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Two-proton decay of the ^{6}Be ground state and the double isobaric analog of ^{11}Li

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Abstract. Two-proton decay is discussed in a number of light isobaric multiplets. For the lightest two-proton emitter, ^{6}Be, the momentum correlations between the three decay products were measured and found to be consistent with quantum-mechanical three-cluster-model calculations. Two-proton decay was also found for two members of the A=8 and A=11 quintets. Finally, a third member of the A=11 sextet, the double isobaric analog of the halo nucleus ^{11}Li in ^{11}B was observed by its two-proton decay.

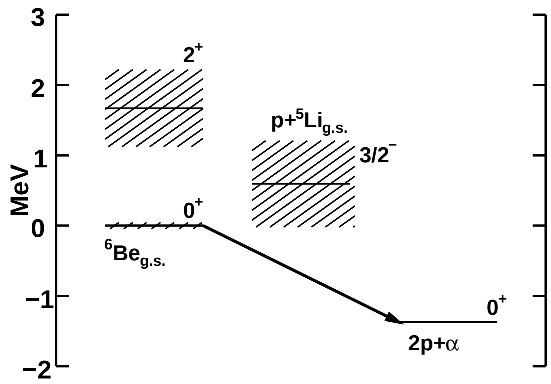

Figure 1. Level scheme of states associated with the $2p$ decay of ^{6}Be

1. Introduction

Simultaneous two-proton decay is the prompt emission of two protons from a nuclear state. It should be differentiated from sequential two-proton decay where the emission of the two protons is separated in time due to the presence of a long-lived intermediate state in the (Z-1,A-1) system. Goldansky described a type of simultaneous emission in ground-state nucleus where the (Z-1,A-1) intermediate ground state is energetically unavailable [1]. Such a situation can be found in some even-Z, proton-rich nuclei where the proton-pairing interaction makes the $1p$ separation energy positive, while the $2p$ separation energy is negative. Examples of Goldansky decay can be found in ^{45}Fe and ^{48}Ni. A second type of simultaneous decay, called democratic two-proton decay, occurs when the intermediate state is very wide and short lived and thus there is no longer a real separation between the two decay steps [2]. In ground-state nuclei beyond the proton-drip line, we also find this situation for even-Z systems. In fact, the two types of two-proton decay are not necessary separate in light nuclei. This can be seen for ^{6}Be $2p$ decay where the levels for the $1p$ and $2p$ decay are shown in Fig. 1. Most of the strength of the $^{5}\mathrm{Li}_{g.s.}$ intermediate state is inaccessible so this gives the decay a Goldansky character. However, the width of this state is very wide (Γ=1.23 MeV) and so the decay is also democratic.

2. Two-proton decay of ^{6}Be

^{6}Be is the lightest two-proton ground-state emitter, and as it is relatively easy to make, it should become a benchmark system for studying two-proton decay. We have formed $^{6}\mathrm{Be}_{g.s.}$ in two ways: via the α decay of an inelastically-excited ^{10}C beam [3] and via neutron knockout from a ^{7}Be beam [4]. In both cases the momenta of each of the three decay products were measured permitting us to examine their correlations. These correlations can be represented as two-dimensional distributions [3]. Figure 2(a) show one such representation, the Jacobi T system, where the two dimensions are chosen as E_x/E_T, the fraction of the total decay energy in the relative motion of the two protons, and θ_k, the angle between the relative p-p and the α-particle momenta.

In comparison, a theoretical prediction is shown in Fig. 2(b) from the quantum-mechanical three-cluster model of Grigorenko *et al.* [3]. Here the decaying wavefunction is constructed with outgoing asymptotics and good success has been obtained in describing the observed correlations in the two-proton decay of ^{45}Fe [5]. This model also reproduces the experimental data for ^{6}Be quite well in Fig. 2, in particularly it reproduces the regions of small yield, i.e., E_x/E_T=0 and $\cos(\theta_k)$=$\pm$1, E_x/E_T $\sim$0.62. These regions occurs where two of the three fragments have almost zero relative velocity and thus in a prompt-decay scenario where the fragments are all initially close together, the long-range Coulomb interaction will lead to a suppression of such events.

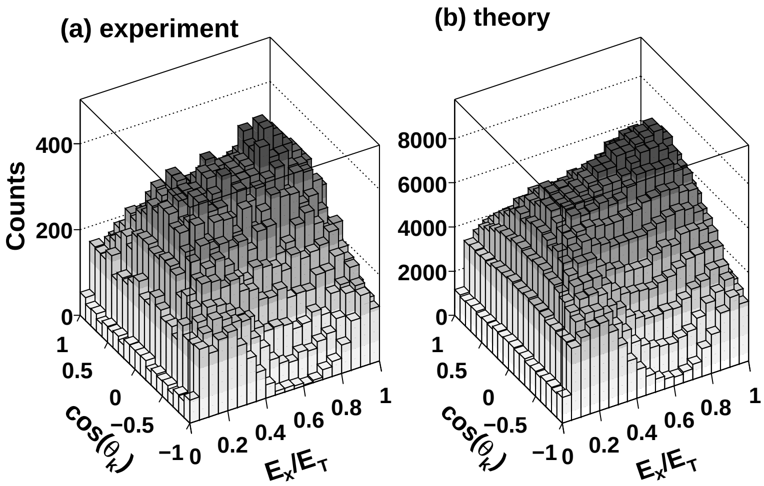

Figure 2. Comparison of (a) the experimental and (b) the theoretical correlation distributions in the Jacobi T system for the two-proton decay of $^{6}\mathrm{Be}_{g.s.}$.

3. Two-proton decay in the A=8 and 11 quintets

There is a close connection between two-proton decay and 2-neutron halo nuclei. For instance, ^{6}Be is the mirror of ^{6}He the lightest $2n$ halo nucleus and thus ^{6}Be could be considered to have a leaky two-proton halo. These two nuclei are part of an isospin triplet (T=1) with the third member being the isobaric analog state in ^{6}Li. As all members of an isospin multiplet have very similar structure, this state could be considered to have a two-nucleon halo, i.e., an α core with a neutron plus a proton in the halo with important T=1, n-p pairing interactions.

We recently showed that $^{8}\mathrm{C}_{g.s.}$ also undergoes two-proton decay, in fact it undergoes two steps of two-proton decay thought the $^{6}\mathrm{Be}_{g.s.}$ intermediate state [4]. ^{8}C is the mirror nucleus of ^{8}He, a $4n$ halo system and these two nuclei are connected by an isospin quintet (T=2). Again we expect that all members of this quintet will have similar halo structure. We have recently demonstrated that a second member of the quintet also undergoes two-proton decay, i.e., the isobaric analog of ^{8}C in ^{8}B [4]. This system undergoes $2p$ decay to the isobaric analog state in ^{6}Li, which subsequently gamma decays. Two-proton decay is the only isospin-allowed decay mode for this state, and thus, to the extent that isospin is conserved, this is a Goldansky-type decay.

A second example of such a decay was recently observed in the A = 12 quintet [6]. Both $^{12}\mathrm{O}_{g.s.}$ and its isobaric analog in ^{12}N were observed via two proton, i.e. from the $2p$+^{10}C and $2p$+$^{10}\mathrm{B}_{IAS}$ exit channels. ^{12}O is a democratic $2p$ emitter, while $^{12}\mathrm{N}_{IAS}$, similar to $^{8}\mathrm{B}_{IAS}$, is also of the Goldansky type to the extent that isospin is conserved. This was the first time that $^{12}\mathrm{N}_{IAS}$ has been observed.

Wigner showed that the masses of the members of an isobaric multiplet should follow a quadratic dependence called the isobaric multiplet mass equation (IMME) [7];

$$M(T,T_Z) = a + bT_Z + cT_Z^2. \tag{1}$$

Deviations from this behavior can be due to isospin-nonconserving forces, however, the quadratic dependence works quite well in practice. The largest known deviations are for the A=8 quintet and the A=7 and 9 quartets, where the maximum deviation is <100 keV [8]. With the completion of the A=12 quintet and the measurement of the $^{12}\mathrm{N}_{IAS}$ mass and a re-measurement of the $^{12}\mathrm{O}_{g.s.}$ mass we are now able to look to deviations from the IMME in this system. However in this case, no deviations from the quadratic dependence were found [6]. The reasons for the difference between the A=8 and A=12 quintets is not understood.

4. Two-proton decay in the A=11 sextet

We have also looked at two-proton decay in the A=11 sextet (T=5/2). This sextet is anchored on the neutron-rich side by the two-neutron halo nucleus ^{11}Li (T_Z=5/2) which has a very extended halo. In the halo-and-core model of Suzuki and Yabana [9], the wavefunctions of the three most neutron-rich members are expressed in terms of their core and halo components as

$$\left|^{11}\mathrm{Li}_{g.s.}\right\rangle = \left|^{9}\mathrm{Li}_{g.s.}\right\rangle |nn\rangle\,, \tag{2}$$

$$\begin{aligned}\left|^{11}\mathrm{Be}_{IAS}\right\rangle &= \sqrt{3/5}\left|^{9}\mathrm{Be}\right\rangle_{T=3/2}|nn\rangle \\ &+ \sqrt{2/5}\left|^{9}\mathrm{Li}_{g.s.}\right\rangle |np\rangle_{T=1}\,,\end{aligned} \tag{3}$$

$$\begin{aligned}\left|^{11}\mathrm{B}_{DIAS}\right\rangle &= \sqrt{3/10}\left|^{9}\mathrm{B}\right\rangle_{T=3/2}|nn\rangle \\ &+ \sqrt{6/10}\left|^{9}\mathrm{Be}\right\rangle_{T=3/2}|np\rangle_{T=1} \\ &+ \sqrt{1/10}\left|^{9}\mathrm{Li}_{g.s.}\right\rangle |pp\rangle\,.\end{aligned} \tag{4}$$

For the isobaric analog of $^{11}\mathrm{Li}_{g.s.}$ ($^{11}\mathrm{Be}_{IAS}$), the two-neutron halo contribution (60%) is bound, but the n+p contribution (40%) is unbound by 1.020(20) MeV explaining why $^{11}\mathrm{Be}_{IAS}$ was discovered at RIKEN in 1997 through the n+p+^{9}Li exit channel[10]. For the double isobaric analog state (DIAS) of ^{11}Li in ^{11}B, in addition to $2n$ and n+p halo contributions, we now have a small component with a $2p$ halo (10%). The latter two components are both expected to be unbound and in this work we report on the observation of this third member of the sextet, the double isobaric analog state (DIAS) in ^{11}B, through the detection of its $2p$+^{9}Li exit channel.

The experimental data comes from a previously published experiment utilizing a secondary ^{12}Be beam at E/A=50 MeV produced at the Coupled-Cyclotron Facility at the National Superconducting Cyclotron Laboratory at Michigan State University. See Refs. [11, 12] for details of the experiment. The beam impinged on a 1-mm-thick target of polyethylene or a 0.4-mm-thick target of carbon. The $2p$+^{9}Li decay products were detected in the 16 element HiRA array. Figure 3 shows the spectrum of the total decay kinetic energy (E_T) for ^{11}B to this exit channel. It was determined from the three detected fragments using the invariant-mass method. This spectrum was obtained with the polyethylene target. The corresponding spectrum obtained with the carbon target was essentially empty indicating that these events came predominately from interactions with the hydrogen component of the target via the ^{12}Be(p,2n)^{12}B reaction.

With now three members of the sextet known, the coefficients of the IMME can be determined and used to extrapolate to the three unknown proton-rich members. With this extrapolation we find that $^{11}\mathrm{O}_{g.s}$, the mirror state of $^{11}\mathrm{Li}_{g.s}$, should undergo two-proton decay with a decay energy of E_T=3.21(84) MeV.

The mass excesses of the known members of the sextet are plotted in Fig. 4 with the quadratic fit to the data. In comparison we also show a curve where the Coulomb displacement energies were determined assuming a homogeneous sphere where the radius was determined from the A=11 doublets (T=1/2). The curve was shifted up in mass to match the $^{11}\mathrm{Li}_{g.s.}$ mass. It

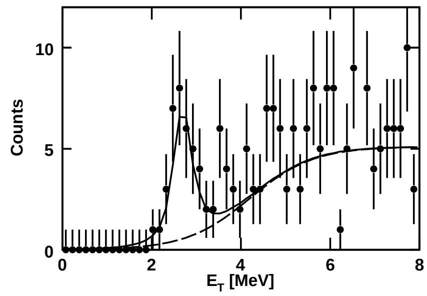

Figure 3. Distribution of ^{11}B total decay energy determined for detected $2p$+^{9}Li events. The curves shows a fit to the double isobaric analog state and the background under it.

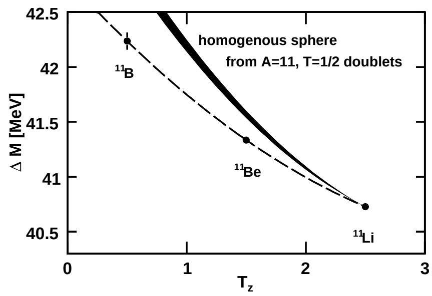

Figure 4. Mass excesses of the three neutron-rich members of the A=11 sextet. The thin-dashed curve shows the quadratic equation through the three data points used to extrapolate to the proton-rich members. The thick curve shows the expected dependence for a homogeneous sphere who radius was determined from the A=11, T = 1/2 doublets.

is clear that the mass dependence is significantly reduced in the sextet (T=5/2) compared to the doublets (T=1/2) and this undoubtedly reflects the reduced Coulomb energy due to the more extended halo structure of the sextet. In fact the observed dependence can be reproduced when the core-halo Coulomb energies are determined from the halo wavefunctions calculated for ^{11}Li$_{g.s.}$ by Hagino and Sagawa [13].

5. Conclusion

In conclusion we have looked at two-proton decay along a number isobaric multiplets. The correlation between the momenta of the decay products in the two-proton decay of ^{6}Be were were well described by a quantum-mechanical three-cluster model. Two proton decay was also observed in the proton-rich members of both the A=8 and A=12 quintets. Finally, we have observed a third member of A=11 sextet; the double isobaric analog of the halo nucleus ^{11}Li in ^{11}B. The variation in mass along this multiplet was found consistent with an extended halo structure.

Acknowledgments

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