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β delayed emission of a proton by a one-neutron halo nucleus

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ABSTRACT

Some one-neutron halo nuclei can emit a proton in a β decay of the halo neutron. The branching ratio towards this rare decay mode is calculated within a two-body potential model of the initial core + neutron bound state and final core + proton scattering states. The decay probability per second is evaluated for the ^{11}Be, ^{19}C and ^{31}Ne one-neutron halo nuclei. It is very sensitive to the neutron separation energy.

1. Introduction

Some neutron-rich halo nuclei can emit a proton. This process is possible if the neutron separation energy is very small. Indeed, when a sufficiently weakly bound halo neutron β decays, the produced proton can be emitted, possibly together with neutrons. Processes where this proton is bound with one or two neutrons have been observed in the β delayed deuteron and triton decays of ^{6}He and ^{11}Li [1–8]. Recently we have calculated the branching ratio of an even rarer process where the proton remains unbound but is accompanied by a free neutron [9]. This decay is uniquely possible for ^{11}Li, among nuclei with known separation energies. The study has been performed in a three-body model with a simplified description of the continuum. An even simpler process is however possible.

A one-neutron halo nucleus can be viewed as a normal nucleus, the core, to which a neutron is bound in an orbital with a large radius. The β decay of the bound halo neutron may occur, releasing the proton, under the condition of energy conservation

$$S_{\rm n} < (m_n - m_p - m_e)c^2 \approx 0.782\ \text{MeV}, \tag{1}$$

where $S_{\rm n}$ is the neutron separation energy of the decaying nucleus and m_n, m_p and m_e are the neutron, proton and electron masses, respectively. Among one-neutron halo nuclei for which S_n is known with sufficient precision, this decay is allowed at least for ^{11}Be and ^{19}C, and probably for ^{31}Ne. It should be observable if the branching ratio is large enough. This decay mode of ^{11}Be has been considered by Horoi and Zelevinsky but their results do not seem to have been published [10]. Here we study this rare decay mode within a two-body potential model. The initial halo nucleus is treated as a core + neutron bound state. The final states lie in the core + proton continuum. How rare is this decay is the main question raised in the present exploratory study.

2. Decay probability for β delayed proton emission

The β decay of the halo neutron releases the resulting proton from the core. The distribution of decay probability per time unit as a function of the energy $E < Q$ of the relative motion of the two particles is given by [9]

$$\frac{dW}{dE} = \frac{1}{2\pi^3}\frac{m_e c^2}{\hbar} G_\beta^2 f(Q-E)\left(\frac{dB(\mathrm{F})}{dE} + \lambda^2 \frac{dB(\mathrm{GT})}{dE}\right), \tag{2}$$

where $G_\beta \approx 2.996 \times 10^{-12}$ is the dimensionless β-decay constant and $\lambda \approx -1.268$ is the ratio of the axial-vector to vector coupling constants. The Fermi integral $f(Q-E)$ depends on the kinetic energy $Q-E$ available for the electron and antineutrino with

$$Q = (m_n - m_p - m_e)c^2 - S_{\rm n}. \tag{3}$$

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The total decay probability per time unit W is obtained by integrating (2) from zero to Q. The branching ratio can then be derived as

$$\mathcal{R} = W t_{1/2} / \ln 2, \tag{4}$$

where $t_{1/2}$ is the half life of the halo nucleus.

In the present model, the halo nucleus is described as a two-body core + neutron system in its ground state with total angular momentum J_i resulting from the coupling of the orbital momentum l_i of the relative motion and the neutron spin $s = 1/2$. The spin of the core is assumed to be zero. The parity of the initial state is $(-1)^{l_i}$. The radial wave function is denoted as $u_{il_iJ_i}$ with the normalization $\int_0^\infty |u_{il_iJ_i}(r)|^2\,dr = 1$. It is obtained from a potential V_i adjusted to reproduce the experimental neutron separation energy S_n.

The final scattering state of the core and the proton is a distorted wave with wave vector $\boldsymbol{k}$. Because of selection rules, only some partial waves with total angular momentum J_f resulting from the coupling of the orbital momentum l_f and the proton spin s are allowed. The radial wave functions $u_{kl_fJ_f}$ for a wave number $k = \sqrt{2\mu E/\hbar^2}$ where μ is the core–proton reduced mass are obtained with a potential V_f describing the core + proton system. They are normalized according to $\int_0^\infty u_{kl_fJ_f}(r) u_{k'l_fJ_f}(r)\,dr = \delta(k - k')$. The potential V_f is usually poorly known when the core is unstable.

Within this model, the Fermi reduced decay probability is given by

$$\frac{dB(\mathrm{F})}{dE} = \frac{1}{\hbar v} |I_{l_iJ_iJ_i}|^2 \tag{5}$$

since $J_f = J_i$, and the Gamow–Teller reduced decay probability is given by

$$\frac{dB(\mathrm{GT})}{dE} = \frac{6}{\hbar v} \sum_{J_f} (2J_f + 1) \begin{Bmatrix} J_f & s & l_i \\ s & J_i & 1 \end{Bmatrix}^2 |I_{l_iJ_iJ_f}|^2 \tag{6}$$

with the relative velocity $v = \hbar k/\mu$ and the radial integrals

$$I_{lJ_iJ_f} = \int_0^\infty u_{klJ_f}(r) u_{ilJ_i}(r)\,dr. \tag{7}$$

If the final wave function does not depend on J_f, the Gamow–Teller term simplifies as

$$\frac{dB(\mathrm{GT})}{dE} = 3\frac{dB(\mathrm{F})}{dE}. \tag{8}$$

The reduced decay probability can then also be written as

$$\frac{dW}{dE} = W_n \frac{f(Q - E)}{f_n} \frac{dB(\mathrm{F})}{dE}, \tag{9}$$

where W_n is the free-neutron β decay probability per second and f_n is the corresponding Fermi integral.

With respect to a free neutron, the decay probability is affected in two ways. First, the ratio $f(Q - E)/f_n$ is small due to the reduction of phase space, since $f_n \equiv f(Q + S_\mathrm{n})$. It becomes extremely small when E tends to Q. The β delayed proton emission is favored by very small separation energies S_n. Second, the reduced decay probability (5) appearing in (9) is proportional to the square of a radial integral (7). Because of the Coulomb repulsion and the smallness of the Q value, the scattering waves are small at distances where the overlap with the bound state is important. When E tends to zero, they tend to zero as $k^{1/2}\exp(-\pi\eta)$ [11], where $\eta = Z_c e^2/\hbar v$ is the Sommerfeld parameter. They become thus smaller with increasing charge $Z_c e$ of the core. They also become smaller with increasing orbital momentum l_f because of the centrifugal barrier. Hence, at given Q value, we expect the decay probability to be largest for the lightest halo nuclei and for the halo neutron in the s wave.

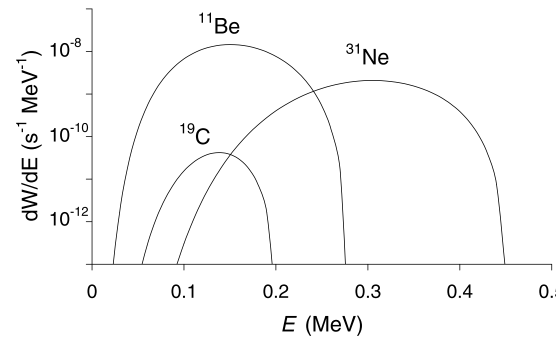

Fig. 1. Distribution of decay probability per second as a function of the energy E of the core + proton relative motion for the β delayed proton emission by ^{11}Be, ^{19}C and ^{31}Ne.

3. Results and discussion

Before making explicit calculations, we have to specify the choice of potentials. The Fermi strength (5) is proportional to the square of the overlap integral (7) between the initial and final radial wave functions. In order to have a realistic overlap, it is useful to have a correct node structure for these wave functions. Indeed, the presence of nodes leads to an integrand that changes sign one or several times and thus to a reduction of the overlap at small distances. Spectroscopic factors can also affect the size of the Fermi strength but, given the limited knowledge on these quantities, we choose to ignore them in the present exploratory study. Finally, absorption in the core + proton optical potential might also play a role. However, the energies of the states after decay are lower than, or comparable to, the energy of the Coulomb barrier. Absorption should be weak and can safely be neglected.

Hence, we shall use real potentials V_i and V_f which should be deep enough to provide a realistic node structure of the initial and final radial wave functions. To keep the model simple we only use central Woods–Saxon potentials with range $r_0 A_c^{1/3}$ where A_c is the mass number of the core. The depth is adapted to the separation energy for the core + n system. The same form factor with an additional point–sphere Coulomb potential is employed for the final core + p elastic scattering. Because of the small energies, the phase shifts are small and the sensitivity to V_f is weak. Let us now consider explicit cases.

The best documented weakly bound one-neutron halo nucleus is ^{11}Be. Its $1/2^+$ ground state has a separation energy of about 501 keV [12] and its half life is $t_{1/2} \approx 13.8$ s [13]. The halo neutron is described by an s wave. The parameters of the Woods–Saxon potential are taken as $r_0 = 1.2$ fm, $a = 0.6$ fm and $V_{i0} = 62.52$ MeV [14]. In the s wave, this potential possesses one unphysical forbidden state. The same parameters are used for the final potential except V_{f0}. The ^{11}B nucleus has a proton separation energy $S_\mathrm{p} \approx 11.228$ MeV [15]. Its lowest $1/2^+$ state is located at the excitation energy $E_x \approx 6.79$ MeV. In the s wave, $V_{f0} = 84.1$ MeV is adjusted so that the potential possesses one forbidden state and one bound state fitted to the energy $E_x - S_\mathrm{p} \approx -4.52$ MeV with respect to the ^{10}Be + p threshold. Bound and scattering states should thus have a reasonable node structure.

The Q value (3) is small, 0.281 MeV. The distribution of decay probability is displayed in Fig. 1. The most probable energies of