A brief report of this work has been recently
published, and a more detailed account (presented at
the International Conference on Nuclear Structure,
Amsterdam, August 30-September 3, 1982) is currently in
press. Follow-up investigations with polarized beams
have been initiated recently.

THE MASS OF $^{59}$Zn

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The nucleus $^{59}$Zn is the heaviest $T_z=1/2$ nucleus
for which the mass and lifetime are known from $\beta$-decay
measurements. This makes it important for mass
predictions and the calculation of Gamow-Teller matrix
elements in nuclear beta decay. The mass measurement
of $^{59}$Zn also represents the first in a series of $Z>N$
nuclei in this mass region which are needed to extend
the Garvey-Kelson symmetric mass predictions to A>56.

Further, since the mass of the $T_z=1/2$ mirror nucleus is
known, the Coulomb energy shift systematics can be
extended to the $2p3/2$ orbit.

The present measurement represents the first use
of the $(p,\pi^-)$ reaction to measure a nuclear mass. The
$(p,\pi^-)$ reaction allows a considerably more accurate
($<50$ keV) mass measurement and $ft$-value calculation
than the beta-endpoint technique commonly used to make
mass measurements of proton rich nuclei.

The measurement was performed at the Indiana
University Cyclotron Facility with a proton beam of 190
MeV. The QSPS spectrometer was set at 30° and used to
determine the outgoing pion kinetic energy. At the
focal plane of the spectrometer a vertical drift
counter measured both position and angle.

The one difference from the standard setup described in
Ref. 5 was the use of an aluminum absorbing wedge
placed after the focal plane detector and between the
first two scintillators which were used to measure
time-of-flight and energy loss. The thickness of the
wedge was chosen to cause the negative pions to stop in
the second scintillator, where they deposit some part
of their rest mass energy plus their kinetic energy.

Thus, by gating on large ($E>40$ MeV) energy signals in
the back scintillator, we were able to reduce the
background by two orders of magnitude while the
efficiency remained virtually unchanged. The
limitation of this technique is that it works for only
a limited range of pion energy due to the geometry of
the wedge and the pion orbits in the spectrometer.

The mass measurement itself was carried out by
determining the Q-value of the reaction $^{58}$Ni$(p,\pi^-)^{59}$Zn
relative to the Q-values of the calibration reactions.

$^{13}$C$(p,\pi^-)^{14}$O \hspace{1cm} Q = -136.650 MeV

$^{25}$Mg$(p,\pi^-)^{26}$Si($E_x=1.796$ MeV) \hspace{1cm} Q = -140.595 MeV

$^{25}$Mg$(p,\pi^-)^{26}$Si($E_x=2.783$ MeV) \hspace{1cm} Q = -139.607 MeV.

Since the QSPS detector system measured angle as well
as position, the $^{14}$O calibration runs were divided into eleven 16 arc angular bins. This gave a calibration point for every channel in the region of the $^{59}$Zn ground state and provided a precise calibration of the spectrograph focal plane. Calibration runs of $^{14}$O were taken before and after each $^{59}$Zn run to monitor changes in the proton beam energy. The same spectrometer parameters were used for all runs. Finally, the target thicknesses were chosen so that the energy loss corrections were the same in each target, within 14 keV, for the reactions studied.

The Q-value for the $^{58}$Ni(p,$\pi^-$)$^{59}$Zn reaction was measured to be $Q = -145.247(40)$ MeV, which gives a mass excess of $ME(59\text{Zn}) = -47.256(40)$ MeV. The measured cross section was $0.080(20)$ nb/sr. This mass compares favorably to the beta-endpoint measurement made by Arai et al. of $ME(59\text{Zn}) = -47.23(10)$ MeV. The weighted average of the two measurements is $ME(59\text{Zn}) = -47.253(37)$ MeV. The experimental spectrum is shown in Fig. 1 along with a typical angular bin of the $^{14}$O calibration.

The uncertainty in the mass measurement of $^{59}$Zn came from four sources. First, the difference in reaction kinematics between $^{58}$Ni(p,$\pi^-$) and the calibration reaction $^{13}$C(p,$\pi^-$) and $^{25}$Mg(p,$\pi^-$) coupled to a 0.5 degree uncertainty in spectrometer angle led to a 20 keV systematic uncertainty in the measurement. Second, the absolute beam energy is known to 200 keV. This led to a 4 keV uncertainty, again due to the difference in reactions kinematics. Third, beam energy fluctuations observed were of the order of 80 keV. Thus, although the $^{59}$Zn runs were shifted and summed according to the observed shifts in the calibration spectra, we conservatively estimated that this fluctuation introduced a 20 keV systematic uncertainty into the mass measurement. Finally, low statistics, due to the small $^{58}$Ni(p,$\pi^-$) cross section, led to a 28 keV uncertainty. All other contributions to the Q-value uncertainty were determined to be less than 4 keV. For the final total uncertainty, all effects were added in quadrature.

The measured low lying level structure of $^{59}$Zn is shown in Fig. 2. Also shown is the level structure of $^{59}$Cu (Ref. 6), the mirror nucleus of $^{59}$Zn. The cross sections are consistent with the observation that the (p,$\pi^-$) reaction selects high spin states due to the pion-proton momentum mismatch. We also attempted to measure the mass of $^{41}$Ti with the reaction $^{40}$Ca(p,$\pi^-$), but no counts were observed above the background. This lack of yield gives an upper limit for the cross section of 0.003 nb/sr.

Since $^{59}$Zn is the heaviest $T_z$=1/2 nucleus for which the mass is measured, it provides a check on the persistence of the Nolen-Schiffer (N-S) anomaly in
proton-pion momentum mismatch. This leads to the selection of high spin states in the residual nucleus over the usually low spin ground state. The failure to observe the ground state of $^{41}$Ti in the $^{40}$Ca($p,\pi^-$) reaction is evidence of this effect. If, however, $^{40}$Ca had a large 2p-2h neutron component in the ground state, it would show up in the ($p,\pi^-$) spectrum. The absence of any observed counts near the expected ground state sets an upper limit of about 25% for the 2p-2h neutron contribution to the $^{40}$Ca wave function.

Due to the low cross sections and lack of suitable targets there are not many uses for the ($p,\pi^-$) reaction in mass measurements. Two remaining possibilities are $^{64}$Zn($p,\pi^-$)$^{65}$Ge and $^{92}$Mo($p,\pi^-$)$^{93}$Ru.

4) M.C. Green, Ph.D. Thesis, Indiana University, unpublished.
6) C.M. Lederer and V.S. Shirley, eds., Table of Isotopes (Wiley, 1978).
7) B.A. Brown and H. Toki, to be published.
9) B.A. Brown, to be published.