Beta-Decay Half-Lives of Isotopes Produced in Projectile Fragmentation

M. J. Murphy, T. J. M. Symons, and G. D. Westfall[a]

Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

and

H. J. Crawford

Space Sciences Laboratory, University of California, Berkeley, California 94720

Beta-decay half-lives have been measured for eight neutron-rich isotopes produced in the fragmentation of 11.4-GeV ^{40}Ar on ^{9}Be. The experiment used a new measurement technique designed to observe very short half-lives. The previously unknown half-lives of ^{22}O (910 ± 350 ms) and ^{32}Al (35 ± 5 ms) have been obtained, as well as six known half-lives to provide a check of the procedure.

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This Letter reports the first application of a significant new technique to measure the β-decay half-lives of large numbers of short-lived exotic nuclei. The method utilizes high-energy projectile fragmentation to produce the nuclei, and suffers none of the limitations of chemical or mass separation techniques for the study of β decay. Moreover, it is the only method at present which can observe many of the most neutron-rich isotopes. With it we have measured for the first time the half-lives of ^{22}O and ^{32}Al, and also obtained the previously known half-lives of ^{25}Ne, ^{27}Na, ^{28}Na, ^{29}Mg, ^{30}Mg, and ^{31}Al.

The properties of such exotic nuclei are fundamental to many problems in nuclear physics and astrophysics. Their β-decay lifetimes control the progress of stellar evolution and nucleosynthesis[1]; the decay rates of nuclei of mass 20–60 in particular are important during the early stages of a star's gravitational collapse.[2] The combination of nuclear lifetimes and masses allows the matrix elements for β decay to be systematically studied, and when mass and lifetime measurements have been made for many isotopes of a given element, new regions of nuclear deformation have been discovered[3] in which the predictions of the spherical shell model are no longer valid.[4]

It was discovered a few years ago that heavy-ion projectile fragmentation at several hundred megaelectronvolts per nucleon produces a broad spectrum of exotic isotopes ranging far from stability.[5-7] The fragments emerge from the reaction with beam velocity and are strongly peaked at 0°, which allows very high detection efficiency. For example, in the fragmentation of 9.6-GeV ^{48}Ca on ^{9}Be, 27 neutron-rich isotopes of unknown lifetime were observed.[7] Most of these isotopes are expected to have half-lives much less than one second.

In order to measure the half-lives of these projectile fragments, it is necessary to (a) stop the fragments, (b) identify the parent isotopes by charged-particle spectroscopy, (c) observe their β decay without transporting the products, (d) interrupt the beam while observing β particles, (e) correlate the delayed β's with the parent nuclei, and (f) minimize the background from more abundantly produced isotopes. All of these conditions are satisfied by the following technique: The forward-peaked projectile fragments are deflected through a magnetic spectrometer to select isotopes of a particular rigidity. Their uniform velocity and charge state allows the spectrometer to cleanly separate the rare neutron-rich isotopes from the more abundantly produced isotopes nearer to stability. The fragments are then stopped in a multielement solid-state telescope; their range and energy loss provide charge and mass identification. Within 2 ms of seeing a specified isotope stop the beam is interrupted, the detector electronics are switched to the higher gain necessary to detect low-energy electrons, and a period of 2 s is allowed to observe the delayed β from the embedded fragment. The stopping detectors are position sensitive in one dimension, so that we may determine that the observed β originated near the position of the fragment.

The solid-state telescope used to stop the fragments consisted of two 5-cm-diam × 800-μm-thick Si(Li) detectors (for a particle trigger) backed by six 7-cm-diam × 5-mm-thick position-sensitive Si(Li) detectors. The telescope was surrounded by scintillators and an active collimator to suppress background. Aluminum degraders

fixed the stopping point of the chosen fragments in the center of the telescope.

The experiment was controlled by a micropro-grammable branch driver (MBD) linked to a PDP-11/34 data-acquisition computer. The MBD examined a hardware particle identification signal for each fragment event in the telescope; if speci-fied identification gates were satisfied the MBD signaled the beam interruption and the change to the high-gain β-detection mode.

For the measurements reported here, an 11.4-GeV ^{40}Ar beam of ~10^6 particles/s from the Lawrence Berkeley Laboratory Bevalac was used to produce neutron-rich isotopes by fragmentation on a ^{9}Be target. Oxygen through argon were ob-served in the charge identification spectrum from the particle telescope. By accurately cali-brating the gains of the detectors and averaging the multiple ΔE-E measurements which a six-element telescope provides, isotopes were clear-ly resolved for oxygen through silicon. A cut of 30% on the tail of the χ^2 for the averaged ΔE-E measurements eliminated much of the dispersion in particle identification due to straggling and reactions in the detectors. An example of the resulting particle identification spectrum for the aluminum isotopes is shown in Fig. 1.

The isotope masses were unambiguously deter-mined by two independent identifications. The particle spectra at the spectrometer position corresponding to $A = 2Z$ were obtained as an ini-tial mass identification. This was extrapolated to spectra from other points on the focal plane through the empirical relation

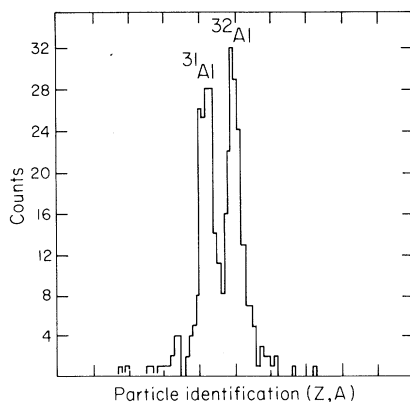$$(E + \Delta E)^{1.78} - E^{1.78} \propto Z^2 A^{0.78}.$$

A later comparison of measured lifetimes with those already known provided an independent verification of the mass identification.

To obtain the half-lives of the isotopes, gates were set around each isotope peak and the delay times for electrons originating in the stopping detector were histogrammed (Fig. 2). With use of the position information, cuts were made on the trajectories of both the stopping isotope and the delayed electron to insure that the electron originated in the vicinity of the identified isotope.

In this first measurement it was possible to ob-tain half-lives for ^{22}O, ^{25}Ne, ^{27}Na, ^{28}Na, ^{29}Mg, ^{30}Mg, ^{31}Al, and ^{32}Al. Their decay curves and least-squares fits are shown in Fig. 2 and are compared to previous measurements in Table I. All of the curves had flat background contribu-tions, which were subtracted. This is the first reported measurement of the half-lives of ^{22}O (910 ± 350 ms) and ^{32}Al (35 ± 5 ms). The known half-lives of the other isotopes provide a check on the accuracy of the technique. In all cases our measurement agrees to within one standard deviation with the previously reported value.

This measurement technique has been developed to make a rapid, comprehensive survey of β-de-cay lifetimes for very-neutron-rich nuclei. One of the important applications of such a systematic measurement will be to the test of nuclear struc-ture models for the parent and daughter nuclei. Spherical-shell-model calculations are often used to predict half-lives, because nuclear β de-cay nearer to the valley of stability typically in-volves the ground states and low-level excitations of nearly spherical nuclei. Such a shell-model calculation has recently been made[8] for several

FIG. 1. The particle identification spectrum for $Z = 13$, showing the clear resolution of ^{31}Al and ^{32}Al.
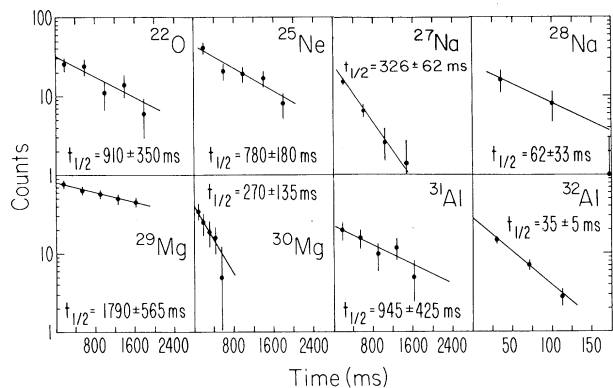

FIG. 2. The β-decay half-life curves observed in this experiment. In all cases flat background compo-nents have been subtracted. The curves are least-squares fits to the data.

TABLE I. Beta-decay half-lives measured for fragments from 11.4-GeV ^{40}Ar + ^{9}Be. Previously measured values and recent theoretical predictions are included for comparison.

Isotope	This measurement (ms)	Previous value (ms)	Prediction [a]
^{22}O	910 ± 350	· · ·	1800
^{25}Ne	780 ± 180	610 [b]	549
^{27}Na	326 ± 62	340 ± 7 [c]	254
^{28}Na	62 ± 33	31 ± 0.4 [c]	23.3
^{29}Mg	1790 ± 565	1470 ± 90 [c] 1090 ± 120 [d]	525
^{30}Mg	270 ± 135	325 ± 30 [d]	320
^{31}Al	945 ± 425	644 ± 25 [e]	· · ·
^{32}Al	35 ± 5	· · ·	28.8

[a] Reference 8.   [d] Reference 11.
[b] Reference 9.   [e] Reference 12.
[c] Reference 10.

of the isotopes which we have observed. The half-lives which this calculation predicts are included in Table I, and compare favorably with our measurements. While these isolated comparisons provide useful checks for specific calculations, we forsee more fundamental tests of nuclear structure. For instance, other fragmentation reactions[7] should yield the half-lives of ^{45}Cl and ^{46}Ar, which are the furthest known N = 28 nuclei from stability. Whether major spherical shell closures such as N = 28 occur in such very-neutron-rich nuclei is a subject of considerable interest.[3]

The first measurement of β half-lives using this new method has provided eight known and new half-lives in two days of data taking. The technique limits accurate measurements to half-lives of less than 1 s. However, it is intended for short half-lives; 1-s activities are accessible in other methods. The lower limit for half-lives is approximately 5 ms, which makes this method nearly unique in its ability to reach a broad range of very-neutron-rich isotopes. With the heavier, more intense beams soon to be available from the Bevalac, we anticipate a significant contribution

to the systematics of nuclear β decay.

(a)Present address: Cyclotron Laboratory, Michigan State University, East Lansing, Mich. 48824.

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