Available online at www.sciencedirect.com

ScienceDirect

Nuclear Physics A 928 (2014) 276–295

NUCLEAR PHYSICS A

www.elsevier.com/locate/nuclphysa

Symmetry energy in nuclei and neutron stars

James M. Lattimer [a,b,*]

[a] *Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA*
[b] *Yukawa Institute of Theoretical Physics, Kyoto 606-8317, Japan*

Received 5 April 2014; accepted 8 April 2014

Available online 23 April 2014

Abstract

The symmetry energy plays an important role in nuclear astrophysics, ranging from the structure of nuclei to gravitational collapse to neutron stars. The BBAL paper by Bethe, Brown, et al., was among the first to recognize its importance. The role of the symmetry energy has evolved since that time when it represented one of the major uncertainties in modeling the equation of state of dense nuclear matter. At present, the parameters of the nuclear symmetry energy are tightly constrained by a concordance achieved from nuclear experiment, astrophysical observations, and *ab initio* theoretical calculations of neutron matter.

Keywords: Nuclear matter; Neutron matter; Equation of state; Neutron stars; Supernovae

1. Introduction

The symmetry energy of nuclear matter can be defined as the difference between the energies of pure neutron and symmetric nuclear matter as a function of density. However, there are alternative definitions in the literature, most usually as the quadratic coefficient of an expansion of the energy in neutron excess. To be definite, we shall write

$$S(n) = E(n, 1/2) - E(n, 0); \qquad S_2(n) = \frac{1}{8}\left(\frac{\partial^2 E(n, x)}{\partial x^2}\right)_{x=1/2} \tag{1}$$

* Address for correspondence: Department of Physics & Astronomy, Stony Brook University, Stony Brook, NY 11794-3800, USA.

http://dx.doi.org/10.1016/j.nuclphysa.2014.04.008

where $E(n,x)$ is the energy per baryon of uniform nuclear matter with baryon density n and proton fraction x. In Eq. (1), $S(n)$ is the nuclear symmetry energy and $S_2(n)$ is the symmetry energy to second order in a symmetry expansion. Evaluated at the usual nuclear saturation density, $n_s \simeq 0.16\ \mathrm{fm}^{-3}$ or $\rho_s \simeq 2.7 \times 10^{14}\ \mathrm{g\,cm}^{-3}$, we have $S_2(n_s) \equiv S_v$ where S_v is the volume symmetry energy in the liquid drop model. Because of symmetries in the nuclear force, only even powers of neutron richness, $1-2x$, appear in the symmetry energy expansion. If higher order terms (i.e., quartic) in a symmetry expansion of E are negligible, then $S_2(n) \simeq S(n)$ and the energy of pure neutron matter is given simply by $E(n,0) = S_2(n) - E(n,1/2)$. However, this need not be the case, and recent theoretical investigations of neutron and neutron-rich matter [1] provide evidence to suggest that higher order terms in the symmetry energy expansion are not completely negligible. We shall return to this point in Sections 4 and 5.

It is important that the symmetry energy has a density dependence. It is useful to further expand S_2 in powers of density near the saturation density:

$$S(n) \simeq S_v + \frac{L}{3}\left(\frac{n-n_s}{n_s}\right) + \frac{K_{sym}}{18}\left(\frac{n-n_s}{n_s}\right)^2 + \cdots \tag{2}$$

Then, assuming higher-than-quadratic terms are ignored, the neutron matter energy at the saturation density is determined by standard nuclear parameters, $E(n_s,0) = B + S_v$. The L parameter is especially important. For example, if $S \simeq S_2$, then the pressure of pure neutron matter at the saturation density is $p(n_s,0) = Ln_s/3$. The parameters S_v and L can be extracted from nuclear experiments, as will be discussed in Section 3.2. The parameter K_{sym} is more difficult to determine from experiments and is not well known. Fortunately, it does not seem to play a major role in the determination of the other parameters from experiment and observations, but this remains to be fully checked.

The symmetry energy plays an important role in many aspects of nuclear physics and astrophysics. Experimental evidence for it was first suggested by the semi-empirical mass formula of Bethe and von Weizsäcker and Bethe [2], which resembles a liquid drop model, contained a term with a coefficient $S_v \sim 25$ MeV, and proportional to AI^2, that represented the volume symmetry energy decrease in binding with increasing asymmetry $I = (N-Z)/(N+Z)$. Later, Myers and Swiatecki [3] refined the drop model by introducing a surface symmetry term, $-S_s A^{2/3} I^2$, representing the decrease in the total symmetry energy due to the fact that some nucleons are in the nuclear surface at lower densities than the interior. When they further refined their model, formulating the liquid droplet model [4] in order to account for the different distributions of neutrons and protons in the nucleus, and to explain the existence of neutron skins on nuclei, the total symmetry energy became written as

$$S_v A I^2 \left(1 + \frac{S_s A^{-1/3}}{S_v}\right)^{-1}. \tag{3}$$

Fits to binding energies suggest that $S_v \sim 30$ MeV and $S_s \sim 45$ MeV, the decrease in S_v being due to the surface energy. However, the precise values of these coefficients cannot be determined from binding energies alone because the range of $A^{1/3}$ of laboratory nuclei is too small. At best, a strong correlation between S_v and S_s can be obtained. In Section 3.1 we will formulate a simple description of nuclei beginning from basic principles that is able to explain a wide variety of nuclear phenomena, including binding energies, dipole polarizabilities, and neutron skin thicknesses. Importantly, we can show that these phenomena predict different trends for the correlations between S_s and S_v. Comparing these to data allows a more precise determination of S_v and S_s. Furthermore, this model also allows the determination of a relatively accurate prediction