Letter of Intent

Measurements of level densities from compound nuclear reactions

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Abstract

We propose to measure the level density of nuclei of medium-light mass region, for excitation energies up to ~ 25 MeV, using as a probe the light particles emitted in fusion evaporation reactions. The main objective is twofold: i) to collect high quality experimental data on level density in the whole proposed range of excitation energy, data which are missing in the literature. This will allow to test the current models and to extract a more precise level density parameterization. ii) to study the behavior of the level density when going gradually away from the stability line, this work being important for future experiments with SPES facility We intend to perform experiments at LNL with Tandem beams, using GARFIELD, 8πLP, and RIPEN experimental set-ups in order to measure high precision evaporative light particle energy spectra and angular distributions. Following a well established method, the level density of specific nuclei can be measured as a function of the excitation energy, from the high energy side of the particle energy spectra, which is expected to arise mainly from the first step emission. At the same time, the whole energy spectrum, which includes the contributions from all the steps of the evaporative chain, is expected to be a stringent test for the level density models.

1. Scientific motivations

Level density is an important characteristic of atomic nuclei. It allows to explore the mechanism of nuclear excitations (which nuclear degrees of freedom are excited and in which proportions), thereby shedding light on the questions about the structure of excited nuclei. The level density is also an indispensable input in reaction cross-section calculations, and thus a vital quantity for practical applications in describing element production in the cosmos as well as nuclear energy issues. In this letter of intent we propose to measure this quantity for nuclei in the medium-light mass region for excitation energy up to ~ 25 MeV. The main goals are: i) the test of the current models of level density on the base of an extended set of new data, presently not available in the literature, ii) study the behavior of the level density when going gradually away from the stability line. This will allow to explore the physics underlying the level density as well as to obtain a more reliable parameterization of this quantity.

1.1 Current status and need for new experimental data on nuclear level densities

Most of the experimental data used as a guide for various level density models come from neutron resonance spacing data. The main drawback of these data is that they give us the level density at one excitation energy only and in a very restricted spin interval. Thus, these data do not tell us anything about the energy dependence of the level density function. The energy dependence is usually assumed to be of a Fermi-gas like level density. The spin cutoff parameter and parity ratio used to convert the neutron resonance spacing to the total level density are usually not well known experimentally. In particular, the most popular model of the nuclear level density is based on the idea that an excited nucleus behaves as a Fermi-gas, implying that the independent particles (protons and neutrons) move in a common potential with equidistant single-particle states. These considerations led to the well-known Bethe formula [1] containing two free parameters which are usually adjusted to fit experimental data. Later, Gilbert and Cameron pointed out that, for some nuclei, the temperature formula [2]. This is opposite to the situation in the Fermi-gas model, where the excitation energy dependence deviates from the Fermi-gas form and is better described by the constant temperature depends on excitation energy as $T=\sqrt{(U/a)}$. The issue of the constant-temperature versus Fermi-gas models is still not completely understood because of the lack of experimental data.

Another set of level-density data comes from particle evaporation spectra of compound nuclear reactions. The experimental method and associated problems and uncertainties are discussed in Refs. [3,4]. Despite the numerous measurements of particle spectra, only few of them were specifically used to extract the functional form (energy dependence) of the nuclear level density. However, even in these very limited cases the data often experience problems because of systematic uncertainties due to pre-equilibrium processes. Pre-equilibrium processes increase with the energy of projectile; therefore the projectile energies of nucleon induced reactions (with neutron, proton and alpha-particles) were typically below ~15 MeV. For these beam energies the excitation-energy range of the extracted level density function is maximum 5-8 MeV, which is not sufficient to distinguish between the constant temperature and Fermi-gas models, for example.

The measurement of the energy dependence of the total level density (for all spins) which we propose would provide a constraint for theoretical models and tell us more about the basic nuclear physics of excited nuclei. This will also allow a proper parameterization of semi-empirical models for practical calculations. In this respect, the current parameterizations based on fitting the parameters to known levels and to neutron resonance data, have typical accuracy in predicting the level density of a factor of 2 or worse. Finally, the proposed measurements will allow to test microscopic level densities, which use realistic nuclear potentials with pairing, shell and collective effects. Nowadays such calculations are available for all nuclei [5].

Our recent experiments on the ^{55}Mn(^{6,7}Li,p) reaction at Edwards Accelerator Lab showed that using 15 MeV ^{6,7}Li projectiles (see Fig. 2) and thick stopping particle detectors allow us to get the energy dependence of the level density of the residual nucleus ^{60}Co up to 20 MeV of excitation energy (to be published). This result shows that the right way to develop the technique of level density measurements is to use light and heavier ions as projectiles with energies above the Coulomb barrier, but less than ~ 4-5 MeV/A to minimize contributions of pre-equilibrium processes.

Level-density measurements from reactions with light and heavier ion projectiles have been studied by the Indian group [6] and the group from INFN [7]. The main drawback of these experiments is that the high-energy part of the particle evaporation spectra was often cut-off because of too thin charged-particle detectors used in these experiments, or insufficient statistics due to low efficiency (small solid angle). The low-energy part of the spectra contains contributions from multiple stages of the reactions and is therefore not sensitive to the specific functional form of the level density function. As a result, the data were mostly used only for the analysis of the global systematic (over many nuclei contributing to the given spectrum) of the Fermi-gas level density parameter a. In addition, the angular distribution was not measured, which further complicated the analysis of the spectra.

There is obviously a lack of experimental efforts nowadays devoted to the study of level densities in atomic nuclei. We would like to address this problem with modern experimental beam facilities and state-of-the-art spectrometers.

1. 1.1. Level density for nuclei far from stability line

Most of the knowledge of the nuclear level density (NLD) concern nuclei close to the valley of stability. Interest in studying this quantity for exotic nuclei, as those that will be produced by the second generation RIB facilities, is growing up. The available semi-empirical models and parameterizations do not distinguish between nuclei on and off the stability line as the isospin effects on the level density are expected to be relatively small for nuclei close to the valley of stability. On the other hand, it is predicted [8,9] that the NLD parameter a for a given nucleus A(N,Z) should decrease with increasing (N-Z) or Z-Z_0, where Z_0 is the atomic number of the stable nucleus with the same mass number A. This last dependence stems from the consideration that the unbound single-particle states that are too wide, cannot contribute to the compound NLD. In particular, the number of nucleons occupying these large-width single-particle states is expected to increase going towards the proton (neutron) drip line, because of the decreasing of the binding energy, producing more and more compound levels having widths too large to be included in the level density. In this picture, a significant reduction of the level density is expected, depending on how far away the nucleus is from the stability line. Preliminary microscopic calculations [10] of nuclear level density for ^{40}Ti, where this effect is taken into account, are shown in Figure 1.

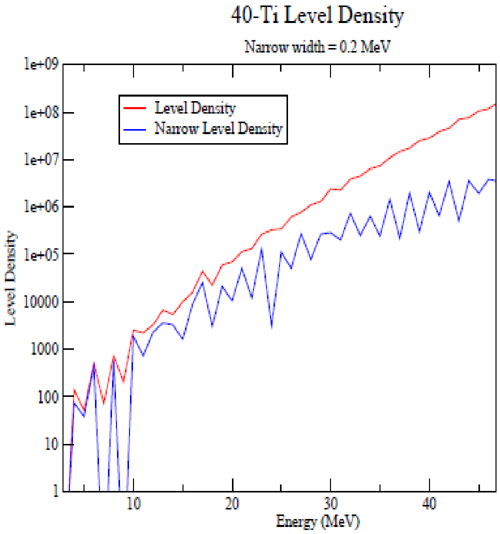

Fig. 1. Calculated level density of ^{40}Ti including all levels (upper curve) and only those with width less than 200 keV (lower curve).

This behavior of the level density has been pointed out on experimental grounds in Ref. [8,9], where this quantity has been studied for nuclei with $20 \leq A \leq 110$, comparing different isospin dependences of the level density parameter *a*. It has been shown that, compared to the prescription based on the N-Z dependence, a reduction factor of the level density based on the distance from the valley of stability $Z-Z_0$ provides a better description of data. This result brings evidence that the level density parameter has dependence on N and Z rather than just on A. These results, which would have strong implications for nuclei far from the stability line, are supported by other recent experimental findings [6,11]. In this framework, we have measured [12] evaporative charged particles from the decay of the composite system ^{139}Eu at E_x=90 MeV with 8πLP apparatus at LNL. Results did not confirm the findings of Ref. [1,2] but suggested that more precise level density measurements need to be done.

1.2. Experimental method proposed

We propose to study the level density using a more powerful approach. This consists in a precise measurement of the level density as a function of the excitation energy according to the well established procedure described in Ref. [13] and selecting a particular residual nucleus. Concerning the procedure, it consists of: i) adjusting the parameters of the statistical model to reproduce the experimental spectra, ii) improving the calculated NLD by binwise renormalization according to the expression:

$$\rho_{\exp}(E,I,\pi) = \rho_{calc}(E,I,\pi)\frac{(d\sigma/d\varepsilon)_{\exp}}{(d\sigma/d\varepsilon)calc}$$

The absolute NLD can be obtained by using discrete level densities.

Concerning the selection of the residual nucleus, this can be performed considering that at moderate excitation energies of the compound nucleus, the high energy part of the particle spectrum arises mainly from the first step decay. Therefore, this part of the spectrum allows to measure the NLD of the residual nucleus ((i.e. the compound nucleus – 1 particle) at excitation energy $E_x = E_o - E_{sep} - \varepsilon$, where the three right terms are the compound nucleus excitation energy, the particle separation energy and the channel energy, respectively. Since the minimum particle energy (E_{th}) in the spectrum arising from the first step increases with the excitation energy of the compound nucleus, the maximum E_x in the residual nucleus for which the NLD can be measured saturates at higher excitation energy of the composite system. The typical range of E_x which can be studied with this method is ~ 5 – 25 MeV. The particle threshold energy E_{th} can be evaluated on the base of the statistical model and it is rather independent from the input parameters.

Possible reactions to study with the above mentioned method are listed in Table 1. The reaction $^{12}C+^{49}Ti$ produces the compound nucleus ^{61}Ni, which has recently been studied by us at Edwards Accelerator Laboratory, Ohio University, with d, ^3He and $^{6,7}Li$ induced reactions (see Fig. 2).

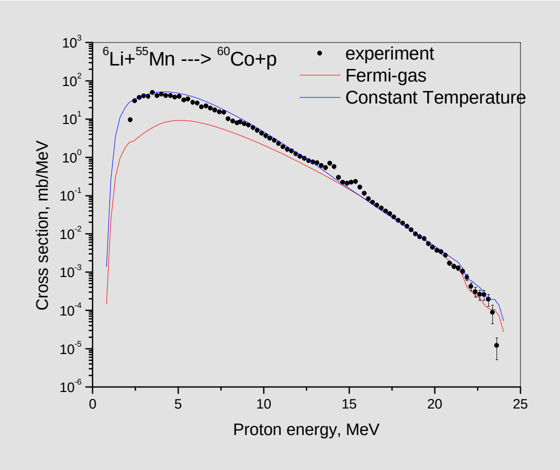

Fig. 2. Proton evaporation spectra from the 15-MeV ^6Li + ^{55}Mn reaction. The points are experimental data, the curves are Hauser-Feshbach model calculations with Fermi-gas (red line) and Constant Temperature (blue line) level density models.

These reactions will be interesting from the methodical point of view to see if we get consistent results. The other three reactions produce compound nuclei with mass number A = 86 but with different proton number Z corresponding to nuclei on the stability line (^{86}Sr), about nucleons off the stability line (^{86}Zr) and about four nucleons off the stability line (^{86}Mo). It will be very interesting to see how the level density of these residual nuclei changes when going gradually away from the stability line.

Projectile energy, MeV	Reaction	Compound Nucleus Excitation Energy, MeV
40	$^{12}C + ^{74}Ge$	45
53	$^{16}O + ^{70}Ge$	45
93	$^{28}Si + ^{58}Ni$	45
40	$^{12}C + ^{49}Ti$	48

Table 1. List of possible reactions to be studied at the Laboratori Nazionali di Legnaro.

2. General idea of the proposed experiments using GARFIELD/8PLP/RIPEN apparatus at LNL

We propose to perform measurements of particle evaporation spectra from compound nuclear reactions induced by light and heavier ions to study the level densities of the residual nuclei. Three experimental apparatus installed in Legnaro at the TANDEM-ALPI are suitable for this study: GARFIELD, 8pLP, and RIPEN, where the first two can be used in alternative, and the third one in parallel.

In particular, the GARFIELD and 8πLP apparatus are both very suitable because they are large solid-angle charged-particle spectrometers which permit measurements with high energy resolution (1%), and a large acceptance of A and Z of the light charged particles over a wide angular range (30-150 and ~ 10-170 deg. in θ for GARFIELD and 8πLP, respectively, both covering 4π in φ). Both the apparatus allow therefore to measure the angular distribution and to collect high-statistics experimental spectra. Moreover, they can be combined with auxiliary detectors suitable for detecting the evaporation residue in order to define the experimental trigger in coincidence with the light products. In addition, the GARFIELD apparatus is suitable for detecting fragments heavier than ^{4}He. The alternative utilization of GARFIELD or 8πLP can be decided upon according to the specific experimental proposal, even in connection with the scientific programs of the two apparatus. The details of the measurements performed with the two apparatus and the possible differences will be provided at the proposal submission stage.

In parallel, the RIPEN neutron apparatus could be used to measure the spectra of neutrons emitted from the reactions to get complementary information on the decay mode. In this case, a very careful reproduction of the trigger set-up in coincidence with the neutron detector has to be prepared.

The wide range of available ion beams allows for producing compound nuclei in a wide range of masses and excitation energies. The high stopping power of the Cs(Tl) detectors (stopping protons of energy ~ 75 MeV) will allow us to measure particle evaporation spectra in a wide angle and energy range. With properly selected target and beam species, nuclei situated off the stability line are also reachable to study. The possibility of low-energy particle identification, good energy resolution, and angular distribution measurements over a wide range, makes the LNL apparatus very important and unique tools for such investigations.

The main idea of the proposed approach is to first study the reaction mechanisms by analyzing the energy and angular distribution of the outgoing particles. The level density of the residual nuclei can be extracted only from those reactions where the compound mechanism is dominant. This procedure will eliminate any systematic uncertainties related to pre-equilibrium processes. The particle spectra need to be measured in the whole accessible energy range up to the maximal energy determined by the *Q*-value and the projectile energy. In this case, the energy dependence of the level density will be possible to study. The expected energy range of the outgoing particles is from a few MeV to at least 25 MeV (the more the better). This will allow us to get absolute level densities up to ~25 MeV of excitation energy (or more) for the residual nuclei. In order to analyze the experimental data, reaction codes calculating particle spectra from compound and pre-equilibrium nuclear reactions (HF, Empire, TALYS, Cascade, Lilita_N97) will be used.

As a future development, it would be highly desirable to measure neutron spectra as well, because the outgoing neutron channel is dominant in compound nuclear reactions. The RIPEN apparatus will be upgraded with modern electronics in order to get a fast response, good n/gamma discrimination and the possibility to measure low-energy spectra. The ratio between the cross sections of the different outgoing channels will constrain the obtained level densities.

Expected results from the experiments

1. Absolute values and energy dependence of level densities from the ground state up to ~25 MeV of excitation energy
2. More precise systematics of level density parameters for existing semi-empirical models
3. Experimental data on the level density for nuclei off stability line

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