Direct Mass Measurements of Neutron-Rich Light Nuclei near $N = 20$

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(Received 18 August 1986)

The simultaneous direct mass measurements of 21 neutron-rich nuclei ranging from ^{19}C to ^{37}P have been performed with a new type of recoil spectrometer. The masses of ^{19}C, $^{27-28}$Ne, $^{32-34}$Al, ^{36}Si, and ^{37}P have been determined for the first time. No evidence of an increase in the two-neutron separation energy as noted for $^{31-32}$Na is observed for $^{30-32}$Mg and $^{32-34}$Al.

PACS numbers: 21.10.Dr, 07.75.+h, 27.30.+t

Measurements of ground-state masses are of fundamental importance to the understanding of nuclei since they manifest all interactions that contribute to nuclear binding. Features such as the finite range of the nuclear force, nuclear pairing, nuclear shell structure, and the macroscopic, shape-dependent properties of nuclei were first identified from the systematic studies of the nuclear mass surface. Nuclear masses also serve as important constraints for nuclear-mass theories whose predictive capabilities are essential to astrophysical calculations of the natural abundance of elements within the universe. This importance has encouraged an experimental program of mass measurements, especially for nuclei far from the valley of beta stability, where increasing deviations from theory have been observed. In this paper we present the first experimental results from the time-of-flight isochronous (TOFI) spectrometer[1] that has been built expressly for direct, systematic mass measurements of light-Z neutron-rich nuclei.

Our first work focuses on the measurement of ground-state masses near the region of deformation observed in the neutron-rich sodium isotopes. A local increase in the two-neutron separation energy $[S_{2n} = -M(A,Z)+M(A-2,Z)+2n]$ for $^{31-32}$Na was observed[2] where a decrease had been expected due to the assumed closure of the neutron sd shell at $N = 20$. This rise in S_{2n} was interpreted as evidence for a shape transition from spherical to prolate deformation analogous to a similar trend observed in the rare-earth region. This interpretation has been supported by Hartree-Fock calculations,[3] by the measured low energy assigned to the first excited 2^+ state of ^{32}Mg,[4] and by the mass measurements of $^{31-32}$Mg.[5] However, no evidence of deformation has been seen[6] in the masses of $^{33-35}$Si or in the mean square charge-radius measurements of $^{21-31}$Na,[7] although the latter could have been hampered by zero-point vibrations.

An important feature of the TOFI spectrometer is that masses of many nuclei over an entire region of the nuclidic chart can be determined simultaneously with one high-precision measurement. This makes possible a continuous internal calibration of the spectrometer. Within TOFI, slower ions travel a shorter path while faster ions take a longer one, resulting in an overall flight time that depends only on the mass-to-charge ratio of the given ion and not velocity. This flight time is measured by microchannel-plate fast-timing detectors[8] located at the entrance (MCP2) and exit (MCP4) of the spectrometer. In this experiment, a timing uncertainty of 230 ps (FWHM) was obtained for a typical flight time of 600 ns, resulting in a mass-to-charge resolution of 3.8×10^{-4}. (This performance was found to be largely limited by the resolution and stability of the timing detectors and electronics and not by the spectrometer itself.) The spectrometer is also focusing in angle and momentum, ensuring a large transmission (e.g., $\Omega = 2.5$ msr, $\delta p/p = 4\%$) and a small focal spot.

Neutron-rich nuclei are produced via fragmentation reactions induced by the interaction of the 1-mA, 800-MeV proton beam of the Los Alamos Meson Physics Facility with a 1.0-mg/cm^2 Th target. A small fraction of these recoils is captured by a transport line consisting of four quadrupole triplets and a mass-to-charge filter and introduced into the TOFI spectrometer. In this experiment the beam line was tuned to transmit recoils with a momentum-to-charge ratio of (200 MeV/c)/Q ($\sim$0.6 T m) which is near the maximum of the production cross section[9] for the neutron-rich nuclei of interest (2–3 MeV/amu and $\bar{Q}/Z \simeq 80\%$). A small mass-to-charge filter consisting of separated electrostatic and magnetic dipole fields was tuned to accept recoils with $A/Q \sim 3.2$ to eliminate the majority of high-yield uninteresting particles such as neutrals, protons, deuterons, alpha particles, and other ions with $A/Q \leq 2.0$.

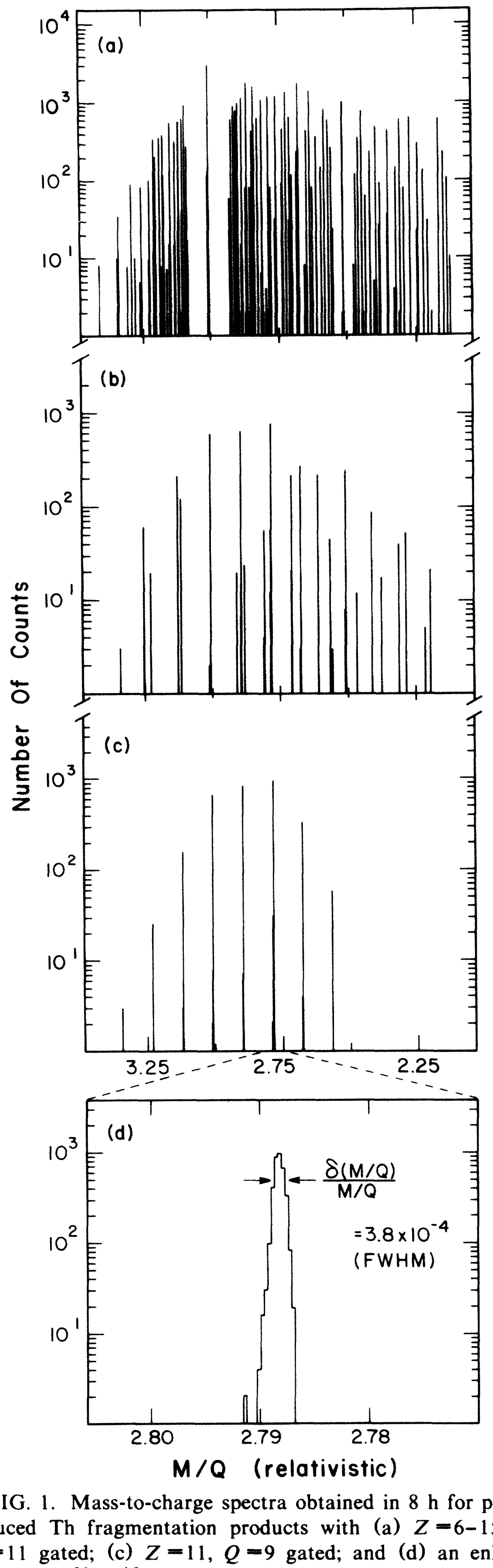

FIG. 1. Mass-to-charge spectra obtained in 8 h for proton-induced Th fragmentation products with (a) $Z=6-15$; (b) $Z=11$ gated; (c) $Z=11$, $Q=9$ gated; and (d) an enlarged view of the $^{26}Na^{+9}$ mass line.

Masses were extracted from the measured mass-to-charge spectrum (see Fig. 1) by our separating out the individual lines according to atomic number (Z) and charge state (Q), and then determining the centroid of each line by moments analysis. Small corrections were applied to the centroid to account for (1) discriminator time-amplitude walk, (2) nonlinearities of the time-to-amplitude and analog-to-digital converters, and (3) shifts resulting from small drifts of the spectrometer's magnetic field. Q and Z values were obtained with resolutions of 1% and 4%, respectively, from measurements of the ions' velocity (measured between MCP2 and a multistep multiwire proportional counter[10] located upstream), stopping power, and total energy (both measured with a solid-state detector telescope positioned after MCP4). A mass-to-charge calibration was obtained by our fitting a quadratic function to the measured centroids of the known mass values taken from Audi and Wapstra[11] for nuclei with uncertainties of 150 keV or better. A typical 8-h run contained ~120 known mass-to-charge values and gave a reduced χ^2 for the quadratic fit of ~1.1. The final mass for each nuclide was determined by our taking a weighted average of masses from (1) ~30 runs and (2) all charge states for a given nuclide (typically two to three charge states were predominant). The final mass uncertainties and the rejection of statistically insignificant data were determined with the method outlined by Hardy and Towner.[12] An error equal to ~2% of the width of each mass line [~(20 keV)/Q] was added in quadrature to account for systematic deviations. The resulting mass excesses are given in Table I.

The most notable feature in our data is the smoothly decreasing trend seen in the two-neutron separation energies (see Fig. 2) with increasing neutron number for $^{30-32}$Mg and $^{32-34}$Al. This behavior is consistent with the trend seen for $^{33-36}$Si, but contrasts sharply with the S_{2n} systematics observed for $^{31-33}$Na. Moreover, no increase is observed at ^{31}Mg, as reported in Ref. 5, since our ^{31}Mg measurement results in a mass that is less bound by 1.4 MeV. A 1.1-MeV discrepancy for ^{30}Na exists when compared to the previous measurement of Ref. 2, but the size of our error bars and the lack of a new ^{31}Na mass measurement preclude us from confirmation or refutation of the observed S_{2n} systematics for the neutron-rich sodium isotopes. Recent shell-model calculations of Wildenthal *et al.*[15] compare well with the S_{2n} data of Fig. 2 (rms deviation of ~0.2 MeV) through the entire *sd* shell. Discrepancies are observed for the $N=20$ isotones ^{31}Na and ^{32}Mg (whose masses are calculated to be less bound by 2.2 and 1.5 MeV, respectively), but not for ^{33}Al. Calculations of Watt *et al.*,[16] in which a truncated $sd+f_{7/2}$ basis was used, indicate a substantial increase in binding for ^{31}Na and ^{32}Mg when neutron excitations from the $d_{3/2}$ shell to the $f_{7/2}$ shell are allowed. Clearly, further measurements and additional calculations are needed to understand the nuclear

TABLE I. Mass excess in unified mass units and in megaelectronvolts with errors given in parenthesis.

^{A}Z	This work (μu)	This work (MeV)	Previous work (MeV)	Ref.
^{19}C	34 680(260)	32.30(0.24)	-	
^{20}N	23 230(280)	21.64(0.26)	22.20(0.34)	13
^{21}N	26 580(200)	24.76(0.19)	25.58(0.50)	13
^{23}O	15 700(300)	14.6(0.3)	14.61(0.63)	13
^{23}F	3530(210)	3.29(0.20)	3.35(0.17)	11
^{24}F	8070(170)	7.52(0.16)	7.86(0.41)	13
^{25}F	12 010(220)	11.18(0.20)	10.51(0.53)	13
^{26}F	19 800(1000)	18.4(0.9)	17.55(1.27)	13
^{27}Ne	6000(600)	5.6(0.6)	...	
^{28}Ne	11 500(400)	10.7(0.4)	...	
^{28}Na	−1220(190)	−1.14(0.18)	−1.14(0.14)	11
^{29}Na	2820(230)	2.63(0.21)	2.65(0.15)	11
^{30}Na	7600(500)	7.1(0.5)	8.21(0.25)	11
^{30}Mg	−9700(230)	−9.04(0.21)	−9.10(0.21)	14
^{31}Mg	−3830(220)	−3.56(0.20)	−4.94(0.70)	11
^{32}Mg	−800(260)	−0.75(0.24)	−1.75(1.58)	11
^{32}Al	−12 160(220)	−11.33(0.20)	...	
^{33}Al	−9490(250)	−8.84(0.23)	...	
^{34}Al	−3800(400)	−3.5(0.4)	...	
^{36}Si	−13 900(600)	−12.9(0.6)	...	
^{37}P	−20 740(400)	−19.31(0.4)	...	

structure of this region.

For lighter nuclei, we find that ^{23}O is 1–4 MeV more bound than predicted by most mass formulas. However, the mass of ^{23}O is consistent with the S_{2n} trend seen in the neutron-rich isotopes of F and Ne. Evidence for a subshell closure at $N=14$ is not apparent in the S_{2n} energies, but a significant decrease in the S_{2n} trend is observed at $N=15$. With the exception of ^{27}Ne (discrepant by 1.0 MeV), the *sd*-shell-model calculations[15] accurately predict the two-neutron separation energies observed in this region. Measurements of $^{24-25}$O would be of particular interest in further testing of the shell-model calculations.

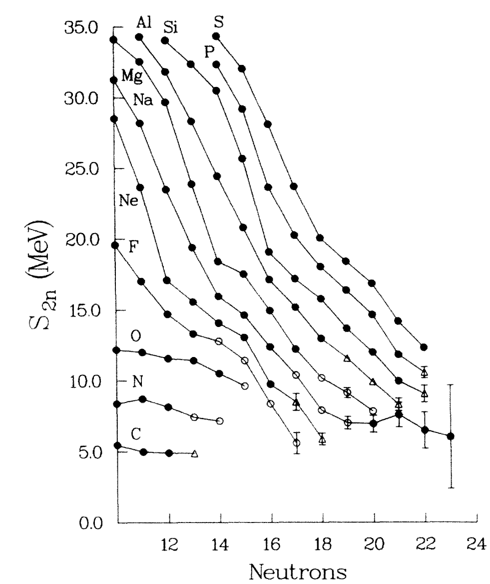

FIG. 2. Two-neutron separation energy vs neutron number for isotopes of carbon to sulfur. Open circles indicate nuclei which have been remeasured, triangles represent nuclei whose mass has been measured for the first time, and the solid points are taken from Ref. 11. S_{2n} values were calculated from the weighted average of the values given in Table I. Error bars are indicated where they are larger than the symbol size.

In summary, 21 masses were determined, 8 of which (^{19}C, $^{27-28}$Ne, $^{32-34}$Al, ^{36}Si, and ^{37}P) were measured for the first time. In comparison of the thirteen masses which have been remeasured with their previous measurements, good agreement is found in all cases except ^{30}Na and ^{31}Mg. In general, the masses reported here are reproduced by *sd*-shell-model calculations, with the exception of ^{31}Na and ^{32}Mg which indicate that neutron excitations into the $f_{7/2}$ shell occur. Improvements in detector and electronic technologies will permit higher-precision mass measurements out to more neutron-rich nuclei by means of TOFI. The development of TOFI and similar recoil spectrometers will provide the means for a new series of systematic mass measurements up to $Z\sim 30$ that will yield new insight into the binding and nuclear structure of exotic neutron-rich nuclei.

It is a pleasure to acknowledge the excellent technical contributions of the Clinton P. Anderson Meson Physics Facility engineering, electronics, and operations group who helped build the spectrometer and transport line. We are grateful for the early encouragement of D. C. Hoffmann, L. Rosen, J. E. Sattizahn, A. M. Poskanzer, and L. P. Remsberg in our undertaking this work. We thank D. S. Brenner and B. H. Wildenthal for valuable discussions. Two of us (K.V. and R.H.K.) acknowledge support from Utah State University and Clark University and the help and guidance of Professor V. G. Lind and Professor D. S. Brenner, respectively. This work was performed under the auspices of the U. S. Department of Energy.

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