IL NUOVO CIMENTO **42 C** (2019) 96
DOI 10.1393/ncc/i2019-19096-7

Colloquia: EuNPC 2018

Relevance of neutron excess in nuclear matter to proton-induced composite-particle pre-equilibrium emission

A. A. Cowley
Department of Physics, Stellenbosch University - Private Bag X1, Matieland 7602, South Africa

received 5 February 2019

Summary. — Formulation of the equation of state (EoS) of nuclear matter has far-reaching implications for issues ranging from the atomic nucleus to crucial aspects of astrophysics. Recent investigations of the influence of the formation of light ion clusters on the development of the EoS are of interest. A study based on a generalized relativistic mean-field model revealed an isotope-dependant quenching of α-clustering on the surface of Sn as the nuclear system becomes more asymmetric. This trend of decreasing α-clustering with increasing mass number of Sn was previously found to be consistent with existing experimental results of an α-pickup reaction. The implications of predictions of the EoS are discussed as being of profound interest to proton-induced α-particle pre-equilibrium emission at incident energies above about 100 MeV.

1. – Introduction

It is recognized that the equation of state (EoS) of nuclear matter is of relevance to a large range of topics in nuclear physics, astrophysics and cosmology. Introduction of light-ion clusters [1] in the nuclear medium, and their formation and disassociation under varying conditions of density and temperature, proves to be especially interesting. Typel *et al.* [1] systematically investigated dynamical properties of these light-ion clusters by means of a microscopic quantum statistical (QS) approach, as well as the alternative generalized relativistic mean-field (RMF) model. The interplay between conditions of the nuclear medium and cluster response naturally leads to an RMF prediction [2] of cluster formation on the surface of Sn isotopes. Of course, the neutron skin thickness is also expected to change concurrently as a function of isotopic mass number.

Cowley [3] found that existing experimental α-pickup data [4] appears to confirm the EoS prediction [2] that α-clustering should smoothly decrease with increasing neutron-proton asymmetry of Sn isotopes.

The reaction mechanism of proton-induced α-particle pre-equilibrium emission at incident energies in the region above about 100 MeV has recently been explored [5-9]. Based on this new insight, and as discussed in this paper, it is speculated that an isotopic

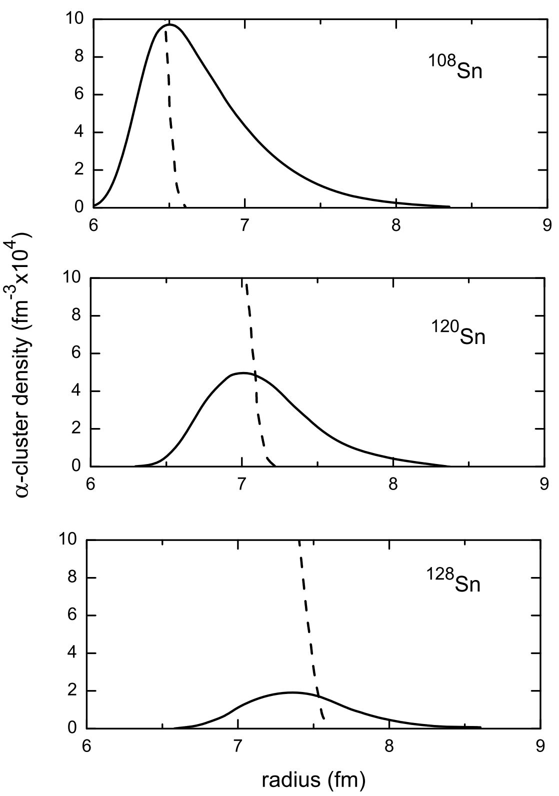

Fig. 1. – Radial density distribution of α-clusters (continuous curves) and neutrons (dashed curves) for isotopes of Sn. Representative examples were selected from the full set of Ref. [2] and they are displayed differently here for improved clarity.

variation of the degree of α-clustering in Sn should manifest prominently in those types of pre-equilibrium reactions. It is suggested that the series of stable Sn nuclear targets could provide further valuable guidance regarding the interplay between three-particle pickup and α-cluster knockout in the mechanism of pre-equilibrium reactions.

2. – Clustering in the EoS

Typel [2] finds that the radial distribution of α-clusters in Sn is concentrated where the density distribution of the neutron skin drops to appropriate low levels. Of course, this varies with the atomic number of the Sn isotopes. In Fig. 1 selected examples are shown, for clarity of display, from the complete set presented in Ref. [2].

As the atomic mass of Sn increases, Fig. 1 indicates the growing radial extent of the neutron distribution (shown as dashed lines only in the extreme range where the neutron density approaches small values.) In the displayed range the α-clusters manifest their presence also, roughly tracking the growing radius of neutrons, but with a weakening maximum density with increasing Sn mass number. The nuclear mass asymmetry therefore strongly influences the α-clustering probability.

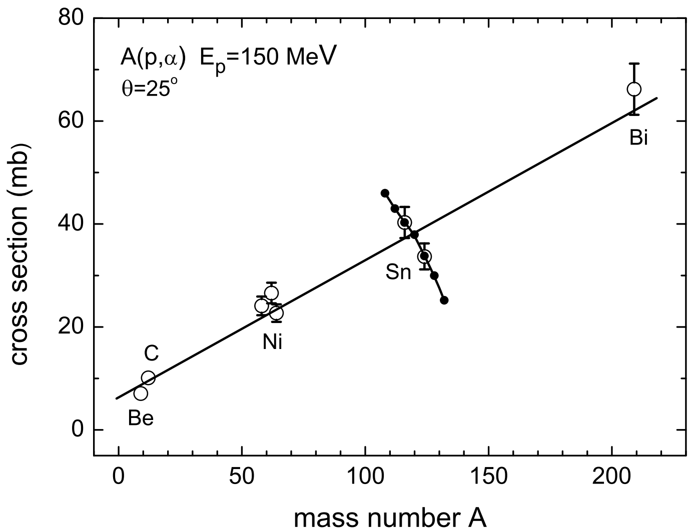

Fig. 2. – Emission-energy integrated cross sections [10] for the (p,α) pre-equilibrium reaction. (Open circles with error bars). Predicted numbers of α-clusters [2] (smaller solid symbols without error bars) are adjusted to the trend suggested by the experimental values of two Sn isotopes.

3. – Influence of α-clustering on (p,α) pre-equilibrium reaction cross sections

It has been known for many years that the mechanism of (p,α) pre-equilibrium reactions can be understood in the framework of the quantum mechanical statistical multistep pre-equilibrium model [11]. However, the competition between triton pickup (or more correctly, three-particle pickup) and α-cluster knockout in the reaction mechanism was perhaps not fully appreciated before recent studies [5-9].

For pre-equilibrium reactions, especially of the (p,α) type, analyzing power, which is accessible as an observable with polarized proton projectiles, is much more sensitive to the mechanism involved in a nuclear reaction than the cross section. Recent (p,α) studies [5, 7] with polarized projectiles reveal individual cases where either knockout or pickup dominates the reaction mechanism, whereas sometimes those processes contribute about equally. The specific result depends on incident energy, as well as nuclear species and the cause is understood in principle. For example, the reason why ^{93}Nb(p,α) changes from totally dominated by knockout at an incident energy of 65 MeV to mostly due to pickup at 100 MeV was shown [5] to be consistent with the kinematics involved in the reaction process and its influence on the basic distorted wave component of the theory.

In the case of Sn it is anticipated that for the isotope with the largest α-cluster preformation probability, knockout should be prominent. A large cross section contribution from that process would follow. With lower clustering from heavier masses, the cross section for knockout would drop. How an additional contribution from pickup would affect the overall result depends on the three-particle spectroscopic factor.

An estimate of the possible observed trend with target mass is illustrated in Fig. 2. The integrated yield for (p,α) pre-equilibrium reactions [10] at a scattering angle of 25° and various targets at an incident energy of 150 MeV is plotted. The trend predicted [2] by the EoS is adjusted in the figure as normalized to the experimental yields for ^{116}Sn and ^{124}Sn. The assumption to justify the normalization is that the α-cluster number is directly proportional to the knockout cross section yield. Of course, this normalization to the experimental data ignores the effect of any contribution from pickup in a pre-equilibrium reaction.

The result in Fig. 2 encourages a study of the (p,α) reaction on various isotopes of Sn. For a better understanding of the process it would by wise to measure the analyzing power also in order to confirm the reaction mechanism, which could change somewhat for different isotopes of Sn.

4. – Summary and conclusion

Inclusion of light clusters in a formulation of the equation of state of nuclear matter (EoS) is known [2] to predict a quenching of ground-state α-clustering with increasing neutron-proton asymmetry of different Sn isotopes. This expectation seems to be reliable, because previously it was shown [3] to be consistent with spectroscopic information extracted from existing [4] data of a (d,^{6}Li) pickup reaction. Based on current insight on the mechanism of (p,α) pre-equilibrium reactions it is suggested that this variation in cluster preformation should be explored further. The interplay between competing α-cluster knockout and three-particle pickup in pre-equilibrium reactions is expected to influence cross section and analyzing power angular distributions prominently as a function of mass asymmetry in Sn. Further detailed insight into the reaction mechanism should follow from this.

* * *

This work is based on the research supported in part by the National Research Foundation of South Africa (Grant Number 115020). This funding is gratefully acknowledged.

REFERENCES

[1] Typel S., Röpke G., Klähn T., Blaschke D. and Wolter H. H., *Phys. Rev. C*, **81** (2010) 015803.
[2] Typel S., *Phys. Rev. C*, **89** (2014) 064321.
[3] Cowley A. A., *Phys. Rev. C*, **93** (2016) 054329.
[4] Jänecke J., Becchetti F. D. and Thorn C. E., *Nucl. Phys. A*, **325** (1979) 337.
[5] Cowley A. A., Dimitrova S. S., Zemlyanaya E. V., Lukyanov K. V. and Van Zyl J. J., *Phys. Rev. C*, **93** (2016) 034624.
[6] Dimitrova S. S., Cowley A. A., Van Zyl J. J., Zemlyanaya E. V. and Lukyanov K. V., *Phys. Rev. C*, **89** (2014) 034616.
[7] Dimitrova S. S., Cowley A. A., Zemlyanaya E. V. and Lukyanov K. V., *Phys. Rev. C*, **90** (2014) 054604.
[8] Cowley A. A., Dimitrova S. S., Zemlyanaya E. V., Lukyanov K.V. and Van Zyl J. J., *EPJ Web of Conferences*, **107** (2016) 08004.
[9] Dimitrova S. S., Cowley A. A., Zemlyanaya E. V. and Lukyanov K. V., *EPJ Web of Conferences*, **107** (2016) 08005.
[10] Segel R., Levensen S. M., Zupranski P., Hassan A. A., Mukhopadhyay S. and Maher J. V., *Phys. Rev.C*, **32** (1985) 721.
[11] Feshbach H., Kerman A. and Koonin S., *Ann. Phys. (NY)*, **125** (1980) 429.