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Microscopic theory of the two-proton radioactivity

J. Rotureau[1,a], R. Chatterjee[1], J. Okołowicz[1,2], and M. Płoszajczak[1]

[1] Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM-CNRS/IN2P3, BP 55027, F-14076 Caen Cedex 05, France
[2] Institute of Nuclear Physics, Radzikowskiego 152, PL-31342 Kraków, Poland

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Abstract. We formulate the microscopic theory of the two-proton radioactivity based on the real-energy continuum shell model. This microscopic approach is applied to describe the two-proton decay from the 1_2^- excited state in ^{18}Ne.

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1 Introduction

Nuclear decays with three fragments in the final state are very exotic processes. The two-proton (2p) radioactivity is an example of such a process which can occur for even-Z nuclei beyond the proton drip line: if the sequential decay is energetically forbidden by pairing correlations, a simultaneous 2p decay becomes the only possible decay branch. In spite of long lasting efforts, no fully convincing experimental finding of this decay mode has been reported (see however data on 2p radioactivity of the ground state of ^{45}Fe [1,2,3] and of the second excited 1_2^- state of ^{18}Ne [4]). Recently, we have developed a theory of 2p radioactivity which is based on the extension of Shell Model Embedded in the Continuum (SMEC) [5,6] for the *two-particle* continuum. In this approach, the configuration mixing in the valence space is calculated microscopically and the asymptotic states are obtained in the S-matrix formalism [6]. This is in contrast to R-matrix based Shell Model (SM) formalism [7] or cluster model which does not account for the microscopic structure of the residual core nucleus [8].

2 Two-particle continuum in the shell-model embedded in the continuum

The Hilbert space is divided in three subspaces: Q, P and T. In Q subspace, A nucleons are distributed over (quasi-) bound single-particle (qbsp) orbits. In P, one nucleon is in the non-resonant continuum and $A-1$ nucleons occupy qbsp orbits. In T, two nucleons are in the non-resonant continuum and $(A-2)$ are in qbsp orbits. The coupling between Q, P and T subspaces changes the "unperturbed" SM Hamiltonian (H_{QQ}) in Q into the effective Hamiltonian:

$$H_{QQ}^{(\mathrm{eff})} = H_{QQ} + H_{QT}G_T^{+}(E)H_{TQ} + \left[H_{QP} + H_{QT}G_T^{+}(E)H_{TP}\right]\tilde{G}_P^{(+)}(E) \times \left[H_{PQ} + H_{PT}G_T^{(+)}(E)H_{TQ}\right], \quad (1)$$

where: $\tilde{G}_P^{(+)}(E) = [E^+ - H_{PP} - H_{PT}G_T^{(+)}(E)H_{TP}]^{-1}$ is the Green's function in P modified by the coupling to T, and $G_T^{(+)}(E) = [E^+ - H_{TT}]^{-1}$ is the Green's function in T. In the above equations, H_{PP}, H_{TT} are the unperturbed Hamiltonians in P, T subspaces, respectively, and H_{QP}, H_{PQ}, H_{PT}, H_{TP} are the corresponding coupling terms between Q, P, and T subspaces. The second term on the r.h.s. of eq. (1) describes a di-proton emission, and the third term describes the modification due to the mixing of sequential 2p, di-proton and 1p decay modes. In solving SMEC problem with $H_{QQ}^{(\mathrm{eff})}$, the radial single-particle wave functions in Q and the scattering wave functions in P and T are generated by a self-consistent procedure starting with the average potential of Woods-Saxon type with the spin-orbit and Coulomb parts included, and taking into account the residual coupling between Q, P and Q, T subspaces [5,6,9]. For the SM effective interaction in H_{QQ} we take either WBT or (psdfp) interaction [9].

2.1 Two-proton decay with three-body asymptotics

We consider the 2p decay mode from the 1_2^- state in ^{18}Ne at the excitation energy of 6.15 MeV. In the limit of no coupling between P and T subspaces, the effective

[a] Conference presenter; e-mail: rotureau@ganil.fr

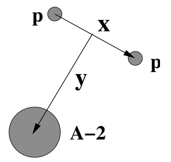

Fig. 1. The three-body Jacobi coordinate system. The hyperradius is $\rho = \sqrt{x^2 + y^2}$.

Hamiltonian (eq. (1)) reduces to [9]

$$H_{QQ}^{(\mathrm{eff})} = H_{QQ} + H_{QP} G_P^+(E) H_{PQ} + H_{QT} G_T^+(E) H_{TQ} \, .$$

First, we calculate the contribution due to coupling with one proton in the continuum of ^{17}F

$$\langle 1_i^- | H_{QQ} + H_{QP} G_P^+(E) H_{PQ} | 1_j^- \rangle,$$

which yields a "mixed" 1_2^- state (ϕ^{mix}) of ^{18}Ne. From this state we go on to calculate the widths due to coupling with the 2p continuum: $\langle \phi^{\mathrm{mix}} | H_{QT} G_T^+(E) H_{TQ} | \phi^{\mathrm{mix}} \rangle$. This can be written formally as $\langle w | \omega \rangle$, where $\langle w | = \langle \phi^{\mathrm{mix}} | H_{QT}$ is identified as the source term and ω, which is an extension of the discrete state wave function in the continuum and is given by: $| \omega \rangle = G_T^+(E) H_{TQ} | \phi^{\mathrm{mix}} \rangle$. It is expanded in hyperspherical harmonics (HH) 3-body Jacobi coordinate system (see fig. 1):

$$\omega(\mathbf{x}, \mathbf{y}) = \rho^{-5/2} \sum_{c \equiv (t, K, L, S, l_x, l_y)} \omega_c(\rho) \mathcal{Y}_{K,L,S}^{l_x, l_y}(\Omega_5).$$

In the above equation, a channel (c) is specified by t —a bound state of the $(A-2)$ residual nucleus, l_x —the relative angular momentum between the two protons, l_y —the relative angular momentum between the two protons and the $(A-2)$ nucleus, S-the total spin of the two protons, $L = l_x \otimes l_y$, and K-the hyper angular momentum. $\mathcal{Y}_{K,L,S}^{l_x, l_y}(\Omega_5)$ is the HH function and $\omega_c(\rho)$ is the solution of inhomogeneous integro-differential coupled channel equations with the SM source $w_c(\rho)$:

$$\left[-\frac{\hbar^2}{2m} \left(\frac{\mathrm{d}^2}{\mathrm{d}\rho^2} - \frac{(K+3/2)(K+5/2)}{\rho^2} \right) - E \right] \omega_c(\rho) \qquad (2)$$
$$+ \sum_{c'} V_{cc'}^{\mathrm{loc}}(\rho) \omega_{c'}(\rho) + \sum_{c'} \int \mathrm{d}\rho' V_{cc'}^{\mathrm{n\text{-}loc}}(\rho') \omega_{c'}(\rho') = w_c(\rho).$$

In the above equation, the local potential $V_{cc'}^{\mathrm{loc}}(\rho)$ contains the interactions between the two protons in continuum states. The non-local potential $V_{cc'}^{\mathrm{n\text{-}loc}}(\rho')$ in eq. (2) is a direct consequence of accounting for the 2-body residual interaction between the emitted protons and *all* the valence particles in the $(A-2)$ residual nucleus. The Coulomb problem is treated approximately by the use of Coulomb functions of half-integer order with Sommerfeld parameter corresponding to an "effective charge" in each hyperspherical channel found by neglecting the off-diagonal Coulomb matrix elements (which are much smaller than the diagonal ones) in the previous equation. In future studies, this will allow us to investigate the influence of the effective SM interaction on the correlations between emitted protons and from that data extract information about the pairing field in the parent nucleus.

Table 1. Widths ($\Gamma^{(\mathrm{seq})}$) and branching ratios ($B^{(\mathrm{seq})}$) for the sequential decay and widths ($\Gamma^{(\mathrm{2p})}$) for di-proton cluster decay with different SM effective interactions.

Interaction	$\Gamma^{(\mathrm{seq})}$ (eV)	$B^{(\mathrm{seq})}_{[^{17}\mathrm{F}^*(1/2^+)]}$	$\Gamma^{(\mathrm{2p})}$ (eV)
psdfp	88.80	92.80%	1.89
WBT	13.60	80.20%	1.01

2.2 Sequential and cluster emissions as limits of the effective Hamiltonian (1)

In the limit of $H_{QT}(H_{TQ})$ being zero in eq. (1), we can calculate the contribution of the sequential 2p emission from the "mixed" 1_2^- state (ϕ^{mix}) of ^{18}Ne as

$$\langle \phi^{\mathrm{mix}} | H_{QP} \tilde{G}_P^{(+)}(E) H_{PT} G_T^{(+)}(E) H_{TP} G_P^{(+)}(E) H_{PQ} | \phi^{\mathrm{mix}} \rangle.$$

In another limit of eq. (1), we can also consider a cluster emission of two protons with $H_{PT}(H_{TP})$ being zero and protons in the cluster being coupled to total spin $S=0$ and with relative orbital angular momentum between them (l_x) to be zero. In this limit, s-wave final state interaction in $p+p$ intermediate system can be included phenomenologically [10]. In both these limits the microscopic structure of the residual nucleus is still accounted for, although the asymptotics become 2-body. The widths $\Gamma^{(\mathrm{seq})}$, and the branching ratios $B^{(\mathrm{seq})}_{[^{17}\mathrm{F}^*(1/2_1^+)]}$ to the $1/2_1^+$ continuum states of ^{17}F for the sequential decay, and the widths for the di-proton cluster decay, for different SM effective interactions are shown in table 1, obtained with a spin-exchange contact force residual interaction [9]. These results indicate that the 2p decay in ^{18}Ne is essentially a sequential process. Strong dependence of $\Gamma^{(\mathrm{seq})}$ on the SM effective interaction is found. The dominant contribution to $\Gamma^{(\mathrm{seq})}$ comes from the resonant continuum of the weakly bound $1/2_1^+$ state of ^{17}F.

3 Conclusions

We have extended the SMEC to describe the 2p radioactivity. This fully microscopic approach with 3-body asymptotics and with realistic finite range interactions will allow us to study the relation between an effective NN interaction and radial features of the pairing field, on one side, and also the proton-proton correlations in the asymptotic state. The calculations for heavy 2p emitters are now being pursued.

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