The role of isospin in fusion evaporation reactions

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Abstract. The isospin dependence of the level density, both through the level density parameter and the symmetry energy contribution has been evaluated. The effects on the most relevant observables in fusion evaporation reactions have been estimated by using the statistical model. We present here the results for the $^{134}$Sn + $^4$He reaction, whose measurement will be possible with the second generation RIB facilities SPES and SPIRAL2. Sizeable effects are predicted on the light particle energy spectra and multiplicities and evaporation residue distribution. In particular, the measure of evaporation residue yields and light particle multiplicities are expected to unfold the two effects. In addition, the same calculations have been carried out for reactions induced by stable beams, in order to search for clues of isospin effects. In this case, the direct comparison of the experimental light charged particle energy spectra for the two reactions $^7$Li+$^{58,64}$Ni at the same excitation energy and angular momentum, is proposed as a good approach to observe isospin effects.

1. Introduction

The nuclear level density is an important ingredient in the statistical model to calculate rates and other properties of compound nucleus reactions. Although much work has been devoted to study this quantity, it still remains uncertain in different regions of mass and excitation energy. Usually one starts from the Bethe formula [1] based on an energy independent level density of single particle states, where isospin effects are neglected. Interest in studying this quantity for exotic nuclei, as those that will be produced by the second generation RIB facilities, is growing up, as the level density is expected to depend on isospin. Recently, an expression of the level density parameter in terms of the distance of the nucleus from the stability line has been proposed [2, 3] and supported by the realistic calculations of Grimes and collaborators [4]. In addition, isospin effects are expected also through the symmetry energy contribution to the nuclear masses which has been usually neglected, although variations of the symmetry energy have strong implications in nuclear astrophysics. Therefore, new experiments are foreseen to look for these effects. In this framework we have undertaken a research project to study both the isospin effects in systems which will be produced by the second generation exotic beams, but also in systems now available with stable beams, using as a probe the evaporative light charged particles (LCPs). In a previous paper [5] we have shown some results on neutron rich nuclei, whose production will be possible by the SPES facility using a $^4$He target. The ratio

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of the 1n to the 2n cross section appears to be sensitive to the different isospin dependences of the level density parameter. On the other hand, light particle multiplicities are sensitive to the symmetry energy contribution. Here, we will present more detailed results of the statistical model simulations for the reaction $^{134}$Sn + $^4$He and, in addition, for the $^7$Li + $^{58,64}$Ni reactions induced by a stable beam.

2. Isospin effects on the level density parameter $a$ and symmetry energy

The level density parameter $a$ appearing in the Bethe formula has been studied at low and high excitation energy. It results that this parameter changes from $A/8.5\text{MeV}^{-1}$ to $A/15\text{MeV}^{-1}$, as supported by several observations [6]. With this description of the level density, the statistical model proved to be able to reproduce most of the data of studied reactions with stable beams.

In the framework of the Fermi-gas model the isospin effects on the level density can be taken into account including a factor related to the isospin component $T_3 = (N - Z)/2$ [7].

Recently, the analysis of an extended set of level density data [7] for nuclei with $20 < A < 110$ has been carried out [2, 3]. Different isospin dependences of the level density parameter $a$ have been tested (Tab.1), where Zo is the atomic number of the $\beta$–stable isobar. The values of $\alpha$, $\beta$

| parameter | expression | $\alpha_1$ | $\beta$ |
|-----------|------------|------------|--------|
| $N - Z$   | $a = \alpha_2 \cdot A / \exp[\beta(N - Z)^2]$ | 0.1062 | 0.00051 |
| $Z - Zo$  | $a = \alpha_3 \cdot A / \exp[\gamma(Z - Zo)^2]$ | 0.1068 | 0.0389 |

and $\gamma$ have been obtained from best fit to the data. The third parametrization provides a better description of the data, predicting a significant reduction of level density for nuclei far from the stability line. This prediction is supported by realistic calculations [4] of the level density of nuclei far from the stability line. The underlining assumption is that the levels of the compound system for nuclei far from the stability line have widths which are large enough to remove them from the category of compound nucleus levels. To have a greater sensitivity to this effect, low excitation energies are more suited, as they limit the contribution of particle emission from nuclei closer to the valley of stability, and can be better analyzed by the statistical model. Bombarding a $^4$He target with medium-mass neutron-rich projectiles, we meet the condition of providing a high fusion cross section at low excitation energy of the composite system. Furthermore, the relatively low angular momenta and excitation energies involved in these reactions are expected to enhance the effects of the isospin on the level density. In order to evaluate these effects we have modified our statistical code (Lilita-N97 [8]) including the three prescriptions given in Tab.1.

As regards the symmetry energy, we used an isospin dependence given by the following formula:

$$E_{\text{sym}}(T) = b_{\text{sym}}(T) \frac{(N - Z)^2}{A}$$

(1)

where $b_{\text{sym}}(T)$ is a functional derived by Donati et al. [9]. In particular, in the frame of the dynamical shell model the symmetry energy increases with increasing of temperature, for $T \leq 3 \text{ MeV}$, due to the decrease of the nucleon effective mass $m^*$. At the same time, this implies a decrease of the level density parameter $a \propto m^*$ [9, 10, 11].

Experimentally, the effects related to the symmetry energy would appear as a change in the particle multiplicity as well as in the relative yields of the compound nucleus decay channels, as it affects the binding energies of the evaporative light particles. As this effect is of the order of
a few MeV in each step of the evaporative chain, relatively low excitation energies are required
in order to observe the effect and perform a test of the current models.

We have included in the statistical model the symmetry energy prescription of Ref.[9] as well
as the temperature dependence of the level density parameter $a$, obtained in the same theoretical
framework [10].

All the statistical model calculations presented in this work have been carried out adopting
the optical model transmission coefficients and the yrast line calculated considering the nucleus
as a rigid sphere with $r_0 = 1.2$ fm.

3. $^{134}$Sn + $^4$He reaction
We report here the results obtained for the reaction $^{134}$Sn + $^4$He, which produces the $^{138}$Te
compound nucleus, adopting different isospin dependences of the level density parameter or
including the symmetry energy contribution or both.

![Figure 1.](image)

**Figure 1.** (Color online) Neutron energy spectra calculated with the three prescriptions of
Tab. 1 for the reaction $^{134}$Sn + $^4$He at a) $E_x = 20$ MeV and b) $E_x = 50$ MeV. Spectra have been
normalized to the maximum to compare the shapes.

In Fig. 1 are reported the simulated neutron energy spectra, obtained adopting the three
prescriptions given in Tab. 1 at two different excitation energies of the compound nucleus ($E_x
= 20$ MeV with $J_{\text{MAX}} = 7h$ and $E_x = 50$ MeV with $J_{\text{MAX}} = 19h$). Significant effects are
observed, indicating the importance of measuring the evaporative neutrons. With the increase
of the excitation energy, channels with a larger number of neutrons will open, and a reduction
of isospin effects will result.

A significant sensitivity to the symmetry energy contribution is observed for the neutron
energy spectra, Fig. 2. We can note that the effects on the neutron spectra of the Z-Zo
prescription and symmetry energy are comparable.

A similar behaviour is also observed for the LCP spectra, but it will be hard to measure them
with the intensity of the second generation RIB facilities.

Predicted multiplicities at $E_x = 50$ MeV for neutrons, protons and alpha particles are shown
in Tab. 2. The effect of Z-Zo prescription is to reduce the neutron multiplicity increasing the
proton one and leaving unchanged the alpha particle multiplicity. As regards the symmetry
energy contribution, the multiplicities show a reduction similar to that produced by Z-Zo for
what it concerns the neutrons, while a very strong enhancement is observed for protons and
alpha particles. In particular, the $E_{\text{sym}}(T) + a(T)$ option promotes the opening of channels
involving LCPs [5], which otherwise would be closed assuming the standard prescription.

Finally, including both effects in the statistical code the difference with respect to the standard
calculations increases for neutrons and protons, but not for alpha particles.
Figure 2. (Color online) Neutron energy spectra calculated with the standard and $E_{\text{sym}}(T) + a(T)$ prescriptions, for the reaction $^{134}\text{Sn} + ^4\text{He}$ at $E_x = 50\text{MeV}$. Spectra have been normalized to the maximum to compare the shapes.

Table 2. Multiplicity of light particles emitted in the decay $^{138}\text{Te}$ at $E_x = 50\text{MeV}$ adopting different prescriptions of the isospin effects.

|               | standard | $Z$-Zo  | $E_{\text{sym}}(T)+a(T)$ | both effects |
|---------------|----------|---------|--------------------------|--------------|
| $M_n$         | 6.03     | 4.87    | 4.43                     | 3.42         |
| $M_p$         | 0.0001   | 0.0004  | 0.0050                   | 0.0057       |
| $M_\alpha$   | 0.005    | 0.005   | 0.071                    | 0.035        |

Figure 3. (Color online) Relative evaporation residue cross sections for the reaction $^{134}\text{Sn}$ on $^4\text{He}$, at $E_x = 50\text{MeV}$. The calculations have been carried out adopting the prescriptions: a) standard, b) $Z$-Zo, c) $E_{\text{sym}}(T) + a(T)$ and d) inclusion of both isospin effects.

In the four panels of Fig.3 we show the relative cross sections of the evaporation residues obtained using the code Lilita_N97 for the reaction $^{134}\text{Sn} + ^4\text{He}$ at $E_x = 50\text{MeV}$, adopting the prescriptions: a) standard, b) $Z$-Zo, c) $E_{\text{sym}}(T) + a(T)$ and d) both isospin effects.

The standard yield is characterized by having the $6n$ channel as the most intense one, while $Z$-Zo produces an enhancement of $5n$ and $4n$ channels with a reduction of $6n$. Coming to the $E_{\text{sym}}(T) + a(T)$ prescription a similar behaviour is observed, but with the $4n$ channel more
intense than the 5n. Combining the two effects d) there is a strong enhancement of the 4n channel and the opening of the 2n channel, all the other channels being depressed. From these results we can conclude that the isospin effects provide significant differences with respect to the standard prescription, and moreover, that evaporation residue yields and particle multiplicities are suitable to disentangle the different effects.

4. Near future experiment with a stable beam

We have explored the possibility to observe clues of isospin effects on fusion-evaporation reactions induced by a stable beam. For this purpose, we have carried out calculations for $^7\text{Li} + ^{58,64}\text{Ni}$ at the beam energies 36.6 MeV and 35.6 MeV, respectively to obtain the same excitation energy $E_x = 50$ MeV and the same maximum angular momentum $J_{\text{MAX}} = 19\hbar$. In the Fig.4, the proton center of mass energy spectra for the two systems are superimposed.

Figure 4. (Color online) Proton energy spectra emitted in the decay of $^{65,71}\text{Ga}$ at $E_x = 50$ MeV. To evidentiate the differences in the shapes, the spectra have been normalized to the maximum. The calculations have been carried out adopting the prescriptions: a) standard, b) $Z-Z_0$, c) $E_{\text{sym}}(T) + a(T)$ and d) combining the two previous isospin effects.

As can be seen in Fig.4a, the standard calculations predict essentially no difference, while including both isospin effects a sizeable difference (Fig.4d) is obtained, which can be measured. The effect produced taking into account both isospin dependences comes out to be larger than that due to different values of $a$ parameter ($a = A/8$ as well as $a = A/10$, remembering that the standard prescription of Tab.1 assumes $a \sim A/9$. It is interesting to show the predictions for each single effect in order to determine the main responsible of possible experimental differences. Assuming $E_{\text{sym}}(T) + a(T)$ we observe an opposite behaviour with respect to the case where both...
effects are present, as shown in Fig.4c. The high energy tail of the proton spectrum is higher in the decay of $^{71}$Ga nuclei than in the $^{65}$Ga nuclei. This increase is due to the higher value of the difference N-Z (9 for $^{71}$Ga and 3 for $^{65}$Ga), that is amplified according to the expression 1.

Looking at Z-Zo effect (Fig.4b), we find a similar behaviour as that with both isospin effects. Due to the higher value of Z-Zo, 1.8 for $^{65}$Ga with respect to the value of 0.4 for $^{71}$Ga, the proton spectrum from the decay of $^{65}$Ga nuclei shows an high energy tail. Therefore, this is an indication of the strong contribution supplied by Z-Zo dependence. In particular, such kind of measure could represent an experimental confirmation for this prescription and, in any case, provides an useful information to improve the adopted parameters. Concerning the spectra the same behaviours have been predicted for alpha particles.

A further observable useful to enlighten the presence of isospin effects is represented by the multiplicity ratios of light charged particles of the two reactions. In Tab.3, it can be observed that the proton multiplicity ratios go from 9 to 26, while the alpha particle ones do not change significantly when the isospin effects are included.

**Table 3.** Multiplicity ratios of light charged particles emitted in the decay $^{65}$Ga and $^{71}$Ga at $E_x = 50$MeV adopting different prescriptions of the isospin effects.

|                     | standard | Z-Zo | $E_{sym}(T)$+$a(T)$ | both effects |
|---------------------|----------|------|---------------------|--------------|
| $M_P(^{65}$Ga)/$M_P(^{71}$Ga) | 9        | 20   | 12                  | 26           |
| $M_\alpha(^{65}$Ga)/$M_\alpha(^{71}$Ga) | 2.91     | 3.26 | 3.52                | 3.44         |

5. Conclusions

Statistical model calculations show that fusion-evaporation reactions are a good probe for studying the level density of neutron-rich nuclei, as those that will be produced by SPES and SPIRAL2 facilities. In particular, light particle energy spectra and multiplicities as well as evaporation residue yields are expected to be good observables in order to enlighten the isospin effects on the level density parameter $a$ and on the symmetry energy allowing to discriminate between the two contributions.

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