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Nuclear excitations at constant temperature

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Neutron and proton evaporation spectra from the ^{6}Li + ^{55}Mn and d + ^{59}Co reactions have been analyzed with the Hauser-Feshbach approach using different input models for nuclear level densities of ^{60}Ni and ^{60}Co nuclei. It has been found that models with a Fermi-gas like temperature dependence fail to reproduce particle spectra from both reactions simultaneously. We obtained the surprising result that the only way to describe our data is to assume the independence of the nuclear temperature on the excitation energy up to about the 20 MeV energy range.

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The understanding of nuclear level density is an old problem of nuclear physics that is still not completely solved. The main reason for this is the lack of experimental data. The most experimental information comes from neutron resonance spacings and discrete low-lying levels. A small portion of data comes from measurements of particle spectra from compound nuclear reactions and γ spectra from inelastic scattering and single-particle transfer reactions. The drawback of all these data is that they are measured in small energy intervals and usually below the particle separation energy. Such restrictions hinder a more thorough study of the excitation energy dependence of the level density, which is governed by single-particle and collective nuclear excitations. Understanding the energy dependence of the level density is an important key to understanding the dynamics of nuclear excitations.

The two-parameter Bethe formula [1] is still widely used to describe nuclear level densities. This formula is based on an assumption of non-interacting fermions distributed in single-particle orbitals with equal energy spacings. One of the main features of this Fermi-gas system is that the thermodynamic temperature T depends on the excitation energy U as $T \propto U^{1/2}$, which determines the excitation-energy dependence of the level density. Because of the two adjustable parameters a and δ, which denote the level density parameter and the pairing energy, respectively, the Bethe formula can be fitted to practically all available experimental data. However, experimental uncertainties and limited energy range do not allow us to study the energy dependence with precision sufficient to comprehensively test the Fermi-gas model.

Gilbert and Cameron noticed [2] that the constant temperature (CT) model describes the level densities of some nuclei better than the Bethe expression in the excitation energy region below the particle separation threshold. In the CT model, the total level density is given by $\rho(U) = \exp(U/T)/T$, with a constant temperature T. Above the particle separation threshold experimental data were absent and the Fermi-gas model was assumed to be valid. This fact led to the creation of the composite Gilbert-Cameron (GC) formula [3] consisting of CT level density below the particle separation threshold and Fermi-gas level density above the particle separation threshold. The problem is that it is still not clear up to which excitation energy the CT component of GC formula is valid. There is still a lack of experimental data capable of distinguishing between a CT and a Fermi-gas energy dependence above the particle separation threshold.

Apart from the merely formal difference, these two components have different physics origins connected to the energy dependence of the nuclear temperature. As already mentioned, the Fermi-gas model results in an excitation energy dependent temperature, while the CT model implies an independence of the temperature on excitation energy. From a macroscopic point of view, if a system gains energy, the temperature remains constant only in the case of phase transitions (ice-water, water-gas). From a microscopic point of view, new excitation modes, or degrees of freedom available with increasing excitation energy, keep the thermodynamic nuclear temperature constant. Thus, the temperature is an important characteristic of the excitation dynamics of atomic nuclei.

Many modern microscopic calculations of the nuclear level density are based on realistic single-particle level schemes and take into account pairing and collective effects [4]. However, it seems that neither of them reproduce the CT energy dependence except possibly for some spherical nuclei. It is therefore extremely important to get more experimental data to better understand the possible weakness in nuclear models currently used for level density calculations.

The main problem from an experimental point of view is that the level density is hard to measure above the excitation energy region of discrete levels, and in a large energy interval. Even though there are indications that the CT model works better for some nuclei [5], no systematic conclusions have been made so far.

The work of Sherr and Brady published in 1961 [6] is one of the few publications where the problem of Fermi-gas versus CT models has been studied by analyzing α-particle spectra of proton induced reactions. The idea behind this analysis was to compare the particle spectra at different energies of protons. If the CT model is correct, the shapes of spectra are supposed to be similar. However, if the Fermi-gas model is correct, they are supposed to be different. It has been found that the shapes of the α-particle spectra from the ^{nat}Ni(p, α)

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and ^{59}Co(p, α) reactions are similar for the proton energies of 15.6 and 19.4 MeV. The same result has been obtained from (p, p') reactions on Ti, V, Fe, Co, and Cu elements at proton energies from 11.3 to 23 MeV. Thus, it has been concluded that the CT model works better for these nuclei in the region of up to 12 MeV of excitation energy. If this is true, the question is how far up in excitation energy does the CT model work? Also, one could ask at what excitation energies will the transition from the CT model to the Fermi-gas model take place?

In this work we investigate the level density energy dependence for ^{60}Ni and ^{60}Co with 7.5 MeV deuterons and 15 MeV ^{6}Li induced reactions on ^{59}Co and ^{55}Mn, respectively. These two reactions form the same compound nucleus ^{61}Ni but at different excitation energies, which are 22.6 and 35 MeV. Such a difference allows us to investigate the shape of the level density for residual nuclei from neutron and proton evaporation spectra in a wider range of excitation energies, up to 20 MeV. On the other hand, using different reactions forming the same compound nucleus would allow us to monitor and eliminate systematic uncertainties connected to the possible contributions of non-compound reaction mechanisms that are a potential problem in determining the level density from particle spectra.

The tandem accelerator at Ohio University's Edwards Accelerator Laboratory provided ^{6,7}Li and deuteron beams with energies of 15 and 7.5 MeV, respectively. Self-supporting foils of 0.743 mg/cm^2 ^{55}Mn and 0.89 mg/cm^2 ^{59}Co (100% natural abundance) were used as targets. The proton spectra from the reactions of ^{6,7}Li on ^{55}Mn and deuterons on ^{59}Co were measured by the charged-particle spectrometer based on the time-of-flight particle identification technique (see Ref. [7] for more details). The neutron spectra were measured for the deuterons and ^{6}Li induced reactions by the time-of-flight method with the Swinger facility of Edwards Laboratory [8]. Here, a flight path of 7 m has been used to determine the energies of outgoing neutrons. The 3-ns pulse width provided an energy resolution of about 100 and 800 keV for 1 and 14 MeV neutrons, respectively. The neutron detector efficiency was measured with neutrons from the ^{27}Al(d, n) reaction on a stopping Al target at $E_d = 7.44$ MeV [9]. This measurement allowed us to determine the detector efficiency for neutrons in the energy interval from 0.2 to 14.5 MeV with an accuracy of ~6%. The neutron and charged-particle spectra have been measured at backward angles (between 120° and 160°). The absolute cross section has been calculated by taking into account the target thickness, the accumulated charge of the incoming beams, and the neutron detector efficiency. The overall systematic error for the absolute cross sections is estimated to be 15%. Particle spectra from the deuteron induced reaction have been analyzed in Ref. [7].

Because the ^{6}Li nucleus has a low breakup threshold, which is 1.4 MeV for the breakup to an α particle and a deuteron and because we observed an excess of α particles and deutrons in the experimental spectra compared to calculations, we did not use the α-particle spectra in the further analysis.

The total experimental proton and neutron spectra from the ^{6}Li and deuteron induced reactions are presented in Fig. 1 along with corresponding calculations performed with

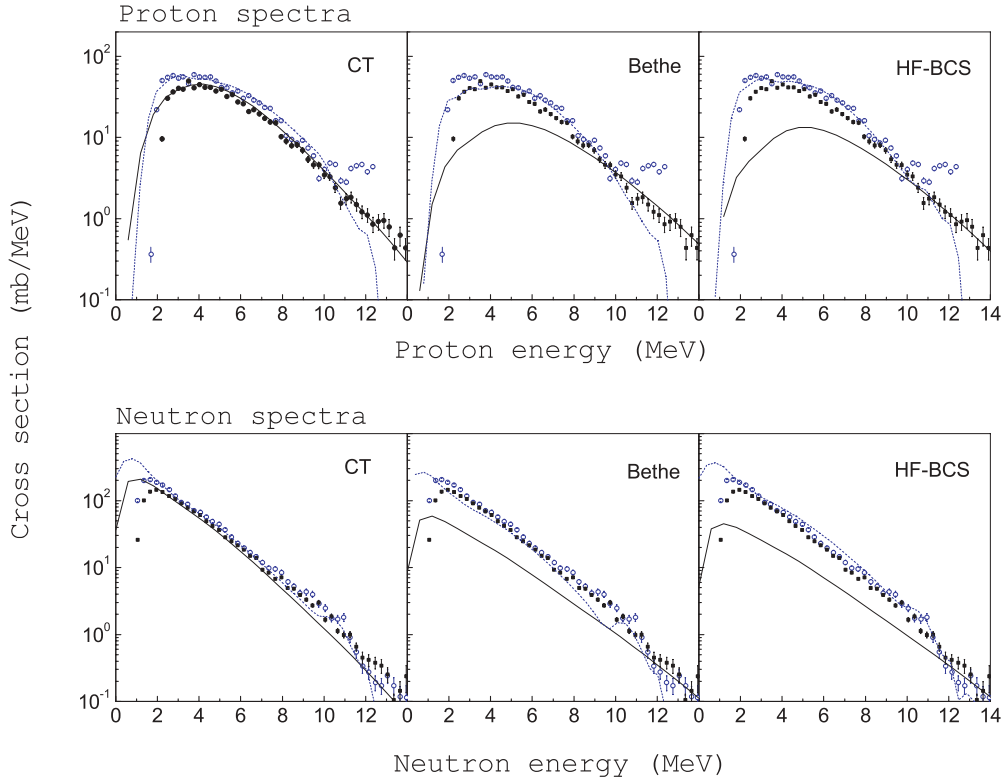

FIG. 1. (Color online) Proton and neutron evaporation spectra from 15 MeV ^{6}Li on ^{55}Mn (solid circles are data points, black lines are calculations) and 7.5 MeV deuterons on ^{59}Co (open circles are data points, blue dotted lines are calculations) reactions. The lines show Empire calculations with the CT (left), Fermi-gas (center), and HF-BCS (right) models.

the Empire code [10]. Secondary protons and neutrons from subsequent decay of the compound nucleus also contribute to the spectra, masking the energy dependence of primary particles. Such contributions are mainly coming from (^{6}Li, np), (^{6}Li, pn), and (^{6}Li, $2n$) reactions and to a lesser extent from (^{6}Li, $2p$), (^{6}Li, αp), and (^{6}Li, αn) reactions. These contributions are included in the calculations revealing that these contributions are not large enough (about 50% at ~4 MeV and down to 20% at ~10 MeV) to disguise the energy dependence of primary particles. The shape of the total particle spectra still remains very sensitive to the level density of the residual nuclei.

In calculations we used the Fermi-gas and CT level density models as inputs with parameters adjusted to reproduce evaporation spectra from deuteron and ^{3}He induced reactions on ^{59}Co and ^{58}Fe, respectively [7]. The level density spin dependence has been accounted for according to the prescription of Ref. [3]. We also tested the microscopic level density calculations from Ref. [4] performed in the framework of the Hartree-Fock-BCS (HF-BCS) approach, which includes a consistent treatment of shell corrections, pairing, and deformation effects. The γ emission in HF calculations is treated statistically using radiative strength functions according to the systematics recommended in Ref. [11]. The influence of particle γ competition on particle spectra is negligible because the fraction of first chance γ transitions is about 0.1% of fusion cross section. The calculations of proton and neutron spectra have been scaled down by about 40% to match the experimental points because of the presence of direct reaction contributions that decrease the compound reaction cross section contribution (see Ref. [7] for more details). Applied level density inputs for ^{60}Co nucleus are shown in Fig. 3.

Because of the different excitation energies of the compound nucleus ^{61}Ni formed in ^{6}Li and deutron induced reactions, the same energy neutrons and protons populate levels of residual nuclei that are about 12 MeV apart, which allows testing the energy dependence of the level density.

One can see that the experimental shapes of both proton and neutron spectra do not depend on the type of nuclear reactions and excitation energy of the compound nucleus. The independence of the type of nuclear reaction gives us the confidence that the reaction goes through a compound

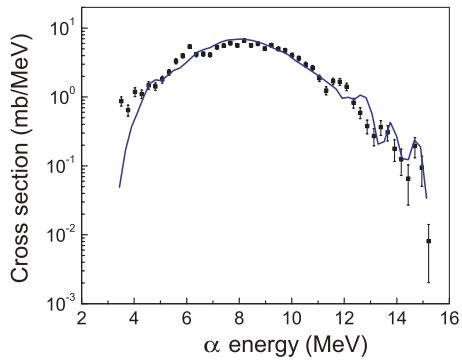

FIG. 2. (Color online). The α spectrum from ^{59}Co$(d,\alpha)^{57}$Fe reaction measured at backward angles. Points are experiments; line is Empire calculation with CT model of level density.

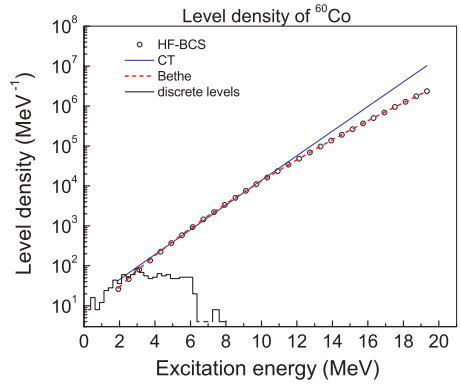

FIG. 3. (Color online). Level density inputs used for proton spectra calculations for ^{59}Co$(d, p)^{60}$Co and ^{55}Mn(^{6}Li, $p)^{60}$Co reactions.

nucleus and possible contributions from direct processes are negligible for the spectra measured at backward angles. The only exception is the 10–12 MeV protons from the ^{59}Co(d, p) reaction for which the enhancement is apparently due to direct reaction contribution. All level density models studied here reproduce the shapes of the spectra from the deuteron induced reaction, but only the CT model is capable of reproducing spectra from both the ^{6}Li and deuteron induced reactions. Figure 1 shows that the similarity of the spectra cannot be explained on the basis of either the Fermi-gas model or the more sophisticated microscopic model of level densities. The most straightforward explanation is to assume that the level densities have a constant temperature energy dependence up to about 20 MeV of excitation energy in both ^{60}Ni and ^{60}Co. This result confirms the similar effect obtained in the ^{nat}Ni(p, α)Co and ^{nat}Co(p, α)Fe reactions [6].

We mentioned that we did not use α spectra from ^{6}Li reaction because of the excess of α particles from lithium breakup. However, this is not the case for deuteron induced reactions and Fig. 2 shows that α spectrum from the ^{59}Co$(d, \alpha)^{57}$Fe reaction can be reproduced with the constant temperature level density model with the same temperature for ^{57}Fe as for ^{60}Ni and ^{60}Co.

One can speculate about other possible explanations of the effect. One of them that is discussed in Ref. [6] is connected to the possible dependence of particle transmission coefficients on excitation energy of residual nuclei. Indeed, particle transmission coefficients are calculated on the basis of optical model parameters obtained from elastic scattering and total reaction cross sections obtained for the ground state of a target nucleus. The accuracy of transmission coefficients usually does not exceed 15–20%. In Hauser-Feshbach calculations we assume that the transmission coefficients do not depend on the excitation energy of the final nuclei. This assumption, in principle, can be incorrect. However, it seems unlikely that the magnitude of the possible increase of transmission coefficients for particles populating excited states is the same for neutrons and protons and exactly matches the increase caused by the assumption of the CT level density.

Another possible explanation is the low-energy contamination of proton and neutron spectra from breakup of ^{6}Li into $\alpha + n + p$. Breakup neutrons and protons are capable of enhancing evaporation spectra in the low-energy range. Again,

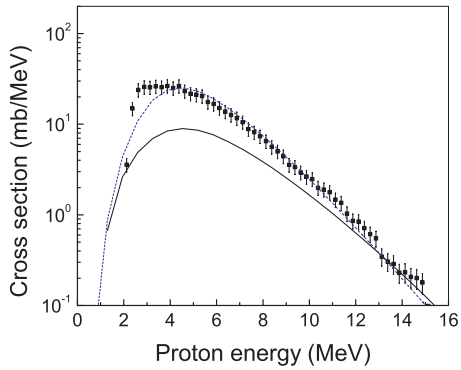

FIG. 4. (Color online). Proton evaporation spectra from the ^{7}Li + ^{55}Mn reaction. Points are experiment, and curves are calculations with CT (top blue line) and HF-BCS (full line) models.

it is not probable that this possible contribution accidentally gives the same effect as the CT model. To ensure that this possibility can be excluded, we have measured the proton spectrum from the ^{7}Li + ^{55}Mn reaction. The nucleus ^{7}Li has an 11 MeV proton production breakup threshold compared to 3.7 MeV for ^{6}Li. Figure 4 shows that the proton spectrum from the ^{7}Li induced reactions can be nicely reproduced by calculations employing the CT model with the same temperature parameter ($T = 1.4$ MeV) as that for the ^{6}Li induced reaction. This indicates that proton spectra do not contain any reaction-specific contributions.

In conclusion, the shape of both neutron and proton evaporation spectra can only be reproduced with a CT model assuming the same temperature $T = 1.4$ MeV for both ^{60}Ni and ^{60}Co residual nuclei. This temperature is in agreement with the temperature obtained from the Ni(p, α)Co reaction in Ref. [6]. The particles evaporated from compound nuclei behave more like particles evaporated from a classical body with a constant temperature. This finding is in contradiction with the Fermi-gas model and also with most of the sophisticated theoretical level density calculations. However, until now, these calculations have not been tested experimentally in a large enough range of excitation energies. From the microscopic point of view the constant temperature can result from fade out of shell and collective effects and the interplay between these and other many-body effects.

We consider our results as a strong argument in favor of the validity of the constant temperature approximation for this mass region when calculating nuclear level densities in a larger range of excitation energies (far beyond the particle separation energy). It will be very important to establish limits of this approximation with respect to both the excitation energy and the nuclear mass range and investigate how it can be understood from the point of view of nuclear structure properties.

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