First Observation of Beta-Delayed Two-Neutron Radioactivity: ^{11}Li

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(Received 17 September 1979)

Neutron-neutron coincidences show that the β decay of 8.5-ms ^{11}Li is followed by the emission of two neutrons in an intensity of $(9 \pm 3)\%$.

Nuclei far from the line of β stability are expected to provide examples of a number of as yet unobserved radioactive decay modes such as ground-state proton radioactivity, two-proton radioactivity,¹ and β -delayed emission of two protons. We wish here to report the observation of the first case of β -delayed emission of two neutrons.

The isotope ^{11}Li is particle stable,² has a half-life of 8.5 ± 0.2 ms³ and emits neutrons in an intensity of $(61 \pm 7)\%$.⁴ It is ideally suited for a search for β -delayed two-neutron emission since its β -decay Q value is 20.7 MeV⁵ and the threshold for breakup of ^{11}Be into $^9\text{Be} + 2n$ lies only 7.315 MeV above the ^{11}Be ground state.⁶ A first attempt to detect $2n$ emission by n - n coincidence measurements from isotopes of sodium and lithium had been made by Roeckl *et al.*⁴

In our experiments, ^{11}Li was produced by bombarding a 12-g/cm² uranium carbide target at 2000 °C⁷ with 1.6- μA 600-MeV protons from the CERN synchrocyclotron. The lithium atoms were mass separated in the ISOLDE separator and the ion beam of approximately 25 atoms s⁻¹ was deflected into a counting cubicle shielded with paraffin and cadmium.

In a first experiment the singles neutron spectrum was measured with three ^3He ionization chambers operated in parallel.⁸ The resulting spectrum, shown in Fig. 1, has three peaks that agree well with known resonances observed in ^{11}Be from $^9\text{Be}(t, p)$ but in addition one notes a broad distribution extending to about 1.7 MeV. In our preliminary report,⁹ we interpreted this distribution as the continuum arising from two-neutron emission.

FIG. 1. Left: the energy spectrum of β -delayed neutrons from ^{11}Li . The expected positions of peaks corresponding to known resonances in ^{11}Be (Ref. 6) are indicated by arrows. Right: the corresponding level scheme. The 8.84-MeV level has a natural width of 200 ± 50 keV; as it is strongly populated in the (t, p) reaction it must have a large overlap with $^9\text{Be} + \text{two neutrons}$, and it is most likely the origin of the two-neutron emission observed in the present work.

In a second experiment this interpretation was verified through n - n coincidences. The ^{11}Li ion beam was directed to the center of a paraffin "long counter," 23 cm in radius and 60 cm long, equipped with eight ^3He proportional counters. As the residence time of a neutron in the detector is long ($\lambda^{-1} = 106 \mu\text{s}$) in comparison with the response time of the counters, it was possible to connect the detectors in parallel and to search for time-correlated neutron events. This was done by letting a detected neutron start a 10-MHz clock, which was read out if a second neutron arrived within 6.55 ms. Since the counting rates were low, this mode of data taking did not result in any appreciable distortion of the time spectrum. The ^{11}Li -correlated n - n events obtained in 490 min of data taking are shown in Fig. 2.

The performance of the long counter was checked by measuring the neutrons from spontaneous fission of ^{238}U , for which we assumed 14.92 ± 0.20 neutrons $\text{s}^{-1} (\text{kg U})^{-1}$ and an average multiplicity of 2.00 ± 0.08 .¹⁰ With a uranium sample of 1.9 kg the singles counting rate was 2.83 s^{-1} . The time spectrum is also shown in Fig. 2. From the singles rate the efficiency ϵ of the detector is determined to be 10.0%. If p_m is the probability of an event that gives rise to m neutrons, the efficiency for observing a two-neutron

event is

$$\epsilon_2 = \sum_{m=2}^{\infty} p_m [1 - m\epsilon(1 - \epsilon)^{m-1} - (1 - \epsilon)^m].$$

With reasonable assumptions for the p_m ,¹⁰ the experimental and calculated ϵ_2 for ^{238}U agree to 10–20%.¹¹ This proves that the correlation experiment behaved as expected.

The ^{11}Li experiment gave a singles counting rate of 1.54 s^{-1} and for correlated events 1.35 min^{-1} . From this, and assuming $(61 \pm 7)\%$ for the total neutron intensity,⁴ we calculated that the ^{11}Li decay has $(9 \pm 3)\%$ two-neutron events per β decay. (The large experimental error is not of statistical nature but allows for fluctuations in the singles background.) The single-neutron events consequently have the intensity $(43 \pm 9)\%$.

The two-neutron decays probably originate predominantly in the 8.84-MeV state of ^{11}Be , characterized by a $\log ft$ value of 4.4 corresponding to an allowed transition. The structure of this state would then be $(p_{3/2})^{-1}$ which would explain both the fast β decay from ^{11}Li and the large overlap with ^9Be plus two neutrons known from the (t, p) experiments.¹²

A more detailed study of the shape of the two-neutron spectrum could be rewarding. Analogously with other three-body breakup reactions in light nuclei,¹³ the energy spectrum is expected to reflect the final-state interactions, in our case n - ^9Be and n - n . Thus a more detailed study of the ^{11}Li β -delayed two-neutron decay may provide a new way of investigating the n - n interaction.

The authors are indebted to Per Scharff-Hansen for help with the data taking system and to A. Poskanzer for valuable comments. The work was supported in part by the Bundesministerium für Forschung und Technologie.

FIG. 2. Distributions of time correlated events in the ^{11}Li experiment and with a 1.9-kg sample of ^{238}U . The full dots in the ^{11}Li distribution have been corrected for random events. The 175-ms isotope ^9Li showed no correlated events as demonstrated in the inset. The slope of the ^{238}U and ^{11}Li curves correspond to a mean residence time for a neutron of $\lambda^{-1} = 106 \mu\text{s}$, which is of the magnitude expected from the dimensions and composition of this detector.

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$$p(t) = \epsilon^2 \lambda \sum_{m=2}^{\infty} p_m m! \sum_{\nu=0}^{m-2} \frac{\epsilon^{\nu} (1-\epsilon)^{m-2-\nu} e^{-\lambda(\nu+1)t}}{(m-2-\nu)! \nu! (\nu+2)}$$

from which one calculates that the $e^{-2\lambda t}$ component initially contributes 7% for ^{238}U .

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Energy and Angular Distribution of Autoionization Electrons from Post-Collisionally Stark-Mixed States

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(Received 5 September 1979)

A model for post-collision interaction is introduced, emphasizing the adiabatic Stark mixing of autoionizing target states in the field of the receding projectile ion. Parity is destroyed as a good quantum number for the Stark-mixed states. As a consequence the angular distribution of the autoionization electrons exhibits deviation from 90° symmetry. Recent experiments on the He $2s2p\ ^1P$ and $2p^2\ ^1D$ states excited by 10-keV Li^+ confirm this result.

When a target atom is excited to an autoionizing state by a colliding projectile, it decays by emitting an electron of well-defined energy. Since the autoionization transition is relatively fast, the decay may occur in the field of the receding projectile ion. Barker and Berry¹ have pointed out that the ejected electron loses energy as it emerges from the attractive field of the projectile. In a series of communications Morgenstern and co-workers^{2,3} and Kessel *et al.*⁴ have shown that the Berry effect¹ causes electrons from closely lying states to be indistinguishable. Thus, interference patterns are produced in the electron spectra when the autoionization states are coherently excited.

In the present work we report on a new model which treats post-collision Stark mixing of autoionizing states. The Stark effect⁵ mixes states of different parity and changes their energies

and lifetimes. It will be shown explicitly that the loss of parity as a good quantum number has the remarkable effect that the angular distribution of the autoionization electrons becomes asymmetric with respect to 90°. After the derivation of the general formalism, specific expressions will be given for two-state systems. Then applications will be made to recent measurements by Brandt, Prost, and Stolterfoht⁶ for the $\text{Li}^+ + \text{He}$ collision system. To emphasize the aspect of post-collision Stark mixing, coherent excitation of the states will be disregarded.

In the analysis an adiabatic approach is used. Figure 1(a) (described in detail below) shows the behavior of two closely lying states under the influence of the projectile field. At large internuclear distance R the states are atomic and characterized by the orbital angular momentum L and the magnetic quantum number M_L . As R decreases