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L. Ni et al.

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Neutron Magicity in the Proton Drip-line Nucleus ^{20}Mg: First Invariant-Mass Reconstruction of ^{19,20}Mg

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The resonant states in ^{20}Mg and ^{19}Mg have been studied by the invariant-mass reconstruction of ^{18}Ne + $2p$ and ^{17}Ne + $2p$ events, respectively. Two new resolved states (4^+_1 and 2^+_2) in ^{20}Mg are found to decay through ^{19}Na intermediate states to the ground state of ^{18}Ne from the examination of the decay-energy spectra for ^{18}Ne + $1p$ subsystems. The deduced $R_{42} = E^*(4^+_1)/E^*(2^+_1)$ ratio of 2.10(1) is close to the expected harmonic-vibrator value and reveals a spherical or weakly deformed shape for ^{20}Mg. Systematic comparison of $E^*(2^+_1)$ and R_{42} along isotopic and isotonic chains with shell model calculations, using the YSOX interaction, suggest the persistence of $N = 8$ shell around the proton drip-line. The relatively higher 2^+_1 excitation energy in ^{18}Mg relative to ^{20}Mg can be ascribed to different excitation characters of the valence protons. The $1/2^+_1$ state in ^{19}Mg has been observed for the first time. The energy differences between the $1/2^-_1$ and $1/2^+_1$ states in ^{19}Mg and its isotones manifest the magnitude of $N = 8$ shell gap.

Since the shell model (SM) was proposed by Mayer [1], Haxel, Jensen, and Suess [2], there has been an intense effort to study the evolution of nuclear shell structure across the nuclear chart. With the recently acquired capability to study nuclei far from the line of β-stability, some traditional magic numbers [3–10], $N = 8$, 20, and 28, have been found to disappear in neutron-rich regions, with the emergence of new ones [11–24] at $N = 14$, 16, 32, and 34. Detailed description of these findings can be found in the reviews of [25–27].

Long isotopic chains extending into the neutron-rich region have enabled extensive study of the shell evolution of this side of stability. Far less is known on the proton-rich side. One intriguing result on the proton-rich side is the breakdown of the $Z = 8$ shell closure, which is indicated by the lowered location of the 2^+_1 or 0^+_2 state in the proton-unbound nucleus ^{12}O [28], an effect ascribed to the proton-neutron monopole interaction [28, 29]. Two recent experimental studies suggested a possible weakening of the $N = 8$ shell closure near the proton drip-line. In one study, a considerable quadrupole deformation in ^{20}Mg was extracted from an inelastic deuteron scattering experiment [30]. In another study, using the invariant-mass method, a higher excitation energy of the 2^+_1 state is found in ^{18}Mg ($N = 6$) than in ^{20}Mg ($N = 8$) [31]. Mean-field [32–42] and beyond-mean-field [43] calculations predict neither that ^{20}Mg is significantly deformed nor a weakening of the $N = 8$ shell, while the macroscopic-microscopic model [44] and a Hartree-Fock calculation, neglecting the pairing correlation [45], do suggest that ^{20}Mg is deformed.

So far, the spectroscopic information for the Mg isotopes around $N = 8$ is scarce. For ^{20}Mg only two resonant structures, including a relatively wide peak at $E^* = 3.70$ MeV, have been reported [30]. It is interesting to note that the resonant structures of ^{20}Mg play a pivotal role not only in determining the fate of $N = 8$ shell but also in estimating the reaction rate of ^{18}Ne$(2p,\gamma)^{20}$Mg, which is a potential breakout reaction from the hot CNO cycle in type-I x-ray bursts [46, 47]. In this Letter, we report on spectroscopic studies of ^{20}Mg and ^{19}Mg using the invariant mass method. The deduced $R_{42} = E^*(4^+_1)/E^*(2^+_1)$ ratio for ^{20}Mg and the energy difference between the $1/2^-_1$ and $1/2^+_1$ states in ^{19}Mg suggest the persistence of $N = 8$ shell around the proton drip-line.

The experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A primary beam of ^{24}Mg was accelerated through the Coupled Cyclotron Facility to $E/A = 170$

MeV and fragmented on a ^{9}Be primary target. A secondary beam of ^{20}Mg at $E/A = 103$ MeV was then selected with the A1900 fragment separator [48, 49]. This secondary beam had an intensity of 5600 pps and a purity of 31%. Particle identification of these secondary beam particles was achieved on an event-by-event basis via their time-of-flight between two plastic scintillators. The ^{20}Mg beam impinged on a 1-mm-thick secondary ^{9}Be target, producing ^{20}Mg and ^{19}Mg resonant states via projectile inelastic-excitation reactions and one-neutron knockout reactions, respectively. These unstable states promptly decayed, and the ^{18}Ne + $2p$ and ^{17}Ne + $2p$ decay channels were investigated. After passing through a 6-mm-thick aluminum absorber, the protons were detected by an array of $\Delta E - E$ telescopes subtending 1.2° to 10.1° in the laboratory and consisting of an annular 1-mm-thick double-sided silicon-strip detector [50] followed by an annular array of CsI(Tl) crystals. The CsI(Tl) array was composed of twenty 50-mm-thick crystals, arranged in two concentric rings with 4 and 16 detectors in the inner and outer rings, respectively.

Most of the ^{18}Ne and ^{17}Ne residues passed through a 10-mm-diameter hole in the center of the $\Delta E - E$ telescope and then through two orthogonal ribbons of scintillating fiber. Each ribbon is comprised of 64 fibers each with square (0.25×0.25 mm^2) cross sections. One end of each fiber was coupled to an element of an 8×8 multianode photomultiplier that was read out from its four edges with a resistor network. This scintillating-fiber array (SFA), provides the hit position of the residue close to the location of proton detection, which improves the invariant-mass resolution by accurately measuring the relative angles between the exit channel fragments. After traversing the SFA, the residues entered the S800 spectrograph [51, 52] where the particles were identified with their energies being determined. Previous results from this experiment pertaining to the structure of ^{18}Mg have been published [31].

The decay energy E_T spectra of ^{20}Mg and ^{19}Mg resonances from the invariant mass of all detected ^{18}Ne + $2p$ and ^{17}Ne + $2p$ events, respectively, are shown in Fig. 1. Four and five peaks can be resolved above a smooth background for ^{20}Mg and ^{19}Mg, respectively. Red curves show fits to these spectra with Breit-Wigner intrinsic lines shapes modified by the simulated experimental resolution as in Ref. [31]. The fitted decay energies, excitation energies, and intrinsic decay widths of these states are listed in Table I.

For ^{20}Mg, the decay paths of the prominent ^{20}Mg→^{18}Ne + $2p$ resonances observed in Fig. 1(a) are studied by examination of the decay-energy spectra of the ^{18}Ne + $1p$ subsystem. As examples, the spectra of the first two resonant states, which are selected using the gates G1 and G2 in Fig. 1(a), are shown in Figs. 2(a) and (b), respectively.

For the first resonant state at $E_T = 0.930$ MeV, the

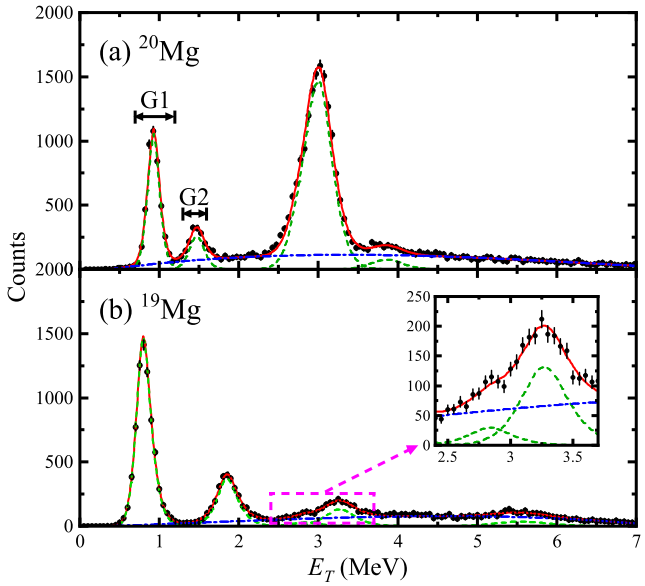


FIG. 1. Decay energy E_T spectra for all detected (a) ^{18}Ne + $2p$ and (b) ^{17}Ne + $2p$ events. The solid-red curves show the fitted spectra along with the contributions of each state (dashed-green curves) and the smooth background (dashed-dotted-blue curves). The inset in (b) highlights the region around $E_T = 3$ MeV of (b).

TABLE I. Decay energies E_T, excitation energies E^*, and intrinsic widths Γ of the resonant states in ^{20}Mg and ^{19}Mg. All the values are expressed in MeV. Excitation energies of ^{20}Mg are based on experimental ground-state energy [53].

^{20}Mg			^{19}Mg		
E_T	E^*	Γ	E_T	E^*	Γ
0.930(2)	3.348(3)	0.019(30)	0.794(1)	0	0.000(70)
1.468(5)	3.886(5)	0.045(60)	1.844(3)	1.050(3)	0.015(50)
3.008(2)	5.426(3)	0.209(90)	2.82(1)	2.03(1)	0.00(7)
3.91(2)	6.33(2)	0.07(17)	3.26(1)	2.47(1)	0.04(15)
			5.54(3)	4.75(3)	0.00(4)

^{18}Ne + $1p$ subsystem displays two peaks at 0.315 and 0.615 MeV. The lower energy of these corresponds to the decay energy of the ground state of ^{19}Na [see the inset in Fig. 2(a)]. This ^{20}Mg state can thus be understood to undergo a sequential two-proton decay. The first proton decay leads to this ^{19}Na intermediate state which then proton decays to the ground state of ^{18}Ne. This scenario is also confirmed by a simulation of this decay, as shown by the solid red curve in Fig. 2(a). The second ^{20}Mg resonant state, at $E_T = 1.468$ MeV, decays differently. Two peaks at 0.467 and 1.001 MeV are observed in the ^{18}Ne + $1p$ subsystem in Fig. 2(b). These peaks indicate a sequential $2p$ decay process where the ^{19}Na intermediate state is now the first excited state at $E_T = 0.467$ MeV [see the inset in Fig. 2(a)]. This ^{19}Na excited state also

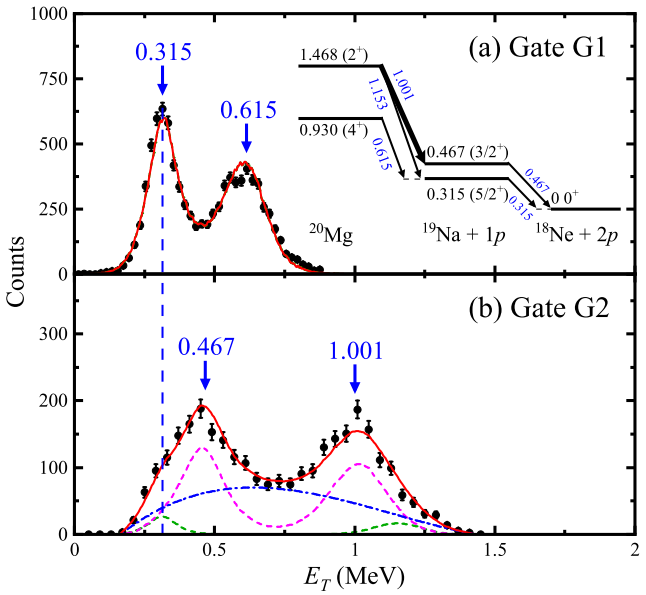


FIG. 2. Decay energy E_T spectra for the ^{18}Ne + $1p$ subsystem with the gates on (a) E_T = 0.930 MeV (G1), and (b) 1.468 MeV (G2) resonant states in ^{20}Mg. Red lines are the results of simulations, assuming sequential decay for the resonant states in ^{20}Mg resulting from decay paths through the state at E_T = 0.315 MeV in ^{19}Na (dashed-green curve) and the state at E_T = 0.467 MeV in ^{19}Na (dashed-magenta curve). A smooth background (dashed-dotted-blue curve) is added in (b) because of the high relative background contribution under the E_T = 1.468 MeV state as shown in Fig. 1(a). The shape of the background reflects the distribution when gating outside of the location of the resonances. The blue arrows with numbers and dashed-blue vertical line show the positions of decay energies in MeV. The inset in (a) shows the main decay paths of the first two resonant states in ^{20}Mg. The energies of the states in ^{20}Mg and ^{19}Na relative to the $2p$ and $1p$ thresholds, respectively, are listed on the levels in MeV. The energies of the intermediate states in ^{19}Na are consistent with the available experimental results [54–56]. The blue numbers in the inset are the $1p$ decay energies in MeV between the corresponding states. The bold arrow is the main decay branch of the 1.468-MeV state in ^{20}Mg.

proton decays to the ground state of ^{18}Ne. The fit to this spectrum is improved if a minor sequential $2p$ decay branch through the intermediate state at E_T = 0.315 MeV in ^{19}Na is included. The third resonant state at E_T = 3.008 MeV in ^{20}Mg is found to overwhelmingly decay through the ^{19}Na ground-state at E_T = 0.315 MeV, which is similar to the first resonant state and not shown here.

In Fig. 3(a), the excitation energies of the four resonant states in ^{20}Mg observed in this work are compared with the experimental results of Ref. [30] and with the SM calculations therein. The previous experiment observed two resonant structures in ^{20}Mg and the relative wide resonant peak at E^* = 3.70 MeV was suggested to be comprised of an overlap of the 4^+_1 and 2^+_2 states [30].

As shown in Fig. 1(a), the higher resolution of the present work allows these two states to be fully resolved. Their energies are in good agreement with both the SM predictions from Ref. [30] [see Fig. 3(a)] and the mirror systematics [$E^*(4^+_1)$ = 3.570 MeV and $E^*(2^+_2)$ = 4.072 MeV in the mirror nucleus ^{20}O [57]]. The present spin-parity (4^+ and 2^+) assignments for these two resonant states in ^{20}Mg are consistent with their decay paths [see the inset in Fig. 2(a)]: the higher-spin state 4^+ is likely to preferentially decay to the $(5/2^+)$ ground state of ^{19}Na, while the lower-spin state 2^+ tends to rather decay to the $(3/2^+)$ state in ^{19}Na. The third resonant state observed here is also in fair agreement with the higher-lying state observed in Ref. [30].

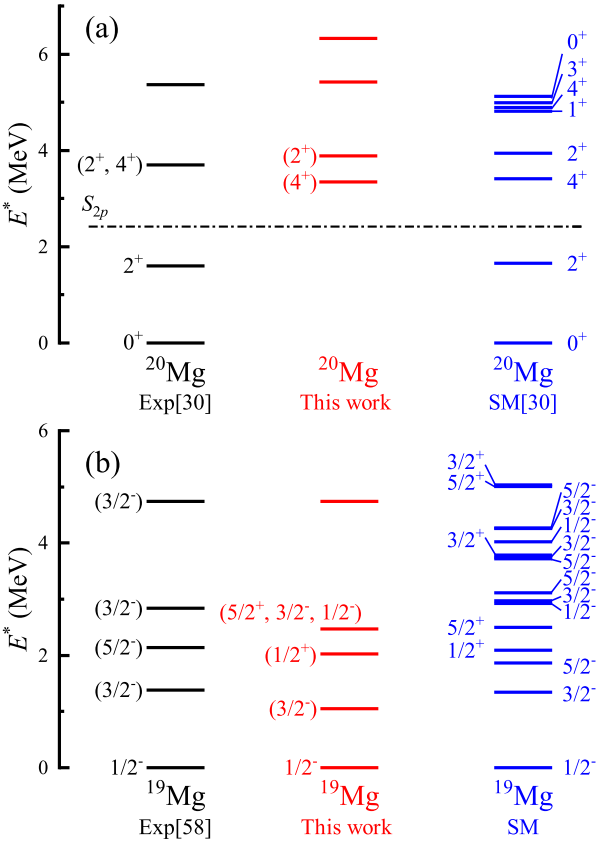


FIG. 3. The excitation energies E^* of the (a) four resonant states in ^{20}Mg and (b) five resonant states in ^{19}Mg identified in this work (in red). The previous experimental results of ^{20}Mg [30] and ^{19}Mg [58] (in black) and shell model calculations (in blue) for ^{20}Mg from Ref. [30] and for ^{19}Mg, are given for comparison. The dashed-dotted line in (a) indicates the two-proton separation energy S_{2p} of ^{20}Mg.

For ^{19}Mg, five resonant states were observed in the previous experimental works utilizing the in-flight decay method, all of which were assumed to decay to the ground state in ^{17}Ne [58–62]. Here, the decay paths of the first two resonances of ^{19}Mg, which have high statistics, are investigated by examination of the decay-energy spectra

TABLE II. The theoretical and experimental excitation energies and yields relative to the ground state for low-lying resonant states (E^*<3.0 MeV) in ^{19}Mg. The excitation energies are in MeV.

Experimental		Theoretical			
E^*	$\sigma_{\rm exp}$	E^*	$\sigma_{\rm th}$	Configuration	J^π
0	1	0	1	$1p_{1/2}$	$1/2^-$
1.050	0.320(8)	1.341	0.156	$1p_{3/2}$	$3/2^-$
2.03	0.032(6)	2.085	0.016	$2s_{1/2}$	$1/2^+$
2.47	0.214(9)	2.498	0.042	$1d_{5/2}$	$5/2^+$
		2.922	0.029	$1p_{1/2}$	$1/2^-$
		2.971	0.086	$1p_{3/2}$	$3/2^-$

of the ^{17}Ne + $1p$ subsystem [63] and found to be consistent with the conclusions in Refs. [58–62].

The comparison between the experimental states of ^{19}Mg observed in this work and previous experiments [58–62], as well as with our SM calculations, is shown in Fig. 3(b). The SM calculations are performed in the *psd* model space with the YSOX interaction [64], which have been successfully applied to describe properties of loosely bound proton-rich nuclei around A = 20 [65]. In Fig. 3(b) it can be seen that the resonant structures observed in the present work well agree with the SM calculations, and are consistent with those reported in previous experimental studies except for the spin-parity assignment for the second excited state at E^* = 2.03 MeV.

The second excited state at E^* = 2.03 MeV of ^{19}Mg was tentatively assigned as $5/2^-$ in Ref. [58]. In both that and the present work, ^{19}Mg was produced by one-neutron knockout from ^{20}Mg. As the neutron population of the $f_{5/2}$ orbit in ^{20}Mg$_{\rm g.s.}$ is marginal, population of a low-lying $5/2^-$ state in ^{19}Mg should be very weak in both this work and that of Ref. [58].

The relative reaction cross sections for populating resonant states in ^{19}Mg were calculated from a Glauber model of nucleon knockout (MOMDIS code) [66] with the SM spectroscopic factors. The theoretical and experimental yields for low-lying resonant states relative to the ground state in ^{19}Mg are listed in Table II. This comparison indicates that a spin-parity of $1/2^+$, corresponding to the knockout of a $s_{1/2}$ neutron, is a reasonable assignment for the second excited state [E^* = 2.03 MeV] of ^{19}Mg. As for the third excited state at E^* = 2.47 MeV, the SM plus MOMDIS calculations indicate that $5/2^+$, $3/2^-$ and $1/2^-$ are all possible.

Panels (a) and (b) of Fig. 4 display the excitation energies for the 2_1^+ states in even-even Z = 10 and 12 isotopes and N = 10 and 12 isotones, respectively. For the N =10 and 12 isotones [Fig. 4(b)], the 2_1^+ energies peak at Z = 8. Mirror symmetry is seen in the Z = 10 isotopic chain [Fig. 4(a)] which also has a maximum at N = 8. Deviating from this systematics is ^{20}Mg (N = 8) where its 2_1^+ energy is lower than that of ^{18}Mg (N = 6) [31].

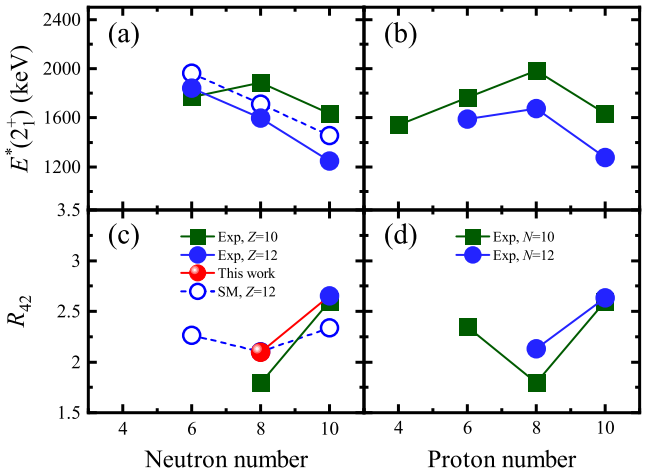


FIG. 4. (a) $E^*(2_1^+)$ and (c) R_{42} ratios for Z = 10, 12 isotopes; (b) $E^*(2_1^+)$ and (d) R_{42} ratios for N = 10, 12 isotones. Experimental data are taken from Ref. [67] and this work. The SM calculations for (a) $E^*(2_1^+)$ and (c) R_{42} in Mg isotopes are given for comparison.

As previously mentioned considerable deformation in ^{20}Mg, and consequently a deformation-driven weakening of the N = 8 shell closure at the proton drip-line, were suggested in Ref. [30]. Fixing the excitation energy of the 4_1^+ state in ^{20}Mg offers a straightforward method for investigating whether ^{20}Mg is deformed. Systematics for the ratio of the excitation energies of the 4_1^+ and 2_1^+ states, R_{42}, are shown in Figs. 4(c) for Z = 10 and 12 isotopes and (d) for N = 10 and 12 isotones. Lower R_{42} ratios at $Z(N)$ = 8 are observed for all four chains [67, 68]. For a deformed rigid rotor $R_{42} \approx 3.3$, while for purely spherical vibrational nuclei this ratio should be equal to 2. The relatively low R_{42} ratio of 2.10(1) suggests a near spherical shape for ^{20}Mg at N = 8 and argues against a deformation-driven weakening of the N = 8 shell closure at the proton drip-line. This experimental result is consistent with both mean-field [32–42] and beyond-mean-field [43] calculations. SM calculations are compared to the experimental results in Fig. 4 where it can be seen that the calculations reproduce the experimental trends. Specifically, a minimum in R_{42} is predicted at ^{20}Mg, indicating a shell closure at N = 8.

The new spectroscopy of ^{19}Mg provides more insight into the evolution of the N = 8 shell at the proton drip-line. The YSOX SM calculations suggest an inversion of the $1/2^+$ and $5/2^+$ states occurs in ^{19}Mg [Fig. 3(b)] compared with ^{21}Mg, which indicates the crossing of the $\nu 2s_{1/2}$ and $\nu 1d_{5/2}$ neutron orbitals.

The lowering in energy of the $1/2^+$ state (compared to $5/2^+$ state) has also been found in all N = 7 isotones from Z = 2 to Z = 10 [5, 67, 69–72]. Consequently, the

energy differences $\Delta E_{1/2}$ between the lowest-lying $1/2^+$ and $1/2^-$ states (originating from $\nu 2s_{1/2}$ and $\nu 1p_{1/2}$ orbitals, respectively) in $N = 7$ isotones can provide valuable information on the magnitude of $N = 8$ shell gap. In Fig. 5 $\Delta E_{1/2}$ values are negative at the neutron drip-line ($Z \leq 4$), indicating the $\nu 2s_{1/2}$ level is intruding into the p shell. This causes a breakdown of the normal shell ordering and has been confirmed for He [73], Li [74, 75], Be [5, 7, 76–79] and B [80]. The maximum of $\Delta E_{1/2}$ at $Z = 8$ reflects the proton magicity [25]. The robustness of the $N = 8$ shell closure in neon isotopes has been verified [68] [also seen here in Fig. 4(a)]. The same is true for carbon isotopes [25]. The similar $\Delta E_{1/2}$ values for ^{17}Ne and ^{19}Mg in Fig. 5, the magnitudes of which are only a little smaller than the value for ^{13}C (which has the $Z = 6$ subshell closure), further support the persistence of $N = 8$ shell near the proton drip-line and the magicity of ^{20}Mg.

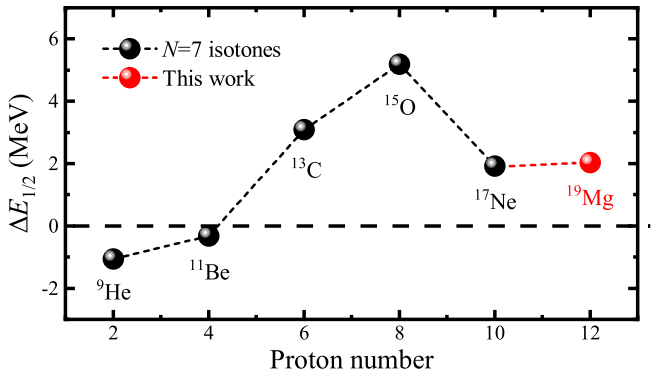


FIG. 5. Systematics of experimental energy differences $\Delta E_{1/2}$ between the lowest-lying $1/2^+$ and $1/2^-$ states in $N = 7$ isotones. Data are taken from Refs. [67, 69, 72] and this work.

The persistence of $N = 8$ shell in Mg isotopes suggests that the 2_1^+ states in even-even ^{20}Mg and ^{18}Mg mainly arise from the excitation of valence protons. The proton effective single-particle energies of Mg isotopes are calculated by the SM and an inversion of $\pi 2s_{1/2}$ and $\pi 1d_{5/2}$ orbitals is predicted to occur between ^{20}Mg and ^{18}Mg. This inversion can be attributed to the nucleon-nucleon monopole interactions [26] with the decreased occupancy of two $1p_{1/2}$ neutrons in ^{18}Mg [25]. This inversion of these orbitals between $N = 8$ and $N = 6$ is well known in the neighboring odd-Z F isotopes [56, 67, 81–83]. According to the SM calculations, with the proton orbital inversion, the 2_1^+ state in ^{18}Mg mainly arises from the excitation of $\pi 2s_{1/2} \rightarrow \pi 1d_{5/2}$, whereas the 2_1^+ state in ^{20}Mg results from the internal excitation within the $\pi 1d_{5/2}$ orbital. Meanwhile, the neutron configurations in 2_1^+ states of ^{20}Mg and ^{18}Mg are almost unchanged compared to their ground states. Thus, the relatively higher 2_1^+ excitation energy in ^{18}Mg relative to ^{20}Mg can be ascribed to different excitation characters of the valence protons.

In summary, the invariant-mass reconstruction of ^{20}Mg and ^{19}Mg have been performed and four and five resonant states are identified in these nuclei, respectively. The R_{42} ratio of 2.10(1) in ^{20}Mg reveals a sphere or weakly deformed shape, which excludes the possibility of deformation-driven weakening of the $N = 8$ shell closure. Systematics of $E^*(2_1^+)$ and R_{42} along isotopic and isotonic chains in comparison with the SM calculations using the YSOX interaction, suggest the persistence of $N = 8$ shell around the proton drip-line. The energy difference between the $1/2_1^-$ and $1/2_1^+$ states in ^{19}Mg is compared with its isotones and manifests the magnitude of the $N = 8$ shell. Due to the inversion of $\pi 2s_{1/2}$ and $\pi 1d_{5/2}$ orbitals in the Mg isotopes near the proton drip-line, the higher excitation energy of the 2_1^+ state in ^{18}Mg than this state in ^{20}Mg can be ascribed to their different excitation characters.

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