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First observation of beta-delayed deuteron emission

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Abstract

Beta-delayed deuteron emission has been observed in the decay of ${}^6\text{He}$ with a branching ratio of $(2.8 \pm 0.5) \times 10^{-6}$. The main features of the measured spectrum are described using the R-matrix formalism. An important fraction of the missing Gamow-Teller sum-rule strength must reside in the 5.7 MeV 1^+ resonance in ${}^6\text{Li}$.

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1. *Introduction.* The established decay scheme of $0.807\text{ s }^6\text{He}$ is extremely simple with a single beta-decay branch to the 1^+ ground state of ^6Li . We report here evidence for a second beta-decay branch leading to an unbound final state with a deuteron and an alpha particle. This result represents yet another mode of beta-delayed particle emission from neutron-rich nuclei in addition to those already found during the last decade: $(\beta, 2n)$ [1,2], $(\beta, 3n)$ [3], $(\beta, 4n)$ [4], (β, t) [5] and (β, α) [6].

The motivation behind the present work would not be complete without mentioning that we hope to be able to observe beta-delayed deuteron emission also from other nuclei near the neutron drip line. The anomalously large matter radii found by Tanihata et al. [7] for ^6He , ^8He and ^{11}Li suggest that the low binding energy of the last neutrons leads to a spatially extended wave function, the neutron halo [8]. One must assume that the halo predominantly consists of a neutron pair in a 1S state, and it is nearlying to conjecture that it can decay into an unbound deuteron with a transition probability corresponding to that of a superallowed beta decay. This decay mode is energetically permitted for the cases mentioned. It is doubtful whether ^6He can be viewed as having a well-developed halo, cf. also theoretical calculations of its radius [9,10], but we nevertheless decided to begin with this case, which offers a very favourable production rate and a simple, clean decay.

2. *Experiment and results.* The ^6He activity (10^7 atoms/s) was produced [11] at the ISOLDE on-line isotope separator at the CERN Synchro-cyclotron. With the experimental set-up sketched in fig. 1 deuterons and alphas were detected in opposite directions with counters positioned 10 cm from the collection point. Collimators were placed around the collection point and just in front of the detectors giving a solid angle of about 7×10^{-4} sr for both, and coincidences between the two detectors were recorded and analyzed off-line. The spectrometer allowed an investigation of the angular dependence near 180° .

With the spectrometer set to 180° , a total of 147 coincidences were observed in 24 h. A run of 2 h with the isotope separator set at a mass position between 5 and 6 served to check for cross-contamination and gave zero counts. Another run of 5 h with one spectrometer arm turned by 6° served to test the angular distribution and again zero counts were seen, which shows that the observed events must arise from two-body break-up. The magnetic field assures that the particles are heavier than protons. The only beta-delayed particle branch that is energetically possible for ^6He is the one leading to a deuteron and an alpha particle (see the decay scheme in fig. 2). The coincident spectrum, shown in fig. 3, therefore must arise from beta-delayed deuteron emission, an interpretation that is further supported by the good agreement between calculated and measured energy spectra discussed later in this paper.

The following experimental effects must be considered in the analysis: (i) Energy loss in the carbon foil and in the deadlayer of the Si detector, and multiple scattering and charge exchange in the foil. (ii) Geometrical cut-offs due to the collimators, giving an energy-dependent coincidence efficiency. (iii) Summing of the alpha and deuteron spectra due to the lack of particle identification. A reliable unfolding of the deuteron and alpha spectra for ^6He was possible, however, since the alphas initially have half the energy of the deuterons and a larger energy loss. These effects were modelled in Monte-Carlo calculations, which were tested with data from the beta-delayed alpha decay of ^8Li , and the right hand side of fig. 2 shows the deduced excitation spectrum for ^6Li as a function of the c.m.-energy in the alpha-deuteron system. The branching ratio for deuterons with more than 250 keV is $(2.8 \pm 0.5) \times 10^{-6}$, and the deuteron intensity below this energy is presumably small.

3. *Discussion.* The low branching ratio corresponds, if converted into a beta strength function, to a total strength of about 5×10^{-3} in units of $6140/(ft g_A^2/g_V^2)$. This is too small for the picture of direct beta-decay into the continuum to hold, but we shall show that it follows from the structure of known ^6Li resonances. There are two 1^+ states (fig. 2) accessible to beta-decay, the upper one through its tail only, so that the measured spectrum has a maximum in a region where no 1^+ levels are present. This arises from the combined phase space of the beta and deuteron channels.

Figure 2. Schematic illustration of the allowed Gamow-Teller beta-decay of ${}^6\text{He}$ into 1^+ states of ${}^6\text{Li}$, both of which lie outside the energy window symbolized by the shaded area. On the right hand side is shown the deduced spectrum of the beta-decays into the continuum.

The spectrum was calculated from R-matrix theory [12], for which a detailed account of the formalism and references to the literature is given in ref. [13]. The results are particularly transparent for the case of a single broad resonance λ . Here, the beta decay probability per unit c.m. energy E can be written in a form that resembles the Breit-Wigner shape,

$$w(E) = \frac{\ln 2}{K} f(Q-E) G_A^2 B_{GT} \times \frac{1}{\pi} \sum_l \frac{\Gamma_l(E)/2}{(E_\lambda + \Delta_l(E) - E)^2 + \Gamma_l(E)^2/4} \quad (1)$$

The first factor contains the normal beta-decay probability $(\ln 2/K)/G_A^2 B_{GT}$ with $K/G_A^2 = 3862s$, $f(Q-E)$ is the statistical rate function, and B_{GT} the Gamow-Teller reduced transition probability. The summation is over angular momentum l . The level position parameter is E_λ , the threshold for particle emission is E_p and the functions $\Delta_l(E)$ and $\Gamma_l(E)$, the level shift and the width, are defined as

$$\Delta_l(E) = -\gamma_l^2 S_l(E-E_p) \quad (2)$$

$$\Gamma_l(E) = 2\gamma_l^2 P_l(E-E_p) \quad ,$$

where γ_l^2 is the reduced width of the level, and P_l and S_l are the penetration and shift factors. The energy dependent factors are all known; stated briefly, they come from phase space in the "incoming channel" (the beta-decay) and from the penetrability and phase space in the "outgoing channel" (the

particle emission). The parameters entering into the theory are the resonance energy, the reduced width of the state, giving the shape of the distribution, and the reduced beta-decay transition probability, giving the absolute strength.

Figure 3. The energy spectrum of coincident events measured in the Si-detector corrected for the electronic coincidence efficiency. As the experiment has no direct particle identification, the spectrum represents the sum of the alpha and deuteron contributions. We note that the channel electron multiplier has an approximately constant response down to energies of order 10 keV whereas the Si detector has a cut-off, which in our case was at 180 keV, shown as a dashed line. The total uncertainties are shown by the error bars. The curves are R-matrix calculations as explained in detail in the text; the calculated spectra have been folded with the experimental efficiencies, corrected for energy loss and normalized to the total collected activity, corrections giving rise to an uncertainty of 25 % on the absolute scale. Finally the spectra of alphas and deuterons have been added. The dotted line is the contribution from the 5.7 MeV state alone, dominated by d -wave emission, and the full-drawn line includes also contributions from the ground state leading to significant interference in the s -wave channel.

The expressions given above apply if the (β, d) decay is attributed entirely to the 1^+ excited state. The parameters for the outgoing channel are then determined from the $d + \alpha$ scattering experiments by Hardekopf et al. and Jenny et al. [14], who found an energy of 5.7 ± 0.1 MeV and reduced widths of 5 keV (s wave) and 2500 keV (d wave). The channel radius, which determines the penetration factors, was taken to be 4.12 fm, and the same value has been used in the present work. The strength in the incoming channel can be estimated from the Gamow-Teller sum rule $\sum B_{GT} - \sum B_{GT}^+ = 3(N - Z) = 6$, by making the reasonable assumption that β^+ strength arising from the filled $0s$ shell is negligible. The measured strength to the ground state is $B_{GT}(gs) = 4.75$ and ascribing all missing strength to the 1^+ resonance one has $B_{GT}(5.7) = 1.25$. The result of this calculation is shown in fig. 3 as a dotted line, where in this case the s -wave contribution is unimportant. Qualitatively there is good agreement with experiment, but one notes that the calculated intensity is low and, more important, that the shapes differ, so

that there is an excess of intensity at low excitation energies. The latter problem cannot be ascribed to the overall normalization and cannot be remedied by another choice of $\gamma_2^2(5.7)$. One therefore must consider contributions from the 1^+ ground state of ${}^6\text{Li}$, which is known both from experiments, e.g. [15,16], and from calculations [17] to have a large $\alpha + d$ content.

It may offhand seem unnatural that the bound 1^+ state, which has zero width, should contribute a "tail" in the continuous spectrum. This phenomenon, however, is a familiar one in neutron-resonance reactions and it is described in a natural way in R-matrix theory, in which the vanishing penetrability below the particle threshold leads to zero width. The full-drawn curve in fig. 3 shows the result of a two-level R-matrix calculation based on the following reasoning. The Gamow-Teller strength to the ground state is known, but the reduced width can only be obtained in an indirect way. We note to begin with that the d -wave admixture in the ground state theoretically is believed to be relatively unimportant, and that furthermore the penetrability P_2 is small at low energies. Consequently there is one unknown parameter only, the s -wave reduced width γ_0^2 . The relative sign of the two s -wave amplitudes is not known; if it is taken to be positive there is good agreement for $\gamma_0^2 = 7.5$ keV. Negative relative sign leads to constructive interference between the s -waves at low energies and requires $\gamma_0^2 = 2.0$ keV, only. We find the former solution more attractive but both agree well with the experimental data and cannot be distinguished.

4. Conclusion. We have observed beta-delayed deuteron emission in the decay of ${}^6\text{He}$. The analysis suggests that the decay must represent contributions from two virtual levels, the ${}^6\text{Li}$ ground state and the 5.7 MeV state, both outside the energy window for the process (fig. 2). In order to explain the intensity of the deuteron spectrum one must assume that a sizeable fraction of the missing GT sum-rule strength resides in the 5.7 MeV 1^+ state.

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