Proposal

Measurements of level densities from compound nuclear reactions

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Abstract

Following the LNL PAC positive comments about our Letter of Intent, we propose to measure with high precision evaporative proton spectra from ^{58}Ni(^{16}O,p) and ^{58}Fe(^{16}O,p) reactions using the GARFIELD experimental set-up. The first reaction populates proton rich ^{74}Kr nucleus which is about 3 units away from stability line. The second reaction produces the same mass nucleus ^{74}Se which is closer to the stability line. 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. The energy of the ^{16}O has been chosen to be 47 and 40 MeV such that to be able to acquire reasonable statistics in the whole energy range up to the maximum energy in the spectrum. We ask 4 days of beam time for each reaction and one additional day for the GARFIELD CsI calibration with a 30 MeV ^{7}Li beam for a total of 9 days. Only TANDEM is needed to reach the required bombarding energies.

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 our submitted Letter of Intent to the LNL PAC [1], we propose to measure this quantity for nuclei in the medium-light mass region for excitation energy up to ~ 25 MeV. The main goals were: 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)) the study of the level density behavior when going gradually away from the stability line. This will allow us 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. It is usually assumed 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 [2]. 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. On top of that, Gilbert and Cameron pointed out that, for some nuclei, the excitation energy dependence deviates from the Fermi-gas form, in which the temperature depends on excitation energy as $T=\sqrt{(U/a)}$, and is better described by the constant temperature formula [3]. 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 in compound nuclear reactions [4,5]. Mostly light particles (up to ^{4}He) were used as projectiles. The most common problem of such measurements is the systematic uncertainties due to pre-equilibrium processes which increase with projectile energy. This is a severe constraint for incoming beam energies resulting in a restriction of the excitation energy interval for the population of residual nuclei under study. Only excitation energies below the particle separation threshold are available for study from such experiments.

For the purpose of eliminating the pre-equilibrium mechanism, reactions with heavy ions look promising. At the same energy per nucleon, ions possess greater kinetic energy, (compared to nucleon induced reactions) extending essentially the excitation energy interval available for study. It allows keeping the energy of projectile per nucleon relatively low thereby eliminating the pre-equilibrium mechanism of nuclear reactions. It is established that pre-equilibrium contributions begins at energies greater than 5 MeV/A [6]. Our recent experiments with the ^{55}Mn(^{6,7}Li,p) reaction at Edwards Accelerator Lab showed that using 15 MeV ^{6,7}Li projectiles (see Fig. 1) allows testing the energy dependence of the level density of the residual nuclei up to 20 MeV of excitation energy (to be published). We propose to continue such kind of measurements with ion beams and state of the art high efficiency spectrometers.

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

Most of the knowledge of the nuclear level density (NLD) concerns 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. On the other hand, it is predicted [7] that the NLD parameter a for a given nucleus should decrease with increasing Z-Z_0 according to the expression:

$$a = a_0 \exp(-0.038 \cdot (Z - Z_0)^2) \quad (1)$$

where Z_0 is the atomic number of the stable nucleus with the same mass number and NLD parameter a_0. This last dependence stems from the consideration that the unbound single-particle states that are

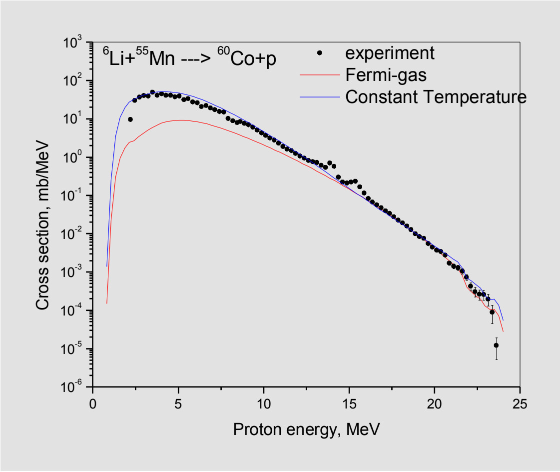

Fig. 1. Proton evaporation spectra from the 15-MeV ^{6}Li + ^{55}Mn reaction. The points are experimental data, the curves are Hauser-Feshbach model calculations with Fermi-gas (red line) and Constant Temperature (blue line) level density models.

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 decrease 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 show that the effect should be noticeable when going off the stability line (to be published).

2. Experimental method proposed

We propose to study the level density using a more powerful approach. Below the particle separation threshold of residual nuclei the level density can be measured precisely as a function of the excitation energy according to the well established procedure described in Ref. [8]. It consists in: i) adjusting the parameters of the statistical model to reproduce the experimental spectra, ii) to improve the calculated NLD by binwise renormalization according to the expression:

$$\rho_{\exp}(E,I,\pi) = \rho_{calc}(E,I,\pi)\frac{(d\sigma/d\varepsilon)_{\exp}}{(d\sigma/d\varepsilon)calc} \qquad (2)$$

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 one to measure the NLD of the residual nucleus (i.e. the compound nucleus minus 1 particle) at excitation energy E_x=E_o-E_{sep}-ε, where the three right terms are the compound nucleus excitation energy, the particle separation energy and the channel energy, respectively.

At energies above the particle separation threshold, the different temperature dependence and level density parameter systematics can be tested (see fig 2). Therefore the goal of this proposal is to measure particle evaporation spectra in a wide energy range including the top energy range where the first step decay dominates.

2.1 Proposed experiments

We propose to start our experimental campaign measuring proton evaporation spectra from ^{58}Ni(^{16}O,p) and ^{58}Fe(^{16}O,p) reactions. The first reaction populates proton rich ^{74}Kr nucleus which is about 3 units away from stability line. The second reaction produces the same mass nucleus ^{74}Se which is closer to the stability line. The energy of the ^{16}O has been chosen to be 47 and 40 MeV such as to be able to acquire reasonable statistics in the whole energy range up to the maximum energy in the spectrum. Fig.2 shows that there is no difference in proton spectra from these reactions if the isotopic effect (1) does not apply. Otherwise, the slope of the proton spectrum from ^{58}Ni+^{16}O reaction would be flatter because of the compound state reduction effect discussed above.

The specific shape of proton spectra from these reactions will also allow us to test different models and model parameterizations. Fig 2 also shows calculations with Fermi-gas and constant temperature level density formulas which produce different shapes of proton spectra. So the purpose of this experiment is to measure shapes of proton evaporation spectra in order to study level densities and their parameterization for nuclei on and off stability line.

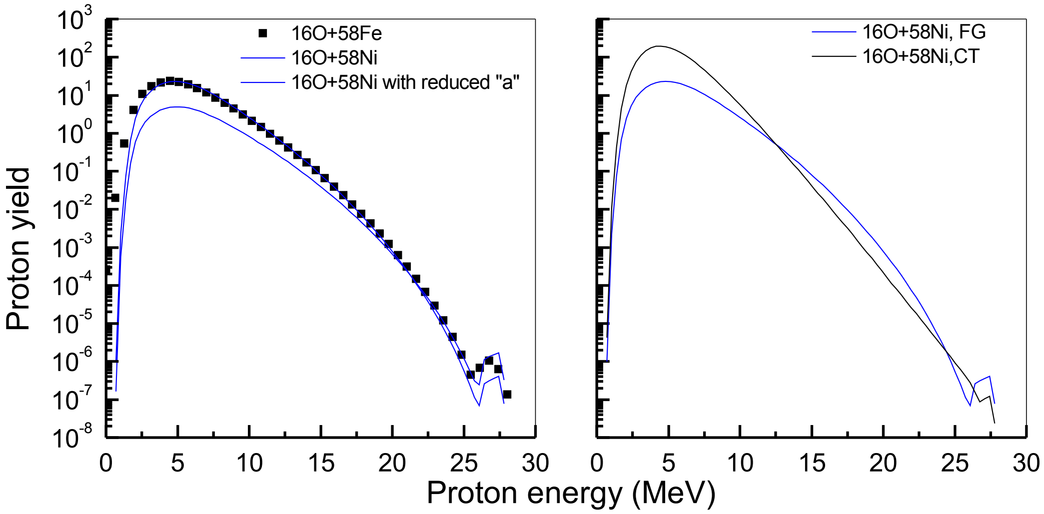

***Fig.2** Proton spectra calculated with Empire computer code with different level density inputs (see text for explanations). FG-fermi gas Bethe formula, CT-constant temperature formula.*

3. Experimental apparatus and beam time estimate

To measure light charged particle spectra we are going to use GARFIELD apparatus which is a large solid-angle charged-particle spectrometer. It permits measurements with high energy resolution (1%), and a large acceptance of A and Z of the light charged particles over a wide angular range (29°< θ <151° and 4π in ϕ) [9].

Considering that the elastic scattering is abundant even at large angles due to the very low bombarding energies (the grazing angle in the Laboratory system for the reaction at 40 MeV on Fe is 124°, while for the 47 MeV beam on Ni is 88°), some shielding of the detector are needed, in order to avoid unwanted high counting rate. The shielding will be a compromise to keep a low threshold on the proton spectra and a cut of the high rate elastic projectile. In this way we expect an efficiency of about 50% for proton detection.

Taking into account the proton emission cross-sections (calculated with the Empire evaporation code) and assuming a current of 0.5 pnA and a target thickness of 300 μg/cm2, we should collect about 100 protons at 22 MeV in the CM reference system for the 40 MeV ^{16}O+^{58}Fe reaction in 4 days of data taking. This statistics would allow measuring the level density at an unprecedented limit in the energy spectra, where the yield dropped about five orders of magnitude down the maximum located around the Coulomb barrier. The same beam time is required for the 47.0 MeV $^{16}O+^{58}Ni$ reaction, for which a slightly higher cross section is expected, but a lower beam current should be used. In fact the beam current cannot exceed 0.5 pnA for the first reaction and 0.2 pnA – 0.3 pnA for the second one, due to the limitation imposed by the maximum counting rate sustainable by the DAQ system. It is necessary to maintain high performance of the detection system in terms of both dead time and overall resolution.

The crucial detectors for this experiment are the 180 CsI(Tl) crystals of the GARFIELD array. An accurate energy calibration is needed due to the non-linear response of CsI(Tl) scintillators. To keep the precision of the incident energy reconstruction within 3-4 %, an additional lithium beam at low energy (30 MeV) is required. The reaction of 30 MeV ^{7}Li on 200 μg/cm^2 Au target will permit to illuminate most of the crystals. Considering a lithium beam current of 1pnA, we ask for 1 day of continuous and stable beam on target.

Summarizing our request are as follows:

beam	pulsing	period	energy MeV	intens pnA	target	days
16O	about 2 ns	200 ns	40	0.5	^{58}Fe	4
16O	about 2 ns	200 ns	47	0.2	^{58}Ni	4
7Li	DC	--	30	1	^{197}Au	1

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