal gas of free clusters. This dataset is further compared to a relativistic mean-field model, and seen to be reasonably compatible with a universal correction of the attractive σ-meson coupling.

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Light nuclear clusters play an important role in the warm and low-density nuclear matter [1,2] that can be found in core-collapse supernovae and neutron star mergers [3–7]. Their main role is to affect the weak interaction rates, and, as a consequence, the dynamic evolution of these violent events [1]. In neutron star mergers, their abundance has a direct influence on the fraction of the ejecta that is converted into r-process elements [8], or on the viscous evolution of the accretion disk after the merger [9], and, therefore, on the amount of matter that becomes unbound from the disk.

The most popular equations of state (EOS) only consider α clusters (for a list of available EOS see the CompOSE database [10]), but deuterons and tritons have been proven to be more abundant than free protons [4,5,11], and a reliable estimation of the cluster abundances in the different thermodynamic conditions is needed.

Nuclear clusters have been measured in heavy-ion collisions, under similar thermodynamic conditions. In Refs. [12,13], the authors presented chemical equilibrium constants for four light clusters that were the first available constraints for in-medium modifications of light clusters at finite temperature.

The problem of evaluating those abundances arises from the fact that their ground state properties are expected to be modified in a dense medium. Mass shifts arising from in-medium correlations were calculated in the framework of quantum-statistical approaches, but only in a limited density domain, and for a limited number of nuclear species [14]. For this reason, phenomenological models were developed [15], where the interactions with the medium are governed by coupling constants that must be fixed through comparison with experiment [16,17].

Very recently [18], the INDRA Collaboration presented new sets of data, complementing the unique constraint which was previously available from NIMROD data [12]. However, as already observed in Ref. [18], the weak point of both experimental works is that the thermodynamic parameters, in particular the baryon density ρ_B and the temperature T, are not directly measured, but they are deduced from the experimental multiplicities using analytical expressions that explicitly assume that the physical system under study can be modeled as an ideal gas of clusters. This is in contradiction with the very purpose of the analysis, which is to extract the in-medium modifications with respect to the ideal gas limit.

In this Letter, we propose to solve this methodological inconsistency by modifying the ideal gas expressions relating the thermodynamical parameters to cluster yields. This correction is estimated using Bayesian techniques,

under the unique condition that the volume associated to the thermal motion of each cluster species should be the same, which is a necessary (even if not sufficient) condition to be able to interpret the experimental sample in terms of thermodynamic equilibrium.

The new chemical constants evaluated from the INDRA data [18] using this improved data analysis are then compared to the relativistic mean-field model of Ref. [17], in order to extract the in-medium modifications. We show that a single parameter, expressing a universal reduction of the scalar attractive field to the nucleons bound in clustered states, can be tuned so as to obtain a reasonably good description of the chemical constants. The suppression effect is smaller than the one obtained from the comparison to the equilibrium constants of Ref. [12], where ideal gas expressions were used to extract the thermodynamical parameters, but still corresponds to important in-medium modifications of the binding energies.

Under well-defined thermodynamic conditions, as given by the temperature T, total baryon density ρ_B, and proton fraction y_p, equilibrium chemical constants $K_c(A,Z)$ of a cluster of mass (charge) number A (Z) are defined in terms of the number of clusters per volume, i.e., the particle densities ρ_{AZ}, or of mass fractions ω_{AZ}, as

$$K_c(A,Z) = \frac{\rho_{AZ}}{\rho_{11}^{Z}\rho_{10}^{A-Z}} = \frac{\omega_{AZ}}{A\omega_{11}^{Z}\omega_{10}^{A-Z}}\rho_B^{-(A-1)}. \quad (1)$$

An experimental measurement of such constants requires the detection of particles and clusters from a statistical ensemble of sources, and an estimation of the associated thermodynamic parameters (T,ρ_B,y_p).

Under the assumption that chemical equilibrium holds at the different time steps of the emission from the expanding source produced in central ^{136,124}Xe + ^{124,112}Sn collisions, the Coulomb corrected particle velocity $v_{\rm surf}$ in the source frame can be used to select statistical ensembles of particles corresponding to different emission times, and therefore different thermodynamic conditions [12]. A detailed comparison between the four reactions was performed in Ref. [19], verifying the statistical character of the emission. A strong argument confirming the crucial hypothesis of chemical equilibrium as a function of time was given in Ref. [18], observing that the extracted thermodynamic parameters as a function of $v_{\rm surf}$ are independent of the entrance channel of the reaction.

The detected multiplicities $Y_{AZ}(v_{\rm surf})$ allow a direct experimental determination of the mass fractions $\omega_{AZ} = AY_{AZ}/A_T$, as well as of the total source mass $A_T(t)$ as a function of the emission time, but the measurement of the baryonic density $\rho_B(t) = A_T/V_T$ additionally requires an estimation of the source volume, at the different times of the expansion. This latter is given by the free volume V_f with the addition of the proper volume V_{AZ} of the clusters which belong to the source at a given time, $V_T = V_f + \sum_{AZ} V_{AZ}\omega_{AZ}A_T/A$, with $V_{AZ} = 4\pi R_{AZ}^3/3$, where R_{AZ} is the experimental radius of each cluster.

The free volume can be extracted from the differential cluster spectra $\tilde{Y}_{AZ}(\vec{p}) = Y_{AZ}(v_{\rm surf})/(4\pi p^2\Delta p)$, which can be related to differential cluster densities as $f_{AZ}(\vec{p}) = \tilde{Y}_{AZ}(\vec{p})/V_f$ [12,18]. Supposing an ideal gas of classical clusters with binding energies B_{AZ} in thermodynamic equilibrium at temperature T in the grand-canonical ensemble, the differential mass densities read:

$$f_{AZ}^{\rm id}(\vec{p}) = \frac{g_{AZ}}{h^3}\exp\left[\frac{1}{T}\left(B_{AZ} - \frac{p^2}{2M_{AZ}} + Z\mu_p + N\mu_n\right)\right], \quad (2)$$

with $M_{AZ} = Am - B_{AZ}$, $g_{AZ} = 2S_{AZ}+1$ the mass and spin degeneracy of cluster (A,Z), m the nucleon mass, and the superscript stands for "ideal." In-medium effects are expected to suppress the cluster densities [14], with respect to Eq. (2), $\rho_{AZ} = C_{AZ}\rho_{AZ}^{\rm id}$, where the in-medium correction $C_{AZ} < 1$ can depend on the thermodynamic conditions, the cluster species, and their momentum [14]. If we normalize the cluster spectrum by the proton and neutron spectra at the same velocity, the unknown chemical potentials $\mu_{n,p}$ cancel, and the free volume V_f can be independently estimated from the different cluster species as

$$V_f = h^3 R_{np}^{(A-Z)/(A-1)} C_{AZ} \times \exp\left[\frac{B_{AZ}}{T(A-1)}\right]\left(\frac{g_{AZ}}{2^A}\frac{\tilde{Y}_{11}^A(\vec{p})}{\tilde{Y}_{AZ}(A\vec{p})}\right)^{1/(A-1)}, \quad (3)$$

where the free neutron-proton ratio R_{np} is estimated from the multiplicities of the $A=3$ isobars, $R_{np} = (Y_{31}/Y_{32})\exp[(B_{32}-B_{31})/T]$, and B_{AZ} are the experimentally known vacuum binding energy of the clusters.

The presence of in-medium corrections is clearly confirmed by the experimental data, as shown by Fig. 1, which displays the value of the free volume obtained from Eq. (3) for the ^{124}Xe + ^{112}Sn system, using different particle species. A clear hierarchy is observed as a function of the cluster mass if $C_{AZ} = 1$ is assumed, corresponding to the ideal gas limit. It is clear from Eq. (3) that to have consistent estimations of the volume, the deuteron requires a larger correction with respect to the heavier He isotopes. The volume splitting increases with decreasing $v_{\rm surf}$, showing that the in-medium effects additionally depend on the thermodynamic conditions. Fully compatible results are obtained from the other three datasets (not shown).

The correction factors C_{AZ} are, therefore, introduced as a modification of the cluster binding energies due to the presence of the medium. We introduce a very general four-parameters expression as

$$C_{AZ}(\rho_B,y_p,T) = \exp\left[-\frac{a_1A^{a_2} + a_3|I|^{a_4}}{T_{\rm HHe}(A-1)}\right], \quad (4)$$

where the temperature is estimated through the isobaric double isotope ratio Albergo formula [21], and it is indicated

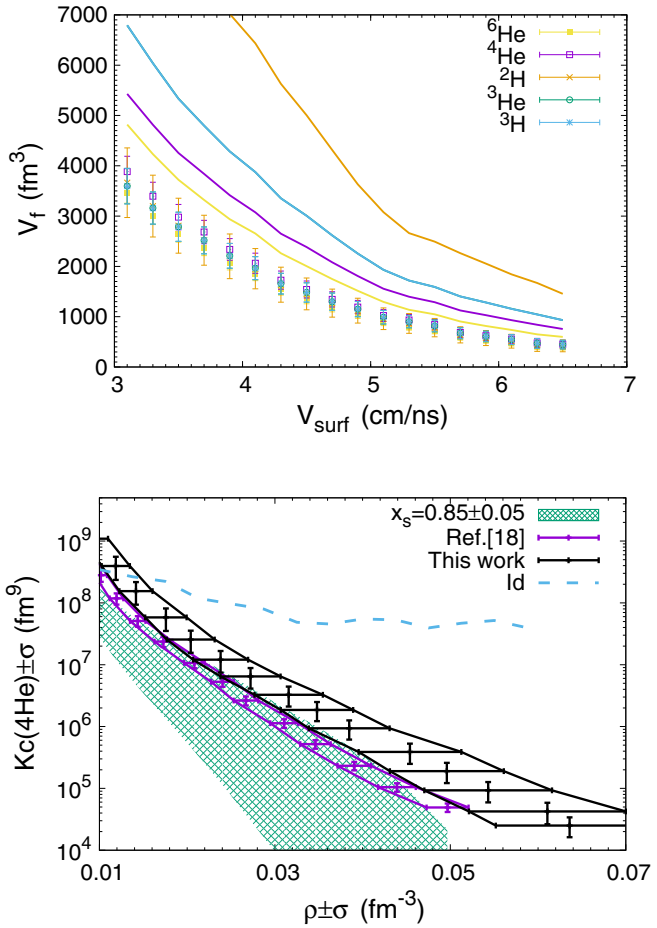

FIG. 1. System ^{124}Xe + ^{112}Sn. Top: Free volume estimated from the different clusters as a function of $v_{\rm surf}$ from Eq. (3). Lines show the ideal gas limit $C_{AZ} = 1$. Note that the lines of ^{3}H and ^{3}He overlap. Symbols show the Bayesian determination of the in-medium correction. Bottom: Chemical equilibrium constant of ^{4}He as a function of the density, estimated from the data with the ideal gas prescription for the volume (lower set of points) and with the corrected one (upper set). For comparison, the predictions of Ref. [20] with a coupling such as to fit the uncorrected results from Ref. [12] are shown as a continuous band labeled $x_s = 0.85 \pm 0.05$, and the ideal gas prediction is shown by a dashed line.

as $T_{\rm HHe}$. The unknown parameters $\vec{a} = \{a_i(\rho_B, y_p, T), i = 1\text{–}4\}$ are taken as random variables, with a probability distribution fixed by imposing that the volumes obtained from the experimental spectra $\tilde{Y}_{AZ}$ of the different (A, Z) nuclear species in a given $v_{\rm surf}$ bin correspond to compatible values. To minimize the *a priori* assumptions, we take in each $v_{\rm surf}$ bin uninformative flat priors, $P_{\rm prior}(\vec{a}) = \theta(\vec{a}_{\rm min} - \vec{a}_{\rm max})$, within an interval largely covering the physically possible reduction range of the binding energy, $0 \le a_1 \le 15$ MeV, $0 \le a_3 \le a_1$, $-1 \le a_2 \le 1$, $0 \le a_4 \le 4$.

The posterior distribution is obtained by imposing the volume observation with a likelihood probability as follows:

$$P_{\rm post}(\vec{a}) = \mathcal{N} \exp\left(-\frac{\sum_{AZ}[V_f^{(AZ)}(\vec{a}) - \bar{V}_f(\vec{a})]^2}{2\bar{V}_f(\vec{a})^2}\right). \quad (5)$$

Here, $\mathcal{N}$ is a normalization, $V_f^{(AZ)}(\vec{a})$ is the free volume obtained from the (A, Z) cluster using Eq. (3) with the specific choice $\vec{a}$ for the parameter set of the correction, and $\bar{V}_f(\vec{a})$ is the volume corresponding to a given parameter set $\vec{a}$, averaged over the cluster species.

The posterior expectation values of the volume as estimated from the multiplicities of each cluster from Eq. (3), with the associated standard deviations, are shown as symbols in Fig. 1. It is clear that when we include the correction, the volumes decrease and the estimations obtained from the different cluster species are compatible within error bars. Concerning the functional dependence of the correction, we can observe that we have as many parameters as different independent volume estimations, meaning that we are allowing independent corrections for the different nuclear species. It would be interesting to have chemical constant measurements for other nuclear species, such as to check if a universal dependence of the in-medium effects on A and I, as it is supposed in different theoretical models [15–17], is supported by the data.

The bottom panel of Fig. 1 shows the corresponding modification of the ^{4}He chemical equilibrium constant in the system ^{124}Xe + ^{112}Sn. Similar results are obtained for the other particles and the other systems (not shown). In this figure, the standard deviations associated to the experimental equilibrium constants are joined by full lines. The estimation with $C_{AZ} = 1$ as in Ref. [12], already shown in Ref. [18], is given by the lower set of points [22], while the higher dataset gives the result employing the posterior distribution of C_{AZ} from Eq. (5). We can see that both the average and the standard deviation of the estimation are increased. Concerning the effect on the average, a reduction of the volume corresponds to an increase of the baryonic density, up to a factor of 2, and therefore an increase of the chemical equilibrium constants with respect to the estimation employing the ideal gas assumption [see Eq. (1)]. Concerning the variance, while in the previous analysis no experimental error was associated to the volume estimation, the Bayesian determination of the volume distribution allows a more realistic estimation of the systematic uncertainties of both density and chemical constants, with increased error bars. Realistic uncertainties might be even slightly larger on the low-density side, because we cannot exclude that the in-medium effects could lead to an increased proper size of the clusters V_{AZ}. The results of the different systems almost perfectly overlap, confirming the expectation that chemical constants are isospin independent (not shown). If we compare the experimental chemical constants with the ideal gas expectation Eq. (2) (dashed line in Fig. 1), we can observe an important suppression of ^{4}He clusters at high density. But this

suppression is less pronounced than the one obtained with the previous analysis, with important consequences on the present estimation of in-medium effects for theoretical applications in the astrophysical context, as we now discuss.

In Ref. [17], a novel approach for the inclusion of in-medium effects in the equation of state for warm stellar matter with light clusters was introduced. This model includes a phenomenological modification in the scalar cluster-meson coupling, and includes an extra term in the effective mass of the clusters, which acts as an exclusion-volume effect. The scalar coupling acting on nucleons bound in a cluster of mass A is defined as $g_s(A) = x_s A g_s$, with g_s the scalar coupling of homogeneous matter, and x_s a free parameter. A constraint on this parameter was obtained in the low-density regime from the virial EOS, but a precise determination of x_s needs an adjustment at densities close to the Mott density corresponding to the dissolution of clusters in the medium. The parameter x_s measures how much the medium affects the binding of the cluster. The smaller the x_s, the stronger the in-medium effect, and the smaller the dissolution density of the cluster.

The chemical equilibrium constants obtained with this model were compared with the NIMROD results [12] obtained assuming an ideal gas expression for the determination of the nuclear density [17,20], and a satisfactory agreement was obtained for all clusters but the deuteron using $x_s = 0.85 \pm 0.05$.

The prediction of this model is shown, for the thermodynamic conditions explored by the Xe + Sn systems, in the bottom panel of Fig. 1. We can see that the calculation can reproduce the INDRA data only if these latter are analyzed using the same hypotheses as in Ref. [12] (lower set of points). This suggests that the two sets are compatible, which points toward the validity of the statistical equilibrium hypothesis for both of them. However, it is also clear that the estimation $x_s = 0.85 \pm 0.05$ overestimates the in-medium effects, once the consistent inclusion of the C_{AZ} is accounted for.

To estimate the effect of the correction, and, at the same time, determine the value of the in-medium parameter x_s in a consistent way, we have compared the model of Refs. [17,20] with this new analysis.

In order to make this comparison, we fix the temperature in each (ρ_B, y_p) point by imposing that the isotopic thermometer T_{HHe} evaluated in the theoretical model correctly reproduces the measured T_{HHe} value. A small difference between the input temperature of the theory and the one estimated in the same calculation via the double ratios is obtained, which does not exceed 10% at the highest temperature. Indeed, the Albergo thermometer [21] used to estimate the temperature is only valid under the assumption that the in-medium corrections to Eq. (2) cancel in double isobar ratios, which is, in principle, not the case, if the correction does not scale linearly with the particle numbers. The resulting chemical constants are compared to the experimental ones in Fig. 2. As we can observe, the deuteron chemical constant behavior is now reproduced, and the chemical constants of ^{3}He and ^{3}H are almost superposed. Very similar results are obtained for the other two experimental entrance channels (not shown).

In Refs. [17,20], we used $x_s = 0.85$ in order to reproduce the results of Qin *et al.* [12]. With this improved analysis, a higher value $x_s > 0.85$ is needed, corresponding to smaller corrections and a larger dissolution density. An optimal value can be extracted as $x_s = 0.92 \pm 0.02$. This value seems to reproduce reasonably well the whole set of experimental constants, and we have checked that it is still within the virial EOS limits. This can be understood from the fact that the virial limit only concerns very low densities, where the predictions with the two different values of x_s are very close (see Fig. 1).

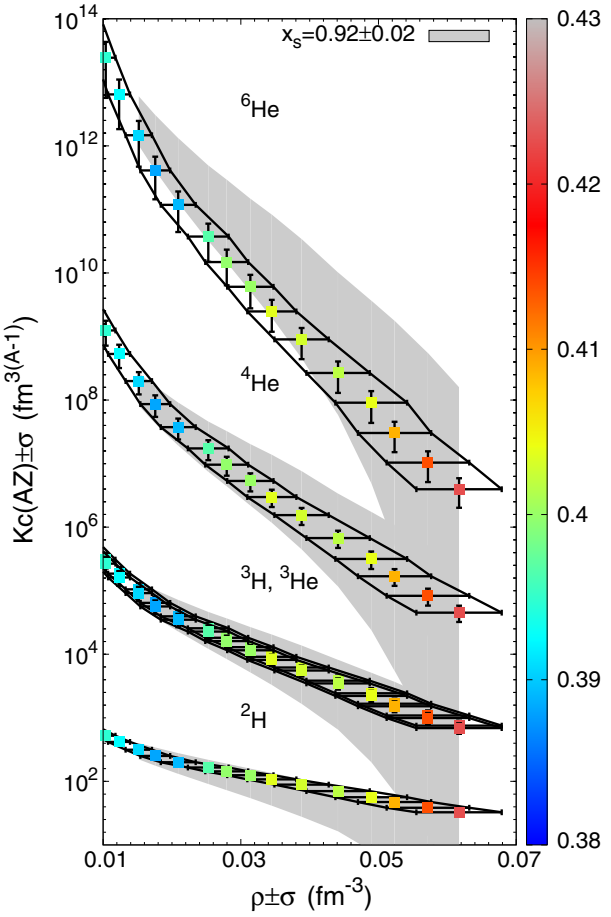

FIG. 2. System ^{136}Xe + ^{124}Sn. The equilibrium constants as a function of the density. The full lines join the $1-\sigma$ uncertainty intervals. The gray bands are the equilibrium constants from a calculation [20] where we consider homogeneous matter with five light clusters, calculated at the average value of (T, ρ_{exp}, $y_{pg_{\mathrm{exp}}}$), and considering cluster couplings in the range of $x_{s_i} = 0.92 \pm 0.02$. The color code represents the global proton fraction.

TABLE I. The experimental density and temperature from Ref. [12], and the theoretical calculation of the chemical equilibrium constant for the α particle, with two different scalar cluster-meson couplings.

		$K_c(^4\mathrm{He})$ (fm^9)	$K_c(^4\mathrm{He})$ (fm^9)
ρ (fm^{-3})	T (MeV)	$x_s = 0.85$	$x_s = 0.92$
0.003	5.1	0.22×10^{10}	0.36×10^{10}
0.005	5.6	0.58×10^{9}	0.12×10^{10}
0.007	6.1	0.20×10^{9}	0.49×10^{9}
0.009	6.5	0.59×10^{8}	0.19×10^{9}
0.013	7.3	0.14×10^{8}	0.58×10^{8}
0.015	7.8	0.59×10^{7}	0.29×10^{8}
0.018	8.3	0.24×10^{7}	0.14×10^{8}
0.021	9.0	0.10×10^{7}	0.69×10^{7}
0.022	9.5	0.62×10^{6}	0.45×10^{7}
0.025	10.0	0.34×10^{6}	0.27×10^{7}
0.026	10.4	0.23×10^{6}	0.20×10^{7}

The effect of the different estimation for the scalar coupling can be better appreciated from Table I, which reports the predictions of the model for the (ρ_B, T, y_p) trajectory estimated in Ref. [12], for which a large set of models and model assumptions was tested in Ref. [16]. We can see that if we impose the consistent analysis of the INDRA dataset as a new constraint, the theoretical model predictions for the chemical constants (last column) increase by a factor of $\approx$1.5–10, increasing with the density. This points toward smaller in-medium modifications than the ones extracted from the previous results in Ref. [16].

In conclusion, a new analysis was performed based on INDRA data presented in Ref. [18]. We have shown that the presence of in-medium effects suppressing the cluster yields is necessary to explain the experimental data, giving rise to larger baryonic densities compared to the ideal gas limit. The reduction factors were directly extracted from the data, under the unique condition that the different nuclear species in a given sample must correspond to a unique common value for the density of the expanding source. We have verified that the three different datasets lead to fully compatible results for the corrections. In the framework of a relativistic mean-field theoretical model [17,20], these corrections can be interpreted as a stronger scalar meson coupling of the nucleons bound in clusters, which shifts the dissolution to higher densities.

In a future work, it would be extremely interesting to perform a new analysis of the experimental data of Ref. [12], with the same method as the one presented in this Letter, in order to check the consistency of the different datasets, and to settle the model dependence of the results.

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[1] M. Oertel, M. Hempel, T. Klähn, and S. Typel, Rev. Mod. Phys. **89**, 015007 (2017).
[2] M. Hempel, M. Oertel, S. Typel, and T. Klähn, J. Phys. Soc. Conf. Proc. **14**, 010802 (2017).
[3] A. Arcones, G. Martínez-Pinedo, E. O'Connor, A. Schwenk, H.-T. Janka, C. J. Horowitz, and K. Langanke, Phys. Rev. C **78**, 015806 (2008).
[4] K. Sumiyoshi and G. Röpke, Phys. Rev. C **77**, 055804 (2008).
[5] T. Fischer, M. Hempel, I. Sagert, Y. Suwa, and J. Schaffner-Bielich, Eur. Phys. J. A **50**, 46 (2014).
[6] S. Furusawa, H. Nagakura, K. Sumiyoshi, and S. Yamada, Astrophys. J. **774**, 78 (2013).
[7] S. Furusawa, K. Sumiyoshi, S. Yamada, and H. Suzuki, Nucl. Phys. **A957**, 188 (2017).
[8] A. Bauswein, S. Goriely, and H.-T. Janka, Astrophys. J. **773**, 78 (2013).
[9] S. Rosswog, Int. J. Mod. Phys. D **24**, 1530012 (2015).
[10] CompOSE databse, https://compose.obspm.fr/.
[11] M. Hempel, T. Fischer, J. Schaffner-Bielich, and M. Liebendöerfer, Astrophys. J. **748**, 70 (2012).
[12] L. Qin, K. Hagel, R. Wada, J. B. Natowitz, S. Shlomo *et al.*, Phys. Rev. Lett. **108**, 172701 (2012).
[13] K. Hagel, R. Wada, L. Qin, J. B. Natowitz, S. Shlomo *et al.*, Phys. Rev. Lett. **108**, 062702 (2012).
[14] G. Röpke, Phys. Rev. C **92**, 054001 (2015).
[15] S. Typel, G. Röpke, T. Klähn, D. Blaschke, and H. H. Wolter, Phys. Rev. C **81**, 015803 (2010).
[16] M. Hempel, K. Hagel, and J. Natowitz, G. Röpke, and S. Typel, Phys. Rev. C **91**, 045805 (2015).
[17] H. Pais, F. Gulminelli, C. Providência, and G. Röpke, Phys. Rev. C **97**, 045805 (2018).
[18] R. Bougault *et al.*, J. Phys. G **47**, 025103 (2020).
[19] R. Bougault, E. Bonnet, B. Borderie, A. Chbihi, D. Dell'Aquila *et al.*, Phys. Rev. C **97**, 024612 (2018).
[20] H. Pais, F. Gulminelli, C. Providência, and G. Röpke, Phys. Rev. C **99**, 055806 (2019).
[21] S. Albergo, S. Costa, E. Constanzo, and A. Rubbino, Nuovo Cimento A **89**, 1 (1985).
[22] It has to be noted that the definition of chemical constants in Ref. [18] differs by a factor A with respect to the one of Refs. [12,14,17]. To allow an easier comparison with previous works, we have here adopted the definition of Ref. [12]. Because of the different definitions, in Fig. 9 of Ref. [18], the NIMROD data should have been multiplied by a factor A for a direct comparison.