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USING A COMBINED ENERGY AND TIME-OF-FLIGHT TECHNIQUE

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DIRECT MASS MEASUREMENTS IN THE LIGHT NEUTRON-RICH REGION
USING A COMBINED ENERGY AND TIME-OF-FLIGHT TECHNIQUE^{*}

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INTRODUCTION

Of approximately 300 new atomic masses reported since 1975, the most important measurements taken to test atomic mass models have been those involving a concentrated set of measurements that extend far from beta-stability.¹ Two excellent examples are the isotopic series of mass measurements carried out on the alkali elements² and the alpha-decay chain Q-value measurements originating from $^{176,178}\text{Hg}$.³ Both provided extensive sets of new data that helped to reveal systematic deficiencies in a variety of atomic mass models. But extensive as these measurements were, each was limited by what could be measured (i.e., a particular isotopic sequence or a particular decay chain). In the experiment described here, we attempted to further extend mass measurement capabilities by developing a more general approach in which whole array of nuclei that lie far from stability can be measured simultaneously, independent of their N or Z. We demonstrate that direct mass measurements can be performed for fast recoiling nuclei by using a combined energy and time-of-flight technique.

EXPERIMENTAL METHOD AND RESULTS

The high-intensity 800 MeV proton beam of LAMPF was used to bombard a thin uranium target (300-450 $\mu\text{g}/\text{cm}^2$) supported on pyrolytic carbon (0.6-1.1 mg/cm^2) backing. Reaction products resulting from the fragmentation of uranium were detected in the 45° flight tube of the Thin Target experimental area. The detection system consisted of two secondary-electron channel-plate (CP) fast timing detectors⁴ (~25 $\mu\text{g}/\text{cm}^2$ carbon foils) located approximately 285 and 468 cm from the target, respectively, and a gas ionization counter⁵ for energy determination and particle identification.

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The atomic number of each event was determined using the ΔE_2 -E or ΔE_2 -TOF table lookup method⁶ after correcting for gas density variations. These two semi-independent Z values were further corrected to remove their mass dependences. The mass was calculated from the total energy, time-of-flight, and flight-path distance. The total energy was determined by summing the energy deposited in the ion counter (i.e., $\Delta E_1 + \Delta E_2 + E$) with the energy lost in the CP1/CP2 foils and gas isolation window. The latter energy losses were calculated using a method in which the ΔE_2 -E table served as a dE/dx table. The time-of-flight used in the mass determination was that derived from the target-to-CP2 timing in which a beam pickoff method was employed⁶. In all but the most energetic cases the mass resolution was limited by the energy resolution.

Fig. 1 shows the mass spectra for nitrogen and fluorine isotopes. The centroid (more specifically the mean) of each mass line was determined using a moments analysis approach. Centroids extracted in this fashion were also found to agree well with those determined from gaussian or gaussian plus exponential tail peak fits.

Fig. 1. The mass spectra for: (A) nitrogen and (B) fluorine isotopes.

Fig. 2 shows a plot of the difference between the known⁷ mass and the extracted mass centroid (i.e., $\delta = m_{\text{known}} - \text{mean}$) versus the mass number for the range of nuclei measured in this experiment. We observe a smoothly varying surface of differences ranging from -0.15 amu for ^{15}O to $+0.11$ amu for ^{26}Ne . These experimental deviations result from the difficulty

of correctly determining the energy and time-of-flight on an absolute scale over a broad range of Z , A , and energy. To evaluate how fundamentally limiting these experimental deviations are to this technique, we attempted to fit and extrapolate these deviations as a function of A or Z . For isotopic sequences a quadratic expression in A described the data well. Since the isotonic and isobaric sequences did not have as many nuclides as did the isotopic series, the difference between adjacent isotonic or isobaric members (i.e., $\delta_{Z+1}^{A+1} - \delta_Z^A$ or $\delta_{Z+1}^A - \delta_Z^A$, respectively) was fit as a linear function of A . In Table I (column 2) the weighted average of the three extrapolated deviations is given for several neutron-rich light nuclei. Comparing these to the known deviations (column 3), good agreement is found in every case.

Fig. 2. The measured mass deviation versus mass number. Isotonic and isobaric members are connected by dashed lines and labeled according to their N or Z . Errors are contained within the size of the data points unless otherwise indicated.

The masses of several neutron-rich light nuclei were determined by adding the extrapolated deviation to the measured mass centroid. Although the error bars are relatively large (3-8 MeV) for these measurements, excellent agreement with the known masses (column 5) is found. In all cases errors were limited by the statistical uncertainty of the mass line centroid not by the extrapolation error. Two new masses have been determined for the previously unmeasured nuclei, ^{20}N and ^{24}P . These agree well the systematic predictions of Wapstra and Audi.⁷

Table I. Comparison between extrapolated and measured mass deviations; Determined vs known mass excess for light neutron-rich nuclei. Masses given in square brackets are systematic predictions taken from Ref. 7.

A_Z	Extrapolated Deviation δ_{ext} (amu)	Measured Deviation δ_{obs} (amu)	Measured Mass Excess (MeV)	Known ⁷ Mass Excess (MeV)
¹⁷ C	-.0107($\pm$.0030)	-.0118($\pm$.0044)	20.0($\pm$ 4.9)	21.025($\pm$.035)
¹⁸ C	.0187($\pm$.0041)	.0211($\pm$.0076)	22.7($\pm$ 8.0)	24.890($\pm$.150)
¹⁹ N	-.0046($\pm$.0020)	-.0029($\pm$.0026)	14.3($\pm$ 3.0)	15.867($\pm$.047)
²⁰ N	.0288($\pm$.0033)	----	21.9($\pm$ 5.7)	[22.10] ----
²¹ O	.0267($\pm$.0018)	.0261($\pm$.0028)	8.7($\pm$ 3.1)	8.127($\pm$.052)
²² O	.0634($\pm$.0033)	.0632($\pm$.0059)	9.7($\pm$ 6.3)	9.443($\pm$.087)
²³ F	.0609($\pm$.0023)	.0597($\pm$.0024)	4.5($\pm$ 3.1)	3.354($\pm$.170)
²⁴ F	.1018($\pm$.0027)	----	8.3($\pm$ 4.5)	[8.75] ----
²⁵ Ne	.0734($\pm$.0020)	.0735($\pm$.0034)	-2.2($\pm$ 3.6)	-2.156($\pm$.091)
²⁶ Ne	.1114($\pm$.0023)	.1122($\pm$.0054)	-0.4($\pm$ 5.5)	0.440($\pm$.072)

Conclusion

In conclusion, this experiment has demonstrated that direct mass measurements can be performed (albeit of low precision in this first attempt) using the $M \propto ET^2$ method. This technique has the advantage that many particle-bound nuclei, produced in fragmentation reactions can be measured simultaneously, independent of their N or Z. The main disadvantage of this approach is that both energy and time-of-flight must be measured precisely on an absolute scale. Although some mass walk with N and Z was observed in this experiment, these uncertainties were largely removed by extrapolating the smooth dependence observed for known nuclei which lie closer to the valley of β -stability. Mass measurements for several neutron-rich light nuclei ranging from ¹⁷C to ²⁶Ne have been performed. In all cases these measurements agree with the latest mass compilation of Wapstra and Audi⁷. The masses of ²⁰N and ²⁴F have been determined for the first time.

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