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Nuclei at the proton drip-line and their relevance to nuclear astrophysics

Lidia S. Ferreira[*]
Centro de Física das Interacções Fundamentais, and Departmento de Física, Instituto Superior Técnico, Universidade de Lisboa, Av Rovisco Pais, 1049 001, Lisboa, Portugal
E-mail: `flidia@ist.utl.pt`

Enrico Maglione
Dipartimento di Fisica e Astronomia "G. Galilei", Via Marzolo 8, I-35131 Padova, Italy
and Istituto Nazionale di Fisica Nucleare, Padova, Italy

Monika Patial, P. Arumugam

Department of Physics, Indian Institute of Technology, Roorkee 247667, India

The structure of proton rich nuclei relevant to nuclear astrophysics phenomena, is discussed in connection with the observation of proton radioactivity.

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[*] Speaker.

1. Introduction

One important issue in nuclear astrophysics is the possibility to describe the production of proton rich nuclei, and their abundances in the solar system. The observation of different types of meteorites, present anomalies in the abundance ratios of isotopes, which are quite different from theoretical predictions. The path for p-processes is not well established yet, and it might be possible that rapid proton or alpha capture reactions along the proton drip line could provide a mechanism to generate heavy proton rich nuclei[1], but this will certainly depend strongly on structure details of nuclei along the path.

An example is given by the existence of specific resonance states in ^{18}Ne, which guarantee sequences of alpha particle reactions, responsible for breakout paths from the hot CNO cycle. However, the spectrum of ^{18}Ne is not fully understood, in spite of the few experiments performed until now, to determine it[2]. The cross section for proton capture in ^{17}F to produce ^{18}Ne was measured in the inverse kinematics regime[3], and the low energy 3^+ state in ^{18}Ne was identified as the strongest resonance contribution to the transfer. In inverse kinematics, the ^{17}F(p,γ)^{18}Ne reaction is just the emission of a proton from an excited state of ^{18}Ne, and this nucleus can decay to ^{16}O by the emission of two protons. Therefore, proton emission can be a process to study these reactions and grasp the underlying nuclear structure involved in the process.

In the region of production of medium heavy isotopes, N≈Z nuclei play an important role, since rp processes seem to follow the N=Z line up to the neighbourhood of ^{100}Sn. The structure of these nuclei influences the rates at which the reactions can proceed, and the residual pairing proton neutron interaction can be quite influential. Proton emission from odd-odd nuclei, can also be useful in this context, since the emission of one proton is quite dependent on the state of the unpaired neutron.

Proton emission guided the mapping of a large part of the proton drip line, and at the same time, using decay tagging techniques, has provided a unique way to observe the decay spectra of drip line nuclei. It is thus the purpose of this work to discuss how through the theoretical interpretation of proton radioactivity one can obtain valuable information on the structure of proton rich nuclei, relevant to nuclear astrophysics.

2. Nuclear structure information from Proton emission

Proton emission from the ground and excited states of exotic nuclei has not only been extensively measured[4], but a solid theoretical interpretation of the decay process was achieved[5]. Using realistic mean field models, it was possible to reproduce the experimental half-lives and branching ratios, and predict the nuclear shape parameters and quantum numbers of the decaying states[6].

Two proton emission from ^{18}Ne was analyzed in terms of a sequential decay, were a first proton was emitted, creating ^{17}F in an excited state from where the second proton was emitted leading to ^{16}O left in the ground state. ^{18}Ne is a spherical nucleus, and the half-life can be calculated according to scattering theory, from the knowledge of the proton state and the spectroscopic factor. The latter, was determined from a standard shell model calculation with a realistic interaction, fitted to the experimental excitation energies, and that reproduces the experimental data for all sd nuclei.

In our analysis we found evidence for states of negative parity at quite high energies, which are very narrow, and prefer to decay by one proton emission to the excited states of the daughter ^{17}F, than to the ground state. To see the possibility of emission of a second proton, branching ratios for decay to unbound proton states in ^{17}F were calculated, and meaningful values were found for decay from negative parity states at quite high energy. The results are reported in Table 1 of Ref: [7]. These states are most likely the candidates for sequential two-proton decay, and some were confirmed by the experimental studies of Raciti and collaborators[8]. These results, show the power of proton emission to identify the spectra of proton radioactive nuclei.

When both neutrons and protons are away from magic numbers, one has to take into account also the residual quadrupole interaction between unlike particles. This interaction gives rise to rotational bands, that can be treated by a transformation similar to the Bogoliubov transformation for pairing. Rotational invariance is broken giving rise to a deformed mean field, and the spectroscopic factor will depend not only on the u^2 of the BCS, but also on the amplitude of the component of the Nilsson state with angular momentum equal to the one of the ground state. This fact makes possible to get detailed information on components of the wave function that can be quite small, and not detectable by other means. Decay to the first excited state of the daughter nucleus has also been observed, imposing further constraints on the theory.

A solid theory has been developed which is able to reproduce the experimental data of deformed nuclei and predict nuclear properties. The non-adiabatic quasiparticles approach[5], accounts for the Coriolis and pairing residual interaction. An interesting case of deformed emitters, and extreme in its complexity, is the decay of odd-odd nuclei, due to the complications introduced by the couplings of the odd nucleons[9]. The daughter nucleus in this case has an odd number of nucleons, and its angular momentum is determined by the Nilsson level occupied by the odd neutron. Different values of this angular momentum, will allow different values of the angular momentum of the escaping proton. The half-life can be obtained within the non-adiabatic quasiparticles approach with the proper treatment of residual pairing and neutron proton (np) interactions.

For example, the spin and parity of the ground state of ^{130}Eu, a highly deformed odd-odd emitter, can be confirmed out of two tentatively known states 1^+ and 2^+. The role of the residual np interaction on the decay width can also be estimated. Out of all possible spin and parity combinations, it is only the positive parity states, close to Fermi surface for protons and neutrons, that appear low in energy and can reproduce the experimental decay width.

The calculated decay width is shown in Fig. 1a for the lowest lying singlet and triplet states, obtained after considering the interaction between four lowest lying single-particle states each for protons and neutrons. The resulting states could be associated to the most dominant basis state by looking into the corresponding amplitudes and hence we can identify whether a state is a triplet or a singlet. By Gallagher Moszkowski rule, the triplet state is favoured to be considered as the ground (proton emitting) state and appears lower in energy in our calculations. These calculations are done over a range of deformation values and in Fig. 1a the results are with Coriolis attenuation parameter $\rho = 0.7$. In these results it can be seen that both the singlet and triplet states can explain the measured decay-width (yellow region) especially considering the uncertainty in the calculated values due to the experimental uncertainty of the Q-value (error bar). Even if the calculated decay-width for the singlet state is closer to the observed one, it is more appropriate to confirm the triplet state as the proton decaying state on the basis of being energetically favoured.

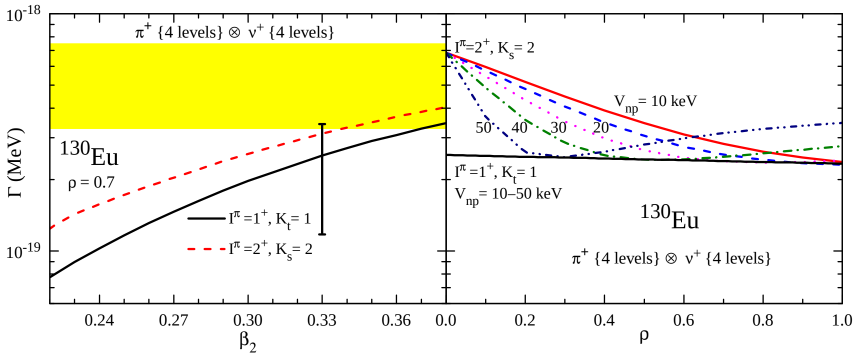

Figure 1: Left panel: Decay-width for proton emission from the ground state of ^{130}Eu. *Right panel:* Effect of residual *np* interaction on decay-widths for different values of the Coriolis attenuation ρ.

One can see the effect of residual *np* interaction on the decay-width in Fig. 1b, noticeable only for the singlet states. The residual *np* interaction itself cannot lead to changes in the decay-width without the Coriolis interaction ($\rho = 0.0$), but plays an effective role in the presence of a strong Coriolis interaction as evident in the figure. The decay-width which is highly sensitive to the wavefunction of the decaying state, and dependent also on the residual *np* interaction. Studying the decay from low-lying singlet (isomeric) states could provide crucial information regarding the residual *np* interaction.

3. Conclusions

We have shown that through the interpretation of proton decay data one accesses nuclear structure information relevant to nuclear astrophysics.

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