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Masses of $T_z = -1/2$ nuclei in the $1f_{7/2}$ shell*

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The $(p, {}^6He)$ reaction was used to observe and measure the masses of the proton-rich nuclei ^{45}V, ^{49}Mn, and ^{53}Co, thus completing all mirror pairs in the $f_{7/2}$ shell. New measurements of the masses of ^{43}Ti, ^{47}Cr, ^{51}Fe, and ^{55}Ni were made using the $({}^3He, {}^6He)$ reaction. Coulomb energy differences of the $T = 1/2$ mirror pairs are extracted, and the new masses are used to predict the masses of proton-rich nuclei with $23 \leq Z \leq 28$.

[NUCLEAR REACTIONS ^{27}Al, ^{50}Cr, ^{54}Fe, $^{58}Ni(p, {}^6He)$, $E_p = 46$ MeV, ^{27}Al, ^{46}Ti, ^{50}Cr, ^{54}Fe, $^{58}Ni({}^3He, {}^6He)$, $E_{^3He} = 70$ MeV, measured Q, deduced mass excess of ^{43}Ti, ^{45}V, ^{47}Cr, ^{49}Mn, ^{51}Fe, ^{53}Co, ^{55}Ni, predicted masses of proton-rich nuclei with $21 \leq Z \leq 28$.]

I. INTRODUCTION

This paper presents the results of the measurements of the ground state masses of the nuclei ^{45}V, ^{49}Mn, and ^{53}Co, and remeasurements of the masses of ^{43}Ti, ^{47}Cr, ^{51}Fe, and ^{55}Ni.[1] The nucleus ^{45}V is observed for the first time, whereas ^{53}Co has been detected previously in a proton-emitting isomeric state,[2] and ^{49}Mn was observed in the $^{40}Ca({}^{12}C, t){}^{49}Mn$ reaction.[3] The Q value of this heavy ion reaction was consistent with the prediction for the mass of ^{49}Mn under the assumption of equal population of ground and first excited states which were unresolved. The present precision mass measurements employed the $(p, {}^6He)$ and $({}^3He, {}^6He)$ reactions on relatively thin targets. The new measurements complete the series of $T = \frac{1}{2}$ mirror nuclei in the $f_{7/2}$ shell and allow comparison of Coulomb energies throughout an entire nuclear subshell to a shell-model prediction.[4] The results of the present measurement also permit the prediction of the masses of proton-rich nuclei far from the $N = Z$ line by means of the symmetric mass relation of Kelson and Garvey.[5]

II. EXPERIMENTAL METHOD

The determination of the new masses was made by comparing the ^6He particles from the $(p, {}^6He)$ reaction on ^{50}Cr, ^{54}Fe, and ^{58}Ni targets to the ^6He particles from the calibration reaction $^{27}Al(p, {}^6He){}^{22}Mg$ in a magnetic spectrograph. The remeasurements of masses of ^{43}Ti, ^{47}Cr, ^{51}Fe, and ^{55}Ni were made by comparing the ^6He particles from the $({}^3He, {}^6He)$ reaction on ^{46}Ti, ^{50}Cr, ^{54}Fe, and ^{58}Ni targets to the ^6He particles from the $^{27}Al({}^3He, {}^6He){}^{24}Al$ reaction. Beams of 46 MeV protons and 70 MeV ^3He particles from the Michigan State University cyclotron were used. The detection system consisted of a resistive wire proportional counter with an entrance window of 0.0013 cm aluminized Kapton. After passing through the window and gas of the counter, the particles enter directly into an aluminized plastic scintillator which serves as the back of the wire counter. The elimination of a window between gas and scintillator facilitated the detection in the scintillator of the low energy ^6He particles from the $(p, {}^6He)$ reactions. The method and electronics have been previously described.[6] In the $(p, {}^6He)$ measurements, the long flight time of the ^6He particles, which exceeded two cyclotron rf periods caused them to overlap with higher velocity particles from later beam bursts. A pulsing system was employed to allow only one-in-three cyclotron beam bursts to reach the target. This removed the ambiguity in mass identification in the time-of-flight spectrum. The measurements were made at lab angles of 8.0 to 10.6° with a solid angle of 1.2×10^{-3} sr. The targets were foils 85 to 325 $\mu g/cm^2$ in thickness which were measured by means of energy loss of ^{241}Am α particles.

III. RESULTS

Figure 1 shows the spectra obtained in the $(p, {}^6He)$ reactions. A single state dominates each spectrum and is identified by comparison to the mirror nuclei as the lowest $J^\pi = \frac{7}{2}^-$ level. In ^{49}Mn the $\frac{7}{2}^-$ level is not the ground state but an excited state at 0.26 MeV. The ground state is expected to have $J^\pi = \frac{5}{2}^-$ which is the J^π value of its mirror ^{49}Cr. This seniority-3 state is very weakly excited relative to the $\frac{7}{2}^-$ level with a cross section of only 8 nb/sr. Table I lists the mass excesses from both the present and previous measure-

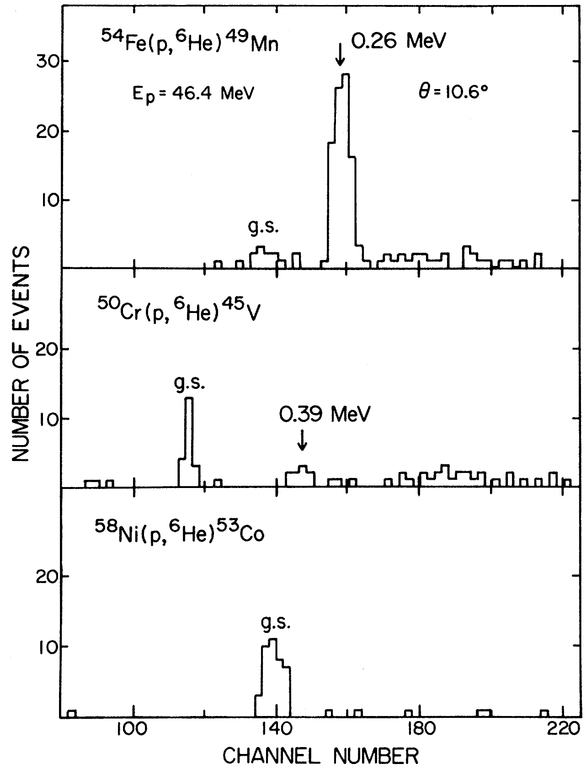

FIG. 1. Spectra of ^{6}He particles at $\theta = 10.6°$.

TABLE I. Experimental results and comparison with previous measurements.

Nucleus	Mass excess (MeV) Present	Mass excess (MeV) Previous [a]
^{43}Ti	−29.328 ± 0.012	−29.341 ± 0.015 −29.321 ± 0.010 [b]
^{45}V	−31.876 ± 0.017	
^{47}Cr(g.s.) [c]	−34.608 ± 0.040	−34.625 ± 0.028
($\frac{7}{2}^-$)	−34.386 ± 0.012	
^{49}Mn($\frac{5}{2}^-$ g.s.)	−37.614 ± 0.024	
($\frac{7}{2}^-$)	−37.351 ± 0.018	
^{51}Fe($\frac{5}{2}^-$ g.s.)	−40.219 ± 0.017	−40.232 ± 0.017
($\frac{7}{2}^-$)	−39.940 ± 0.013	−39.962 ± 0.020
^{53}Co	−42.650 ± 0.018	
^{55}Ni	−45.345 ± 0.011	−45.369 ± 0.015

[a] Previous measurements from Ref. 1 except as noted.
[b] Reference 7.
[c] The $\frac{3}{2}^-$ ground state and the $\frac{5}{2}^-$ excited state of ^{47}Cr are not resolved.

ments.[1,7] The target thicknesses used in the present work ranged from 87 ± 15 μg/cm^2 for ^{50}Cr to 324 ± 40 μg/cm^2 for ^{58}Ni, and the energy loss corrections which were required ranged from 13 to 31 keV for the (^{3}He, ^{6}He) measurements and from 12 keV to 42 keV for the (p, ^{6}He) measurements. The Q values of the calibration reaction used in the present measurements are 19.811 ±0.003 MeV[8,9] for ^{22}Al(^{3}He, ^{6}He)^{24}Al and − 27.1076 ±0.004 MeV[8,10,11] for ^{27}Al(p, ^{6}He)^{22}Mg which differ by less than 2.3 MeV from the Q values of the reactions of interest. This small difference in the Q values leads to a small difference in the magnetic fields and therefore implies an uncertainty of less than 2 keV for magnetic field corrections. The statistical uncertainties in the centroids of $\frac{7}{2}^-$ levels in the nuclei being investigated and of the calibrations used is typically 20 keV in a single spectra. Even though at least three spectra were obtained for each nucleus, the mass uncertainty listed reflects mainly this statistical uncertainty as well as the target-thickness uncertainty. There is a systematic difference of about 15 keV between the previous and present (^{3}He, ^{6}He) mass measurements. This difference appears to be due mainly to the use of thicker targets in the previous work which required approximately five times greater energy loss corrections than in the present work. Also the Q

TABLE II. Cross sections for the reactions.

Reaction [a]	$d\sigma/d\Omega$ (nb/sr)	θ (deg)	Reactions [a]	$d\sigma/d\Omega$ (nb/sr)	θ (deg)
^{50}Cr(p, ^{6}He)^{45}V	200 ± 40	10.6	^{46}Ti(^{3}He, ^{6}He)^{43}Ti	300 ± 25	8
^{54}Fe(p, ^{6}He)^{49}Mn(g.s.)	8 ± 4	10.6	^{50}Cr(^{3}He, ^{6}He)^{47}Cr(g.s.) [b]	144 ± 36	9
^{54}Fe(p, ^{6}He)^{49}Mn($\frac{7}{2}^-$)	120 ± 15	10.6	^{50}Cr(^{3}He, ^{6}He)^{47}Cr($\frac{7}{2}^-$)	560 ± 80	9
^{58}Ni(p, ^{6}He)^{53}Co	600 ± 100	10.6	^{54}Fe(^{3}He, ^{6}He)^{51}Fe(g.s.)	90 ± 30	9
^{58}Ni(^{3}He, ^{6}He)^{55}Ni	1200 ± 120	8	^{54}Fe(^{3}He, ^{6}He)^{51}Fe($\frac{7}{2}^-$)	360 ± 30	9

[a] Cross section to ground state is given unless otherwise noted.
[b] The $\frac{3}{2}^-$ ground state and $\frac{5}{2}^-$ excited state of ^{47}Cr are not resolved.

TABLE III. Coulomb energies and reduced Coulomb energies for the $T=\frac{1}{2}$ mirror pairs in the $f_{7/2}$ shell.

A	ΔE_C [a] (MeV)	$\Delta E_C/Z_<$
41	7.278± 0.005	0.3639± 0.0002
43	7.632± 0.011	0.3634± 0.0005
45	7.906± 0.018	0.3593± 0.0008
47	8.252± 0.012	0.3588± 0.0005
49	8.548± 0.020	0.3562± 0.0008
51	8.841± 0.014	0.3536± 0.0006
53	9.073± 0.023	0.3489± 0.0009
55	9.464± 0.012 [b]	0.3505± 0.0004 [b]

[a] Coulomb energies calculated using present measurements, and mass 71 values (Ref. 8).

[b] A value of −54.0275± 0.0022 MeV for the mass excess of ^{55}Co was used, Ref. 12.

value of the reaction ^{27}Al(^{3}He, ^{6}He)^{27}Al used in the present measurement is more nearly the same as those for the reactions being studied than the calibrations used previously. Thus the present measurements should supercede the previous measurements. Table II lists the cross sections for the various reactions.

IV. DISCUSSION

With these new masses, Coulomb energy differences of the $T=\frac{1}{2}$ mirror pairs can be extracted and compared to shell-model predictions, and their systematic trend can be discussed. For a homogeneously charged spherical nucleus of radius R, the Coulomb energy E_{Coul} is $\frac{3}{5}[Z(Z-1)]/(R)e^2$. Thus, using $Z_<$ to denote the charge of the $T_z=+\frac{1}{2}$ member of the $T=\frac{1}{2}$ mirror pair, the Coulomb energy difference is $\Delta E_C = \frac{6}{5} e^2 Z_</R$. By dividing ΔE_C by $Z_<$, the principal Z dependence is removed, and we can look at the systematics in finer detail. Table III lists the experimental Coulomb energy difference $[\Delta E_C = M(T_z=-\frac{1}{2}) - M(T_z=\frac{1}{2}) + 0.782 \text{ MeV}]$ and the reduced Coulomb energy difference $\Delta E_C/Z_<$ for the lowest $J^\pi=\frac{7}{2}^-$ level of the $T=\frac{1}{2}$ mirror pairs. Figure 2(a) shows a plot of measured $\Delta E_C/Z_<$ for $T=\frac{1}{2}$, $J^\pi=\frac{7}{2}^-$ mirror states in the $f_{7/2}$ shell. The experimental results are indicated by the points with error bars. The solid line is a prediction made by Chung and Wildenthal[4] who used the two-particle Coulomb interaction of Bertsch and Shlomo.[13] The calculation assumed a pure $f_{7/2}$ configuration and no change in the radial form factor for the nuclei from $A=41$ to 55. There is a good agreement between the prediction and experiment for both the size of the Coulomb-pairing interaction and the general dependence of the reduced Coulomb energy on A. The magnitude of the effective Coulomb-pairing interaction for mass A is deduced from the masses of the nuclei by taking the difference between ΔE_C for A and the average of ΔE_C for $A-1$ and $A+1$. From the present data the average value of the Coulomb-pairing interaction in the $1f_{7/2}$ shell is 35 ±10 keV. This small

TABLE IV. Predicted mass excess using Garvey-Kelson, new mass measurements, mass 71 mass values (Ref. 8), and Ref. 10.

Nucleus	Mass excess (MeV)	Separation energy [a] (MeV) One proton	Two protons
		$T_z=-1$	
^{44}V	−23.84	1.80	6.31
^{46}Cr [b]	−29.61	5.02	6.64
^{48}Mn	−29.30	1.98	6.81
^{50}Fe	−34.46	4.14	6.23
^{52}Co	−34.39	1.46	6.35
^{54}Ni	−39.28	3.92	5.52
		$T_z=-\frac{3}{2}$	
^{43}V	−17.93	0.10	3.87
^{45}Cr	−19.69	3.14	4.94
^{47}Mn	−22.64	0.32	5.34
^{49}Fe	−24.77	2.76	4.74
^{51}Co	−27.36	0.19	4.33
^{53}Ni	−29.69	2.59	4.05
		$T_z=-2$	
^{42}V	−8.03	−0.37	2.09
^{44}Cr	−13.60	2.96	3.06
^{46}Mn	−12.62	0.21	3.35
^{48}Fe	−18.17	2.83	3.15
^{50}Co	−17.74	0.26	3.02
^{52}Ni	−22.65	2.58	2.77
		$T_z=-\frac{5}{2}$	
^{41}V	0.08	−1.81	0.43
^{43}Cr	−2.19	1.45	1.08
^{45}Mn	−5.17	−1.14	1.82
^{47}Fe	−7.17	1.84	2.05
^{49}Co	−9.95	−0.93	1.90
^{51}Ni	−12.04	1.59	1.85
		$T_z=-3$	
^{42}Cr	6.12	1.25	−0.56
^{44}Mn	6.36	−1.26	0.19
^{46}Fe	0.52	1.60	0.46
^{48}Co	0.96	−0.84	1.01
^{50}Ni	−4.15	1.48	0.55
		$T_z=-\frac{7}{2}$	
^{45}Fe	13.57	0.08	−1.19
^{49}Ni	7.58	0.66	−0.17
		$T_z=-4$	
^{48}Ni	16.41	0.49	−1.31

[a] Negative binding energy indicates nucleus unbound to particle emission.

[b] Experimental mass excess is −29.46± 0.03 (Ref. 14).

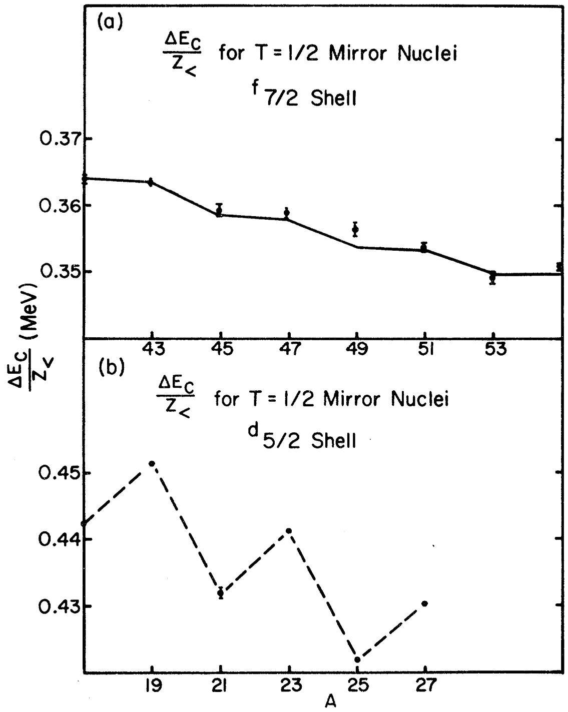

FIG. 2. Graph of $\Delta E_C/Z_<$ versus A for $T=\frac{1}{2}$ mirror nuclei in the $f_{7/2}$ and $d_{5/2}$ shells. In the $f_{7/2}$ graph the points with error pairs indicate experimental data from Table III. The solid line is a prediction by W. Chung and B. H. Wildenthal. The dashed line in the $d_{5/2}$ graph connects experimental points.

value would have been difficult to extract from less accurate mass measurements. Using the same procedure on the masses derived from the shell-model calculation, a value of 44 keV is obtained for this pairing term, which is in good agreement with the empirical value. It is interesting to note that the 44 keV pairing deduced from the shell-model results is significantly less than the 70 keV value entered in the two-body matrix elements of the shell-model code. This is due to seniority mixing since a good seniority scheme would have returned 70 keV as the Coulomb-pairing interaction.

A plot of ΔE_C versus A for the lowest $\frac{5}{2}^+$ level in the $d_{5/2}$ shell is shown in Fig. 2(b). It is clearly seen that the $1f_{7/2}$ mirror states show considerably smaller Coulomb-pairing variations than is seen in the $1d_{5/2}$ shell. It has been pointed out by Sherr *et al.*[15] that the size of the Coulomb energy difference varies more slowly than $A^{-1/3}$ in this region. The present data indicate an $A^{-1/n}$ dependence where $6 \leq n \leq 7$ throughout the $1f_{7/2}$ shell.

Since all $T_z=-\frac{1}{2}$ nuclei have now been observed up to ^{55}Ni, one can use the method of Kelson and Garvey to predict the masses of proton-rich nuclei with atomic numbers ≤ 28. This method, based upon an independent particle model, takes into account size, shell, and pairing effects. In the cases where prediction and experiment can be compared, agreement at the 150 keV level is found with the largest deviations observed when nuclei from more than one subshell are used in the relation. Table IV lists the calculated mass excesses of $T_z \leq -1$ isotopes from V through Ni which are predicted to be stable against α particle emission and one- and two-proton emission. Also listed are the first two isotopes predicted to be unbound to one- or two-proton emission. These predictions for the $T_z=-1$ nuclei agree to within 70 keV with those Harchol *et al.* deduced from the systematic behavior of the Coulomb displacement energies.[16] In view of the predicted particle stability of ^{48}Ni and ^{45}Fe, it appears that the experimental observation of nuclei all the way out to the proton drip line will require some rather exotic heavy ion reactions and pose quite a challenge to the experimentalists.

V. CONCLUSION

The present results complete the measurement of the masses of all the $T_z=-\frac{1}{2}$ nuclei in the $f_{7/2}$ shell. These results have allowed us to calculate the Coulomb energy differences for the $T=\frac{1}{2}$ mirror pairs in the $f_{7/2}$ shell and to predict masses of 32 yet unobserved proton-rich nuclei.

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