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Diproton decay of nuclei on the proton drip line

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The process of direct two-proton decay of nuclei with $Z=22$–28 on the proton drip line is considered. On the basis of new $0d_{3/2}$-$0f_{7/2}$ shell-model mass extrapolations, ^{39}Ti, ^{42}Cr, ^{45}Fe, ^{48}Ni, and ^{49}Ni are found to be bound to single-proton decay but unbound to two-proton decay. New estimates of the spectroscopic factors and lifetimes have been made. The decays of ^{39}Ti, ^{45}Fe, and ^{48}Ni are found to be promising for further experimental investigation.

Nuclei near the proton drip line (i.e., the boundary beyond which nuclei are unbound to direct proton decay) exhibit exotic decay modes, and the understanding of these modes is important for nuclear-structure physics.[1,2] They provide a unique test of the assumed wave functions for these nuclei far away from the valley of stability. Direct two-proton ($2p$) decay is one of the most exotic and elusive of these decay modes. Its occurrence is a result of the odd-even staggering in the single-proton separation energies (S_p) which results in situations where $S_p > 0$ while $S_{2p} < 0$. In all of the cases considered here with $Z=22$–28, proton decay of the ground state is the only open decay channel other than β^+ decay. The process of $2p$ decay was first discussed theoretically many years ago.[3,4] However, in spite of intense experimental efforts,[5] the $2p$ decay mode has not yet been directly observed. The $2p$ decay should dominate over β^+ decay for the ^{6}Be, ^{12}O, and ^{16}Ne ground states, and $2p$ decay of ^{8}C ground state may dominate over the β^+, $3p$, and $4p$ channels. However, for these cases only the total ground-state widths are known.[6] The situation becomes more interesting for heavier nuclei where the higher Coulomb barrier can more easily result in $2p$-decay lifetimes which are comparable to those for β^+ decay. It thus becomes possible to create secondary beams of these nuclei and study their decay in a low-background environment.

The $2p$ decay rates are extremely sensitive to the separation energy S_{2p},[1,2] and hence a good estimate of this quantity is necessary. A common method for predicting the proton-rich masses is based on a generalized version[7,8] of the Kelson-Garvey approach[9] which relates the mirror mass difference $M(A,T_z=-T)-M(A,T_z=T)$ to the sum of the differences of the $T=\frac{1}{2}$ mirror nuclei which lie in between, $\sum[M(A',T_z=-\frac{1}{2})-M(A',T_z=\frac{1}{2})]$, where the sum runs over $A'=A-(2T-1)$ to $A'=A+(2T-1)$. Aystro and Cerny[2] used this method to find that ^{31}Ar ($S_{2p}=-191$ keV), ^{39}Ti ($S_{2p}=-785$ keV), and ^{42}Cr ($S_{2p}=-691$ keV) were promising candidates for study. In addition, they found that ^{22}Si was within about 100 keV of being $2p$ unbound. It has since been found that ^{22}Si (Ref. 10), ^{31}Ar (Ref. 11), and ^{39}Ti (Ref. 5) are all dominated by β^+ decay. These results for ^{22}Si and ^{31}Ar are consistent with the above small (or positive) S_{2p} values. In this paper I will show that one can make improved estimates of the masses and decay rates which are consistent with experiment for ^{39}Ti. These improved estimates will be used to show there are several other candidates for $2p$ decay in the region $Z=22$–28. Half-life estimates for these indicate that ^{39}Ti, ^{45}Fe, and ^{48}Ni are the best available candidates for further experimental study of the $2p$ decay process.

There are two sources of error in the Kelson-Garvey mass extrapolations. Sometimes the experimental error in the mass of the $T_z=T$ neutron-rich nucleus is large, as in the case of ^{22}Si [$\Delta M(^{22}\mathrm{O})=90$ keV (Ref. 12)] and ^{31}Ar [$\Delta M(^{31}\mathrm{Al})=70$ keV (Ref. 12)]. For the cases of interest above $Z=18$ the neutron-rich masses are usually known to an accuracy of 10 keV or better. In addition, the Kelson-Garvey estimate does not take into account the specific nuclear configurations, the charge asymmetry of the nuclear interaction, and the Thomas-Erhman shift associated with the loosely bound protons.[13,14] All of these contribute to the observed differences of up to one MeV between the predicted and measured masses.[7]

An alternative way to predict the proton-rich masses is to use the isobaric mass multiplet equation (IMME);

$$M(A,T,T_z,v)=a(A,T,T_z,v)+b(A,T,T_z,v)T_z+c(A,T,T_z,v)T_z^2$$

(v stands for all quantum numbers other than T and T_z). [In terms of binding energies;

$$\mathrm{BE}(A,T,T_z,v)=a'(A,T,T_z,v)+b'(A,T,T_z,v)T_z+c(A,T,T_z,v)T_z^2\,,$$

where $b'=-b+782$ keV.] It is well known that this series terminates at T_z^2 when any isospin-nonconserving two-body interaction is evaluated as a first-order perturbation.[15] Experimentally, the only known exception to this is for the $J^\pi=\frac{3}{2}^-$, $T=\frac{3}{2}$ multiplet in $A=9$.[15] Thus, if the masses of three or more members of a given isobaric-mass multiplet are known, the a, b, and c coefficients can be determined and the mass of the remaining members of the multiplet can be predicted. In particular, the binding energy difference $M(A,T_z=-T)-M(A,T_z=T)$ is determined by $2T_z$ times the b' coefficient. In practice there are relatively few multiplets whose masses are known accurately enough to predict the proton-rich masses to better than a few hundred keV. In most cases one must resort to some global parametrization of the

IMME coefficients[16] which suffers from the same deficiencies mentioned above with regard to the Kelson-Garvey relation. However, the displacement energy between the neutron-rich ground state and its analog in the neighboring nucleus is usually known to 10 keV or better for most nuclei in the mass region of interest. In this paper I use this information together with a microscopic model of the displacement energies to predict masses of the proton-rich nuclei.

Microscopic shell-model calculations of the isobaric mass shifts are very successful in reproducing the data.[17,18] In particular, it is well known that the $0f_{7/2}$ orbit is rather isolated from its neighboring orbits, and hence the nuclei with $20 \le Z \le 28$ and $20 \le N \le 28$ can be described in zeroth order in terms of $0f_{7/2}$ shell-model configurations. Brown and Sherr[17] have used this model to parametrize displacement energies in this mass region (those for about 60 states) in terms of microscopic charge-dependent and charge-asymmetric two-body interactions. The rms deviation between experiment and theory for a nine parameter fit to these 60 data was 13 keV, which is comparable to the average experimental error in the data. It is straightforward to use the results of these calculations to predict the proton-rich masses for nuclei in the $0f_{7/2}$ shell. The b' coefficients can be obtained by averaging the calculated displacement energies for the neutron-rich nuclei given in Table 4 of Ref. 17 with those of the matching proton-rich displacement energies as given in Table 8 of Ref. 17. In Table I I list the calculated b' coefficients for the $0f_{7/2}$ shell nuclei together with the experimental binding energies[12] of the neutron-rich nuclei $BE_<$. The predicted binding energies of the proton-rich nuclei are obtained from $BE_> = BE_< - 2|T_z|b'$ and compared to experiment where available. The theoretical uncertainties are based on the 13-keV rms deviation mentioned above. The agreement with experiment where available is good. The largest deviations between experiment and theory are for ^{42}Ti and ^{46}Cr. As discussed in Ref. 17, the deviation in the case of ^{42}Ti is probably due to the larger than average admixture of the low-lying four-particle two-hole intruder-state configuration into the predominant two-particle configuration—a similar mechanism is probably responsible for the ^{46}Cr deviation.

The shell-model configurations for the proton-rich nuclei with $N = 17-19$ involved both the $0d_{3/2}$ and $0f_{7/2}$ orbits. In principle, the type of calculations presented above for the $0f_{7/2}$ shell could be extended to this larger model space. However, I note that the interaction between the $0d_{3/2}$ orbit and $0f_{7/2}$ orbit is relatively weak[19] and that the

TABLE I. Binding energies and proton separation energies for nuclei in the $0f_{7/2}$ shell.

$^AZ_<$	$\|T_z\|$	$BE_<$ (exp) (keV)[a]	b' (keV)	$^AZ_>$	$BE_>$ (th) (keV)	$BE_>$ (exp) (keV)[a]	S_p (keV)	S_{2p} (keV)
^{41}Ca	$\frac{1}{2}$	350418	7294	^{41}Sc	343124(13)	343140	1069	9298
^{42}Ca	1	361898	7477	^{42}Ti	346944(26)	346908(6)	3804	4889
^{43}Ca	$\frac{3}{2}$	369813	7618	^{43}V	346977(39)	347000(200)	33	3837
^{44}Ca	2	380963	7780	^{44}Cr	349843(52)	349580(180)	2866	2899
^{45}Ca	$\frac{5}{2}$	388378	7924	^{45}Mn	348758(65)		−1085	1781
^{46}Ca	3	398774	8081	^{46}Fe	350288(78)		1530	445
^{47}Ca	$\frac{7}{2}$	406951	8227	^{47}Co	348462(91)		−1828	−296
^{48}Ca	4	415995	8383	^{48}Ni	348931(104)		469	−1357
^{44}Sc	1	376526	7793	^{44}V	360940(26)	360950(100)	1761	6248
^{45}Sc	$\frac{3}{2}$	387852	7943	^{45}Cr	364023(39)	363900(150)	3083	4844
^{46}Sc	2	396613	8090	^{46}Mn	364253(52)	364200(400)	230	3313
^{47}Sc	$\frac{5}{2}$	407256	8240	^{47}Fe	366056(65)		1803	2033
^{48}Sc	3	415490	8383	^{48}Co	365192(78)		−864	939
^{49}Sc	$\frac{7}{2}$	425623	8539	^{49}Ni	365850(91)		658	−206
^{46}Ti	1	398197	8082	^{46}Cr	382033(26)	381979(20)	4940	6555
^{47}Ti	$\frac{3}{2}$	407075	8222	^{47}Mn	382409(39)	382450(200)	376	5316
^{48}Ti	2	418701	8383	^{48}Fe	385169(52)		2760	3136
^{49}Ti	$\frac{5}{2}$	426844	8527	^{49}Co	384209(65)		−960	1800
^{50}Ti	3	437783	8685	^{50}Ni	385673(78)		1464	504
^{48}V	1	413904	8383	^{48}Mn	397138(26)	397090(100)	2006	6773
^{49}V	$\frac{3}{2}$	425459	8544	^{49}Fe	399827(39)	399630(160)	2689	4695
^{50}V	2	434794	8683	^{50}Co	400062(52)		235	2924
^{51}V	$\frac{5}{2}$	445845	8842	^{51}Ni	401635(65)		1573	1808

[a]From Ref. 12. The error is given if it is larger than a few keV.

wave functions are thus given to a good zeroth-order approximation by the "weak-coupling" configuration. For example, the weak-coupling wave functions for ^{41}K and ^{41}Ti would be $(\pi 0d_{3/2})^{-1}(\nu 0f_{7/2})^2$ and $(\nu 0d_{3/2})^{-1}\times(\pi 0f_{7/2})^2$, respectively. The displacement energy for the configuration $(0d_{3/2})^{-n}(0f_{7/2})^m$, has the general form

$$\Delta \mathrm{BE}=(n+m)b'=nb'[0d_{3/2}^{-n}]+mb'[0f_{7/2}^{m}]+nmV_{\mathrm{ph}}\,.$$

The $b'[0d_{3/2}^{-n}]$ can be obtained from the cases with $m=0$ (^{39}Ca-^{39}K, ^{38}Ca-^{38}Ar, and ^{37}Ca-^{37}Cl). V_{ph} is the average charge-asymmetric interaction between the $0d_{3/2}$ holes and the $0f_{7/2}$ particles. I use a value of $V_{\mathrm{ph}}=-25$-keV based on a fit to the ^{40}Sc-^{40}K and ^{40}Ti-^{40}Ar shifts. Finally, the $b'[0f_{7/2}^{m}]$ are obtained from the $Z=20$ nuclei; I use the experimental values for $m=1$ ($b'=7278$ keV) and $m=2$ ($b'=7495\pm 6$ keV) and the theoretical values for $m>2$ (see Table I). The resulting b' coefficients are given in Table II together with the experimental $\mathrm{BE}_<$ values[12,20] and the predicted $\mathrm{BE}_>$ values. The error bars on $\mathrm{BE}_>$ include the experimental or theoretical error associated with $b'[0f_{7/2}^{m}]$, the experimental error in $b'[0d_{3/2}^{-n}]$ plus the experimental error in $\mathrm{BE}_<$. The agreement with experiment where available is excellent. We note, in particular, that the predicted value for ^{39}Sc is in good agreement with experiment, in contrast to the several hundred keV disagreement found with the Kelson-Garvey relationship.[7] The main reason for this is that our estimate takes into account the correct shell-model configuration for this nucleus, whereas the Kelson-Garvey relation does not.

The S_p and S_{2p} values obtained with our binding energies are given in Tables I and II (the errors are not given but they can be inferred from the errors on the binding energies.) The lightest nuclei between $Z=22$ and 28 which are bound to both one- and two-proton emission are found to be ^{40}Ti, ^{43}V, ^{43}Cr, ^{46}Mn, ^{46}Fe, ^{50}Co, and ^{50}Ni. This is not inconsistent with the present data.[21] The following nuclei are found to be bound to one-proton emission but unbound to two-proton emission: ^{39}Ti, ^{42}Cr, ^{45}Fe, ^{48}Ni, and ^{49}Ni. I next discuss the partial half-lives for the $2p$ and β^+ decay of these nuclei.

From previous studies of the $2p$ decay mechanisms,[3,4] it was found that the correlated decay mode (diproton decay) should dominate because of the absence of a centrifugal barrier in the correlated $L=0$ state. Our estimate of the diproton decay width is based on the standard approximation[14,22] $\Gamma=2\theta^2\gamma^2P_{L=0}(Q_{2p})$. The factor θ^2 is the shell-model spectroscopic factor to be discussed below. γ^2 is the Wigner single-particle width given by $\gamma^2=(3\hbar^2c^2/2\mu R_0^2)$ where μ is the reduced mass. The penetrabilities $P_{L=0}$, which depend on the diproton decay

TABLE II. Binding energies and proton separation energies for nuclei in the $0d_{3/2}$-$0f_{7/2}$ shell.

$^AZ_<$	$\lvert T_z\rvert$	$\mathrm{BE}_<$ (exp) (keV)[a]	b' (keV)	$^AZ_>$	$\mathrm{BE}_>$ (th) (keV)	$\mathrm{BE}_>$ (exp) (keV)[a]	S_p (keV)	S_{2p} (keV)
^{39}K	$\frac{1}{2}$	333725	7313	^{39}Ca		326413	5764	10907
^{40}K	1	341525	7283	^{40}Sc	326959(3)	326953(4)	546	6310
^{41}K	$\frac{3}{2}$	351621	7418	^{41}Ti	329367(7)	329410(40)	2408	2954
^{42}K	2	359156	7523	^{42}V	329064(39)	329230(300)	−303	2105
^{43}K	$\frac{5}{2}$	368797	7667	^{43}Cr	330462(52)		1398	1095
^{44}K	3	376090(40)	7801	^{44}Mn	329284(76)		−1178	220
^{45}K	$\frac{7}{2}$	384958	7950	^{45}Fe	329308(78)		24	−1154
^{46}K	4	391838(16)	8091	^{46}Co	327110(92)		−2198	−2174
^{47}K	$\frac{9}{2}$	400188(8)	8242	^{47}Ni	326010(104)		−1100	−3298
^{38}Ar	1	327345	7110	^{38}Ca		313125(5)	4549	6407
^{39}Ar	$\frac{3}{2}$	333943	7149	^{39}Sc	312496(6)	312490(40)[b]	−629	3920
^{40}Ar	2	343812	7278	^{40}Ti	314700(10)	314707(11)	2204	1575
^{41}Ar	$\frac{5}{2}$	349911	7385	^{41}V	312986(39)		−1714	490
^{42}Ar	3	359340(40)	7523	^{42}Cr	314202(66)		1216	−498
^{43}Ar	$\frac{7}{2}$	364970(70)	7656	^{43}Mn	311378(95)		−2824	−1608
^{44}Ar	4	373320(20)	7801	^{44}Fe	310912(80)		−466	−3290
^{37}Cl	$\frac{3}{2}$	317103	6983	^{37}Ca		296154(22)	3023	4689
^{38}Cl	2	323210	7038	^{38}Sc	295058(22)	294740(300)	−1096	1927
^{39}Cl	$\frac{5}{2}$	331287(19)	7158	^{39}Ti	295497(29)		439	−657
^{40}Cl	3	337090(500)	7263	^{40}V	293512(500)		−1985	−1546
^{41}Cl	$\frac{7}{2}$	345020(160)	7396	^{41}Cr	293248(168)		−264	−2249
^{42}Cl	4	350120(200)	7524	^{42}Mn	289928(210)		−3320	−3584

[a]From Ref. 12 except where noted. The error is given if it is larger than a few keV.
[b]Reference 20.

Q value, $-S_{2p}$, and the channel radius, R_0, were calculated from Coulomb wave functions obtained using the method of Steed as described by Barnett.[23]

The half-lives for the cases of interest obtained with $R_0=4.0$ fm and $\theta^2=1$ are given in Table III. (The sensitivity to R_0 is relatively small compared to the sensitivity to S_{2p}. A reduction of R_0 from 4.0 to 3.5 fm results in a factor of 2–3 increase in the lifetimes given in Table III.) The calculated lifetimes for diproton decay should be compared with those for β^+ decay which are on the order of 10 msec for nuclei in this region. On the basis of this comparison, the diproton decay branches for ^{42}Cr and ^{49}Ni are clearly insignificant compared to β^+ decay. The other three cases are of more interest, and I will now discuss calculations for spectroscopic factors associated with these.

The spectroscopic factor θ^2 can be estimated in the cluster overlap approximation:[24–27] $\theta_c^2=G^2[A/(A-k)]^{\lambda}\times|\langle\psi_f|\psi_c|\psi_i\rangle|^2$, where $k=2$, $\lambda=6$, and $G^2=\frac{5}{4}$ (Ref. 27) for the diproton in the $0f1p$ major shell. ψ_c is a two-proton cluster wave function in which the internal motion of the two protons is in $0s$ state. It is obtained by diagonalizing an SU3 conserving interaction[24,25,28] in the full $0f1p$ basis. The overlap factors were calculated using the shell-model code OXBASH.[29]

These calculations for ^{48}Ni are most complete. The wave functions for ^{48}Ni and the final nuclei involved in diproton decay (^{46}Fe) and β^+ decay (^{48}Co) were obtained with a new $0f1p$ shell interaction[30,31] in the full $0f1p$ basis. The spectroscopic factor for diproton decay turns out to be 0.55. If the basis is truncated to just the $0f_{7/2}$ orbit, the spectroscopic factor is a factor of 4 smaller. This factor of 4 indicates the importance of the full $0f1p$ shell correlations in calculating the diproton decay; a fact which is well established from the study of two-nucleon transfer reactions in the $0f_{7/2}$ shell.[32] The diproton decay lifetime for ^{48}Ni is thus in the range 0.002–0.4 msec with the variation due to the assumed 130 keV error in S_{2p}. The calculated β^+ decay half-life of ^{48}Ni is 9.2 msec. [It is interesting to note that this β decay is the mirror of that studied in the (p,n) reaction on ^{48}Ca (Refs. 31 and 33) which is relevant for the double-β decay of ^{48}Ca.[31]] Thus, the decay of ^{48}Ni should be dominated by diproton decay and the lifetime could be in the range for an on-line experiment.[1] The signature of the diproton decay would be the observation of the subsequent β^+ decay of ^{46}Fe. The calculated β^+ half-life for ^{46}Fe is 13.4 msec. It is calculated to have a 42% branch to the lowest 1^+ state in ^{46}Mn at $E_x=1.0$ MeV and a 21% branch to the isobaric analog state (IAS) at $E_x=5.0$ MeV. The IAS in turn decays by single-proton emission, and this should be the outstanding signature of the $2p$ decay of ^{48}Ni.

I have not carried out complete calculations for the ^{39}Ti and ^{45}Fe decays. However, the spectroscopic factors can be estimated from the fact that the decay proceeds by the emission of two protons from the $0f1p$ shell. Thus, for ^{39}Ti I take the overlap $\langle^{40}\mathrm{Ca}|\psi_c|^{42}\mathrm{Ti}\rangle$, and for ^{45}Fe I take the overlap $\langle^{44}\mathrm{Cr}|\psi_c|^{46}\mathrm{Fe}\rangle$. The resulting spectroscopic factors are given in Table III. Again, they are all seen to be near unity. The decay of ^{39}Ti has recently been observed with a half-life of 28^{+8}_{-7} msec with no evidence for direct two-proton decay.[5] The upper range of the predicted range of lifetimes, 53–260 msec, is consistent with the present experiment, and suggests that two-proton decay should be observed in a more sensitive experiment. Finally, the results for ^{45}Fe are very similar to that of ^{48}Ni discussed above, and this nucleus should also be a good candidate for further study. Clearly, in all of the cases of interest, the theoretical uncertainty in the calculated diproton decay lifetimes is dominated by the uncertainty in the two-proton separation energy. Thus, more precise experimental measurements of the masses will be essential for a quantitative interpretation of the results. My results indicate that two-proton decay mode should be observable in ^{39}Ti, ^{45}Fe, and ^{48}Ni, and they should motivate further experimental work on the masses and decay modes of these nuclei.

TABLE III. Half-lives and spectroscopic factors for diproton decays.

^AZ	S_{2p} (keV)	$t_{1/2}$[a] (msec)	θ^2	$t_{1/2}$[b] (msec)
^{39}Ti	−657(20)[c]	28–140[d]	0.53	53–260
^{42}Cr	−498(66)[e]	10^7–10^{12}		
^{45}Fe	−1154(94)[f]	0.002–0.3	0.78	0.003–0.4
^{48}Ni	−1357(130)[g]	0.001–0.2	0.55	0.002–0.4
^{49}Ni	−206(112)[g]	$>10^{20}$		

[a]Obtained for $\theta^2=1$ and $R_0=4.0$ fm.
[b]Obtained for θ^2 as given in the fourth column and $R_0=4.0$ fm.
[c]The error is determined from the following linear combination of binding energies which follows from the equations given in the text: $S_{2p}=\mathrm{BE}(^{39}\mathrm{Ti})-\mathrm{BE}(^{37}\mathrm{Ca})=\mathrm{BE}(^{39}\mathrm{Cl})_e-\mathrm{BE}(^{37}\mathrm{Cl})_e+\mathrm{BE}(^{42}\mathrm{Ti})_e-\mathrm{BE}(^{42}\mathrm{Ca})_e+150$ keV, where the subscript e indicates that the quantity is taken from the experimental values given in Tables I and II.
[d]The range corresponds to the lower and upper limits on S_{2p}.
[e]See footnote c: $S_{2p}=\mathrm{BE}(^{42}\mathrm{Cr})-\mathrm{BE}(^{40}\mathrm{Ti})=\mathrm{BE}(^{38}\mathrm{Ca})_e-\mathrm{BE}(^{38}\mathrm{Ar})_e+\mathrm{BE}(^{44}\mathrm{Cr})_t-\mathrm{BE}(^{44}\mathrm{Ca})_e+\mathrm{BE}(^{42}\mathrm{Ar})_e-\mathrm{BE}(^{40}\mathrm{Ti})_t+200$ keV, where the subscript t indicates that the quantity is taken from the theoretical values given in Tables I and II.
[f]See footnotes c and e: $S_{2p}=\mathrm{BE}(^{45}\mathrm{Fe})-\mathrm{BE}(^{43}\mathrm{Cr})=\mathrm{BE}(^{39}\mathrm{Ca})_e-\mathrm{BE}(^{39}\mathrm{K})_e+\mathrm{BE}(^{46}\mathrm{Fe})_t-\mathrm{BE}(^{46}\mathrm{Ca})_e+\mathrm{BE}(^{45}\mathrm{K})_e-\mathrm{BE}(^{43}\mathrm{Cr})_t+150$ keV.
[g]Obtained from the theoretical $\mathrm{BE}_>$ values in Table I.

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