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The resonances of ^{18}Ne

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The structure of ^{18}Ne is discussed due to its relevance to nuclear astrophysics phenomena. The possibility of observing two proton emission from excited states of this nucleus is addressed, and the spin, parity and energies of the most probable decaying states were assigned.

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1. Introduction

The determination of resonances in ^{18}Ne is an important issue to obtain the reaction rates in processes relevant for the energy production and element generation in nuclear astrophysics events. Breakout paths from the hot CNO cycle involve sequences of alpha particle reactions that proceed through the ^{18}Ne resonances, which are above the α decay threshold.

The reaction ^{17}F(p,γ)^{18}Ne is particularly important in late nucleosynthesis of massive stars in the presupernovae phase, where the rp-process leads to the production of nuclei up to Cadmium. Many reaction chains include this process that can go via direct or resonance capture of the proton.

A few experiments have been devoted to determine the energy levels of ^{18}Ne, but still some uncertainty prevails. Widths and spin assignments of some relevant levels for the astrophysical processes have been estimated from the properties of the mirror nucleus ^{18}O [1], and data from stable beam studies [2, 3], or from indirect measurements [4, 5], provided the resonance parameters for several states above 7 MeV of excitation energy.

The cross section for proton capture in ^{17}F was measured in the inverse kinematics regime [6], and the low energy 3^+ state in ^{18}Ne was identified as the strongest resonance contribution as suggested in other experiments [7], and its strength measured. A more recent experiment, determined the level structure above the alpha-decay threshold using the ^{16}O(^{3}He,n) reaction [8]. The inverse of the ^{17}F(p,γ)^{18}Ne reaction is just the emission of a proton from an excited state of ^{18}Ne. Therefore, proton emission can be a process to study these reactions and grasp the underlying nuclear structure involved in the process.

Proton emission from the ground and excited states of exotic nuclei has been measured extensively in the last two decades [9], and a good theoretical interpretation of the decay process was achieved [10]. Using realistic mean field models, it was possible to predict the nuclear shape parameters and quantum numbers of the decaying states [11]. Fully self–consistent calculations, using more fundamental interactions based on relativistic density functionals derived from meson exchange and point coupling models, were also able to account for the experimental data of proton radioactivity from spherical nuclei [12]. One proton emission from the ground state, was observed in nuclei beyond the proton drip-line, and provided a way to map the limits of stability. There, the proton and the core are in a resonance state, and after decay the core will be left in the ground or in an excited state.

The simultaneous emission of two-protons was observed for the first time only in 2002, for decay of ^{45}Fe [13, 14] in experiments performed at GSI and GANIL. Research in the field flourished after this breakthrough, and other emitters were found afterwards [15]. There are two possible decay modes for the simultaneous emission of two-protons. The first one is just a three-body direct breakup, involving an uncorrelated emission of the two protons, usually referred to as the democratic emission. The second possibility is an ^{2}He cluster emission, where a pair of correlated protons in a quasi–bound ^1S configuration breaks–up into two protons, which is designated as the di–proton emission. In this case, the two protons will have strong angular and energy correlations, and this will help experimentalist to distinguish between these two decay modes. There is still another option, where one proton will be emitted first, and the emission of the second will follow, a process known as sequential decay. It usually occurs if the channel for one proton emission is energetically open.

In an experiment done in inverse kinematics with a ^{17}F beam incident on a $(CH_2)_n$ target [16], evidence for simultaneous two-proton emission from the 6.15 MeV 1^- state in ^{18}Ne was found, and other resonances were studied. For decays of ^{18}Ne from states below 6.15 MeV, there are no intermediate states in ^{17}F available for sequential decay, so one expects at low energies democratic or correlated two proton emission, but the relative proton–proton energy and angle spectra analysis did not allow to distinguish between di–proton and democratic emission in that experiment.

With the aim to investigate the nuclear levels of ^{18}Ne and the possibility of one and two proton emission, an experiment was performed at LNS by Raciti and collaborators [17]. They observed that the excitation spectrum of ^{18}Ne presents some states that can be seen in the two-proton democratic decay channel to ^{16}O, but are suppressed in the one-proton decay to ^{17}F. They observed 2p decay not only from the 6.15 MeV 1^-, distinguishing di–proton (31%) and democratic (69%) mechanisms, but also from the known 7.06 MeV, 7.91 MeV, and 8.5 MeV levels. These states are above the threshold for sequential decay and could have spin and parity 1^- or 2^+. However, there were other higher lying excited states around 8.5 MeV, 10.7 MeV, 12.5 MeV, and 13.7 MeV, for which there is a favorable energy window for sequential decay, going after the emission of the first proton to excited states of ^{17}F, instead of the ground state, and decaying finally to the ground state of ^{16}O after the second emission.

In fact, the authors of Ref. [17] found that around 30% of the decay goes to the sequential channel. This is quite surprising, since simple barrier penetration considerations would favour a decay with the largest amount of energy being carried out by the proton. Thus, one expects that the emission of the first proton would lead to the ground state of ^{17}F that is bound, and consequently the second proton would not be emitted. Another surprising fact, is that these states are quite narrow.

The authors of Ref. [18] also confirmed correlated two proton emission only from the excited 6.15 MeV state in ^{18}Ne, in good agreement with previous results.

From the discussion above, we can see that if on one side the assignment of spin levels in ^{18}Ne is quite relevant for the determination of astrophysical reaction rates, on the other side, the interpretation of proton decay data can provide unambiguous support to the identification of the nuclear energy levels.

Microscopic calculations to interpret the data strongly rely on a solid nuclear structure description of the parent and daughter nuclei. It is thus the purpose of this work to discuss a microscopic shell-model calculations for sequential two-proton decay from excited states in ^{18}Ne, calculate the decay observables, and identify the levels which are the best candidates for decay.

2. Sequential proton emission and the spectrum of ^{18}Ne

According to scattering theory, the half-life for decay from an initial state i to a final state f by one particle emission is given by, $T_{1/2} = \hbar \ln 2 / \Gamma_j^{if}$, where the decay width can be found [19] from the relation,

$$\Gamma_j^{if} = S_j^{if} \frac{\hbar^2 k \alpha_j^2}{m} \tag{2.1}$$

with m and k standing for the mass and wave number of the proton. The spectroscopic factor S_j^{if}, corresponds to the probability that taking away a particle with angular momentum j from an initial state i, will lead to a final state f. The quantity α_j is the asymptotic normalization of the

Table 1: Calculated excited states in ^{18}Ne with a total width smaller than 200 keV and a branching ratio for decay to unbound states larger than 0.7. The spin and parity, and energy of the decaying level are given in the first two columns, while the branching ratio and width are shown in the third and fourth ones.

J^π	E(MeV)	Br	Γ^i_{Tot} (keV)
5^-	10.239	0.87	162
4^-	10.349	0.84	19
7^-	10.695	1.00	4
0^-	10.776	1.00	200
2^-	10.806	0.77	104
4^-	12.187	0.73	140
6^-	14.734	0.77	168

proton single particle wave function in a state of spin j. It can be obtained from the solution of the Schrödinger equation with outgoing wave boundary conditions, with a realistic mean field potential [20].

The total width for decay is a sum of partial widths, for all possible channels with quantum numbers allowed by parity and momentum conservation, and for all final states, and is given by,

$$\Gamma^i_{Tot} = \sum_{jf} \Gamma^{if}_j \tag{2.2}$$

The branching ratios (Br), are simply the ratio between the partial decay width to the total width.

Besides the knowledge of the proton resonance, the spectroscopic factor is the most important quantity which is needed to obtain the decay width, and is determined from the matrix element of an annihilation operator between the initial and final states. In order to be able to calculate it, a shell-model calculation has to be performed to get the nuclear wave functions for a specific interaction.

We have chosen the interaction determined in Ref. [21]. This interaction was developed with the intent to describe intruder $1\hbar\omega$ negative parity states which appear at low excitation energies of sd shell nuclei, besides the normal $0\hbar\omega$ positive parity states. A p–sd–pf model space was used with a ^{4}He core allowing one nucleon jump between the major shells, and with parameters fitted to the experimental excitation energies. The interaction gives results in good agreement with experimental data for all sd nuclei.

Performing a standard shell model calculation with this interaction, we have determined the energy spectra and wave functions of ^{18}Ne and ^{17}F, and the corresponding spectroscopic factors. Solving the Schrödinger equation with the mean field potential given in Ref. [22], the wave function of the proton resonance were found, and making use of Eq. 2.1 the decay widths for proton emission were determined.

Amongst more than a thousand states we have calculated for the ^{18}Ne nucleus, we have selected only the ones which have a total width smaller than 200 keV, as only states with narrow widths have been observed experimentally. Since we are interested in identifying the cases where the emission of a second proton is energetically possible, we have calculated the branching ratio for decay to unbound proton states in ^{17}F. The latter, is obtained from the ratio from a width given by Eq. 2.2 where the summation is restricted to unbound states, and the total width. Selecting the states whose branching ratio is larger than 0.7, we found that only a few negative parity states fulfil this condition, and they lie at quite high energies.

The results are reported in Table 1, and confirm the experimental findings of Ref. [17]. Most probably, states with very high angular momentum have not been observed experimentally, since in the work of Ref. [17] the excitation mechanism used to populate the states was Coulomb excitation.

3. Conclusions

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, rather than to the ground state, as observed in the experimental studies of Raciti and collaborators [17]. Since at these energies proton decay is faster than γ decay, the nucleus prefers to emit sequentially the second proton to reach ^{16}O, instead of a γ that would lead to bound states of ^{17}F. With this calculation, we have shown that through the interpretation of proton decay data one accesses nuclear structure information relevant to nuclear astrophysics.

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