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The $T = 2$ mirrors ^{36}Ca and ^{36}S: A test for isospin symmetry of shell gaps at the driplines

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Abstract

The first excited 2^+ state of ^{36}Ca has been identified by its γ-decay, exploiting the two-step fragmentation technique at the FRS-RISING setup at GSI. This is the heaviest $T_z = -2$ nucleus in the Segré chart in which a γ-decay of an excited state has been observed. A stable beam of ^{40}Ca at 420*A* MeV impinged on a primary ^{9}Be target. Out of the secondary beam of fragmentation products, ^{37}Ca was separated by the FRS and struck on a second ^{9}Be target at the final focus of the FRS. The energy for the 2_1^+ decay of ^{36}Ca was determined to be 3015(16) keV, which is 276 keV lower than in its $T = 2$ mirror ^{36}S. This mirror energy difference (MED) is discussed in the framework of shell model calculations using a ^{16}O core, the *sd* shell isospin symmetric interaction USD and experimental single-particle energies from ^{17}O and ^{17}F. The results show that the MED within the *sd* shell provide a sensitive test for the evolution of the $N, Z = 14, 16$ subshell gaps towards the driplines. Especially the $N, Z = 16$ gap is determined by Thomas–Ehrman shift in the $A = 17$, $T = 1/2$ isospin doublet, while Coulomb effects are found to have marginal influence.

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Recently, the Coulomb energy difference ΔE_C of isobaric analogue states and especially the MED in $T_z = \pm T$ pairs of nuclei have been extensively studied. In connection with pre-

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cise large-scale shell model calculations these quantities have proved to be a sensitive spectroscopic probe to investigate orbital radii in excited states [1] and the reduced overlap of identical proton and neutron orbitals at the driplines [2]. The MED, defined as $\Delta E_M = E_x(I, T_z = -T) - E_x(I, T_z = +T)$, will be positive for increasing spin I due to alignment and therefore reduced Coulomb repulsion. This can be partly counterbalanced by a reduced orbital overlap as this quenches the two-body matrix elements. The latter effect would have a strong impact on the evolution of (sub)shell gaps. The new $N = 14(16)$ shell stabilisation in $Z = 8$ oxygen isotopes and the $N = 20$ shell quenching in $^{32}Mg_{20}$ below the $Z = 14$, 16 subshells are expected to be dominated by the monopole part of the two-body interaction. Moreover, the scenario is anticipated to be symmetric with respect to the isospin projection T_z and may only slightly be affected by decreasing neutron binding energies [3]. On the other hand, the proton-rich mirror $Z = 20$ (Ca) nuclei are situated close to the proton dripline which may destroy the T_z symmetry. Therefore, the ideal site in the Segré chart where the competing scenarios can be investigated is the $N = 20$ mirror region along the light Ca ($Z = 20$) isotopes. The lightest Ca isotope with detailed spectroscopy is ^{38}Ca, while no excited states are known for the $N = 16$ isotope, and ^{34}Ca is already particle unbound.

For the mirror pair ^{38}Ca and ^{38}Ar the MED of the first excited 2^+ state (^{38}Ca; $2_1^+ - {}^{38}$Ar; $2_1^+ = 39$ keV) is positive, which is expected for a hole configuration due to the different Coulomb repulsion in the 0^+ ground state (g.s.) and excited state. Within a fixed j^n multinucleon configuration the MED changes sign with ph conjugation [4]. A negative MED may be anticipated by approaching the proton dripline. Here the question arises whether the quenching of the two-body interaction due to a reduced orbital overlap may cause the opposite energy shift. Crucial experimental information can be deduced from a measurement of ^{36}Ca; $2_1^+ - {}^{36}$S; 2_1^+, the heaviest $T = 2$ mirror nuclei studied so far.

The FRS-RISING setup [5,6] was used to identify excited states in ^{36}Ca, especially the $2_1^+ \to 0_{g.s.}^+$ decay, employing the two step fragmentation technique. A primary beam of ^{40}Ca, provided by the heavy-ion synchrotron SIS with an energy of 420 A MeV, was incident upon a 4 g/cm^2 ^{9}Be target at the entrance of the FRS. The average beam intensity was 3×10^8 ions/s. The ^{37}Ca fragments of interest were selected and identified in-flight on an event-by-event basis using their magnetic rigidity Bρ, their time of flight between the two scintillation detectors SCI1 and SCI2, see Fig. 1, and their energy loss in the multi sampling ionization chamber MUSIC. In order to optimize the secondary ^{37}Ca beam at the final focus, a wedge-shaped aluminium degrader of 2.31 g/cm^2 was placed at the middle focal plane of the FRS, so that $\approx 85\%$ of the incoming detected ions were ^{37}Ca.

At the final focus, 2×10^3 ^{37}Ca ions/s impinged on a secondary 700 mg/cm^2 ^{9}Be target at an energy of 196 A MeV. The reaction products were selected using the calorimeter telescope array CATE [7], consisting of 3×3 Si–CsI(Tl) modular $\Delta E - E$ telescopes. The energy loss in the Si detectors provided a good charge resolution for unambiguous Z identification after the secondary target. Due to the relatively large momentum transfers in the secondary reactions, the velocities of the reaction products were spread out. Thus, the total energy spectrum did not provide for a complete mass resolution.

The γ-rays emitted by the fragmentation products were measured with 15 Cluster Ge detectors, containing 7 crystals each, and positioned in three rings at extreme forward angles of 16°, 33° and 36° with an opening angle of 3°. In addition, 7 six-fold segmented MINIBALL triple Ge detectors were arranged in two rings with central angles of 51° and 85° relative to the beam line at forward angles. The HECTOR array [8], consisting of 8 large volume BaF_2 detectors, was situated at angles of 85° and 142°. The position sensitivity of the MINIBALL detectors allowed them to be placed at a close target distance of 250 mm, while the Cluster and HECTOR detectors sat at greater distances of 700 and 300 mm, respectively.

In order to obtain the best energy resolution for the γ-rays emitted in flight ($\beta = 0.545$), an excellent tracking of the moving nuclei is mandatory. Different from the RISING setup described in [6], an additional thin position sensitive Si ΔE detector with the dimensions of 5×5 cm^2 was placed directly after the secondary target. Together with the CATE Si ΔE detectors the fragment trajectories were determined with a position resolution of 3×3 mm^2 [7].

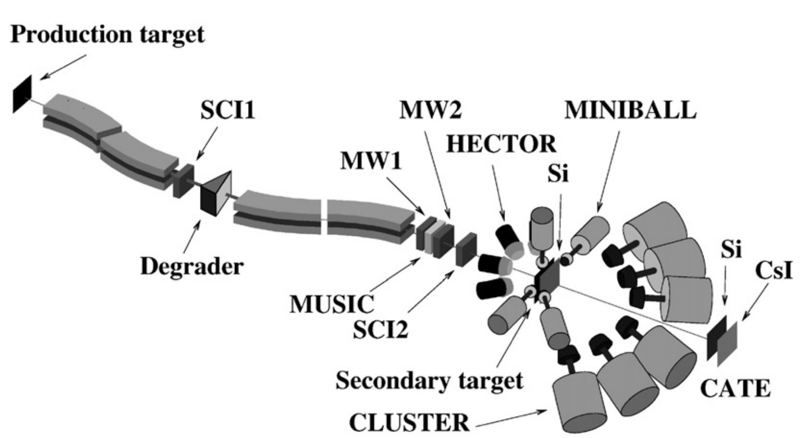

Fig. 1. Schematic layout of the RISING setup at the FRS. See text for details.

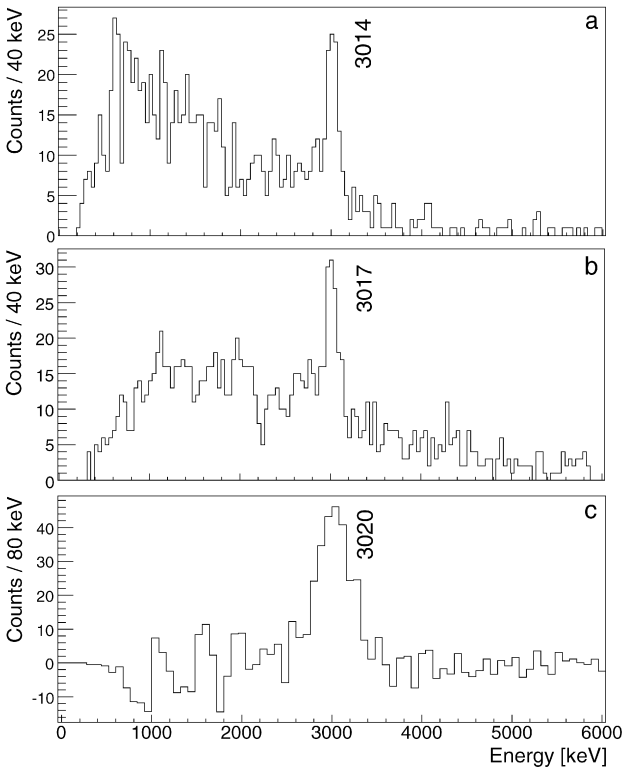

Fig. 2. Doppler corrected ^{36}Ca gated γ-ray spectra measured with the Cluster (a), MINIBALL (b) and HECTOR (c) detectors. For (c) the background was subtracted.

A precise Doppler correction has to take into account the expected lifetime of the decaying state. Since most of the decays of ^{36}Ca took place within the secondary target (the time of flight through the target was 23 ps), assuming a comparable half-life for excited states as in the mirror nucleus ^{36}S, the average β for the Doppler shift correction was given by a Monte Carlo simulation with GEANT4 [9]. The simulation included the reduced velocity due to the energy necessary to ablate nucleons [10] and the momentum distribution from the fragmentation process [11]. Deviations of this mean value, which mainly originated from the fragmentation of the primary beam, were corrected using the time of flight information from the intermediate to the final focus.

The main source of background γ-rays originated from particles identified as Ca in the CATE Si detectors that fragmented during the stopping process in the CATE CsI(Tl) detectors. These events could partially be discriminated from events that occurred in the target by imposing narrow time gates for the particle-γ conditions. Further background reduction was obtained by setting energy cuts in the CsI(Tl) detectors. The total energy deposition of the ^{37}Ca secondary beam particles in the CsI(Tl) detectors was also measured for events without γ-ray coincidence.

Another difficulty to overcome in the analysis was the high $2_1^+ \to 0_{\text{g.s.}}^+$ transition energy around 3 MeV, implying γ-ray energies of more than 5 MeV in the laboratory frame for the Cluster detectors at forward angles due to the Doppler shift. GEANT4 simulations showed, that single-hit photo peak events are then disfavoured with respect to single escape and Compton scattering events. Hence, for the Cluster detectors only addback events which required a γ-ray multiplicity of two individual energy signals were accepted in the analysis. In the case of the MINIBALL detectors the crystal segmentation was used to determine events that scattered within the crystal. This condition also improved the peak to background ratio drastically for observed high energy γ-ray transitions in ^{36}Ca and other fragmentation products.

The obtained Doppler corrected γ-ray spectra gated on ^{36}Ca for the three different detector types are displayed in Fig. 2. An energy resolution for the $2_1^+ \to 0_{\text{g.s.}}^+$ transition of 4.3(6)% was achieved for the Cluster detectors and 4.9(10)% for the MINIBALL detectors. These values are close to the simulated values of 3.8% and 4.5%, respectively. The measured energies of γ-ray transitions from the strongest reaction channels served as consistency check for the correct energy. Known transition energies deviated less than 5 keV with respect to literature values. Differences are expected due to unresolved weak components of close lying γ-lines, Compton-edge components of higher energy transitions and unknown feeding times. The resolution of 14% for the HECTOR array forbids a comparison with known transition energies. Thus, it was excluded in the assignment of a ^{36}Ca transition energy, however the measured HECTOR energy also provided a consistent result for the interesting decay. For the Ge detectors the statistical error of the observed ^{36}Ca γ-transition energy has been determined to be 15 keV, which yields, including the previously mentioned error for known transitions of 5 keV, an assignment of the $2_1^+ \to 0_{\text{g.s.}}^+$ transition to 3015(16) keV. The spin assignment is based on a comparison to the mirror nucleus and on shell model calculations. The 3020 keV peak observed in the HECTOR array is in good agreement with this value. A recent experiment at GANIL has also detected a γ-ray transition at 3025(30) keV in ^{36}Ca [12].

Comparing with the $T = 2$ mirror nucleus ^{36}S, an experimental mirror energy difference $\Delta E_M = E(^{36}\text{Ca}) - E(^{36}\text{S}) = -276(16)$ keV is measured for the $I^\pi = 2_1^+$ states. The new value is about a factor of 5–10 larger than MED observed for $T = 1$ states in the sd shell [13] and predominantly single-j valence $T = 1$ states in the $f_{7/2}$ shell [1,4]. Surprisingly, the Coulomb energy difference for the corresponding $T = 2$ states in ^{36}Cl is only $\Delta E_C = E(^{36}\text{Cl}) - E(^{36}\text{S}) = -27(4)$ keV [14]. This is summarised in Fig. 3, where experimental MED for $I^\pi = 2_1^+$ states of the $1s0d$ shell and the adjacent $0p$ and $1p0f$ major shells are shown. Data are from this work and Refs. [4, 13,15–18]. Though in general the $T = 2$ MED are larger than the $T = 1$ values, which may be due to the proton-rich partner lying closer to the dripline, the unique $A = 36$ and $A = 14$ cases are obvious. Here the first excited $I^\pi = 2^+$ states at the proton-rich side are already unbound.

Due to the known subshell closure for $Z = 16$ in ^{36}S and the anticipated one in ^{36}Ca for $N = 16$ there is no common particle (p) and hole (h) valence space for the g.s. and excited state, but a pure pp (hh) state for the g.s. and a ph state for the $I^\pi = 2_1^+$ state. The same holds for the $A = 14$, $T = 1$ triplet with respect to the subshell closure $Z = 6$ and $N = 6$, respectively, where a similar sign and size of the MED ($\Delta E_M = -422(10)$ keV) is observed [13]. The large MED certainly points to an effect due to shell structure and/or coupling to the continuum for the unbound state in the proton-rich partner ($S_p = 2.56(4)$ and 4.628 MeV for ^{36}Ca and ^{14}O, respectively [19]) and not to a Coulomb effect. This is corroborated by the fact that in both, the $A = 14$ and $A = 36$ mirrors, the $T_z = -T$ partner exhibits the smaller subshell and closed shell gap energies Δ, which are precisely determined by binding energy differences [19]. For example, the neutron gap energy in ^{36}Ca is 550(90) keV smaller than the proton gap energy in ^{36}S which is shown in Fig. 4.

A universal interaction USD for the *sd* model space outside an inert ^{16}O core has been determined by fitting two-body matrix elements (TBME) and single-particle energies (SPE) to experimental binding energies and excitation energies [20]. Experimental data were corrected for Coulomb shifts to warrant strict isospin symmetry of the interaction and SPE. Various shell model investigations, especially for the neutron-rich *sd* shell region close to the “island of inversion” around $^{32}_{12}$Mg$_{20}$, have been performed, which include excitations from the *sd* to the *pf* shell [21–23], preserving full isospin symmetry. To investigate the MED in the $A = 36$ mirror nuclei, the isospin symmetry has to be broken. In the hitherto first systematic attempt based on the USD, MED were calculated for application to the astrophysical *rp* process [24]. In the $T = 2$ cases $A = 24$, 32 and 36 the experimental results are largely underestimated by amounts of 70, 110 and 250 keV, respectively (see Fig. 5). The required modifications of the Thomas–Ehrman shifts in these proton-rich nuclei [25,26] may cause considerable changes in the proton capture rates entering *rp* path network calculations [24].

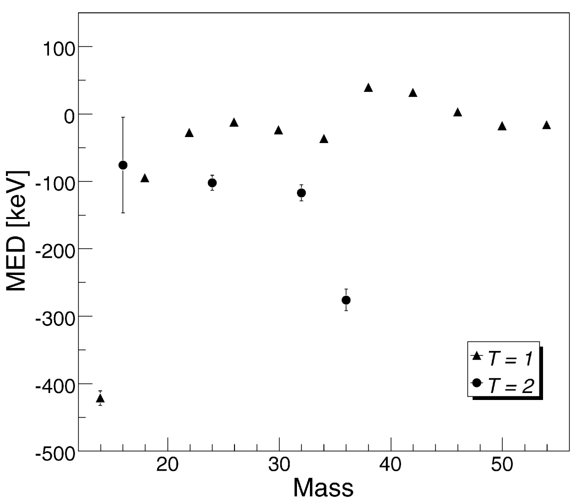

Fig. 3. Experimental mirror energy differences for the first $I^\pi = 2^+$ states of even–even $T = 1$ and $T = 2$ mirror nuclei from ^{14}C–^{14}O to ^{54}Fe–^{54}Ni (for references and details see text).

In a simpler empirical approach, hereafter referred to as USD*, we have replaced the fitted isospin symmetric SPE by the experimental values of the $A = 17$, $T = 1/2$ mirrors. This modification turns out to be the most crucial step in order to reproduce the new large MED in the ^{36}Ca–^{36}S pair. The isospin symmetry in the TBME is preserved. The configuration- and spin-dependent Coulomb corrections to the $T = 1$ proton–proton TBME have not been applied. In a second approach we have used the USD interaction as modified by Utsuno et al. [22] for use with the *pf* model space without pairing corrections. Again experimental SPE were taken from the $A = 17$, $T = 1/2$ mirrors. To get better agreement with the $N, Z = 14$ shell gaps in ^{22}O and in ^{34}Si, respectively, additional monopole corrections were applied, which modify the SPE evolution with increasing shell occupation [27]. The total monopole modifications as defined in Ref. [22] relative to USD are

$$\Delta V_{T=1,0}(d_{5/2}, d_{3/2}) = +0.20, -0.60 \text{ MeV}, \tag{1}$$

$$\Delta V_{T=1,0}(d_{5/2}, s_{1/2}) = -0.10, +0.10 \text{ MeV}. \tag{2}$$

This interaction, hereafter referred to as USD^m, reproduces the $Z, N = 14$, 16 shell gaps, the $I^\pi = 2_1^+$ excitation energies and

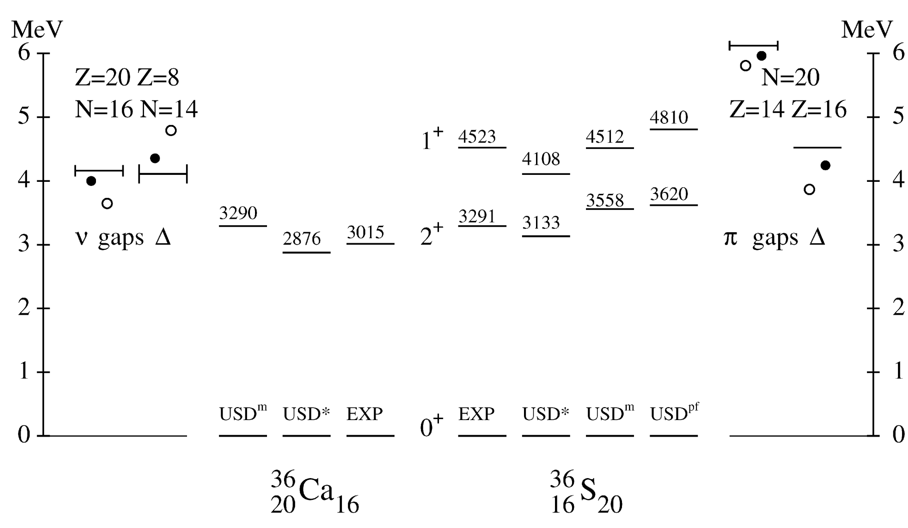

Fig. 4. Experimental ^{36}Ca and ^{36}S (partial) level schemes in comparison to shell model calculations using experimental single-particle energies and the USD interaction [20] (USD*), and a monopole modified USD based on Ref. [22] (USD^m see text). For ^{36}S the levels as calculated in the full $1s0d$–$1p0f$ space [22] (USD^{pf}) are shown, too. The $1s0d$ shell model space subshell gaps Δ for $N = 14$ (^{22}O), $N = 16$ (^{36}Ca), $Z = 14$ (^{34}Si) and $Z = 16$ (^{36}S) are shown as lines with error bars and compared to the corresponding shell model values as indicated by open (USD*) and filled (USD^m) circles.

the ^{40}Ca single-hole energies [28,29], i.e. the $Z = 8$, $N = 20$ and $Z = 20$ sd shell "fringe" nuclei, in total 13 key experimental data, with a mean level deviation [30] MLD = 275 keV. This should be compared to the USD MLD = 440 keV for the same data set. Even smaller MLD values of 224 keV (USD^m) and 207 keV (USD) are obtained for a set of 221 excitation energies in $A = 31$–39 nuclei comprising the original data [20] and new additional experimental results [13]. The results for the $I^\pi = 2^+_1$ respectively 1^+_1 states in ^{36}Ca and ^{36}S and the sd shell relevant $Z, N = 14, 16$ shell gaps are shown in Fig. 4. The calculations were performed with the code OXBASH [31].

The general agreement within the MLD is good for USD^m while the original USD* underestimates the $Z, N = 16$ gaps and correspondingly the $I^\pi = 2^+_1$ excitation energies in ^{36}Ca and ^{36}S. The striking result, however, is that independent from the interaction the use of experimental SPE, which empirically include Coulomb and Thomas–Ehrman [25,26] effects, almost fully accounts for the experimental MED. The values $\Delta E_M(\text{USD}^m) = -268$ keV and $\Delta E_M(\text{USD}^*) = -257$ keV compare well with $\Delta E_M(\text{EXP}) = -276(16)$ keV. It is therefore concluded that further Coulomb corrections beyond one-body contributions are negligible. This may be due to the ph character of the $I^\pi = 2^+_1$ states as ph conjugation changes the sign of mirror energy differences [4]. Moreover, this calculation reproduces the afore mentioned Coulomb energy difference observed in ^{36}Cl $T = 2$ states $\Delta E_C = -27(4)$ keV as -51 keV within the deviation expected from the neglect of two-body Coulomb corrections, which proves that the T_z dependence within the $T = 2$ isospin quintuplet is accounted for. Furthermore, apart from the MED and the subshell gaps at $N = 16$ in ^{36}Ca and $Z = 16$ in ^{36}S, which are robustly fixed by the $A = 17$ SPE, the evolution of shell structure for the proton-rich (^{36}Ca) and the neutron-rich (^{36}S) partners is completely determined by the isospin symmetric two-body interaction as expected for monopole driven shell structure [3,27].

The absolute values are certainly subject to change when sd–pf cross-shell excitations are included, which needs to be discussed. The USD^m $I^\pi = 2^+_1$ energies lie within the MLD but systematically about 270 keV above the experimental values. For ^{36}S a full sd–pf model space calculation within the Monte Carlo shell model (MCSM) was performed by Utsuno et al. [22], which is isospin symmetric in SPE and interaction. Excitation energies of 3620 and 4810 keV were found for the $I^\pi = 2^+$ and 1^+ states (see Fig. 4 USD^{pf}), which should be compared to 3406 and 4357 keV in the original USD [20]. The corrections due to experimental SPE as used in the present work can be estimated to first order from the difference between USD and USD* (Fig. 4) results to be about -260 keV for $I^\pi = 2^+, 1^+$, respectively, bringing the sd–pf values in good agreement to experiment. We also note that the shell gap optimised USD^m accounts well for the cross-shell excitations omitted in the present work. Their common deviation from experiment is of different origin though, namely symmetric SPE in USD^{pf} and neglect of explicit sd–pf excitation in USD^m. In the USD^{pf} approach it is found that an average of 0.74 neutrons (and 0.12 protons) are excited to the pf shell, which in the mirror nucleus ^{36}Ca should give rise to substantial coupling

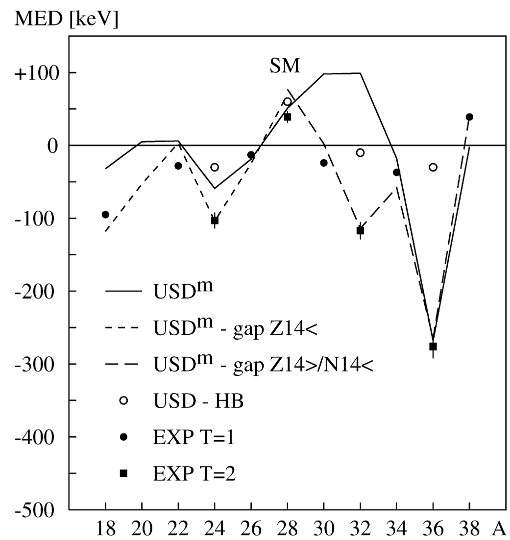

Fig. 5. Experimental mirror energy differences for the first $I^\pi = 2^+$ states of even–even $T = 1$ (filled circles) and $T = 2$ (filled squares) sd shell mirror nuclei in comparison to shell model results of Ref. [24] (open circles) and the present work (USD^m) (full line). The dashed lines correspond to a reduced $Z = 14$ gap in the lower sd shell ($A \leqslant 28$, short dashed) and a reduced $N = 14$ gap with a small increase of the corresponding mirror gap in the upper shell ($A \geqslant 28$, long dashed). For details see text.

of the pf protons to the continuum with a large impact on the MED.

The large value of the $A = 36$, $T = 2$ MED, the excellent agreement with the USD^m result, and the robustness against modification suggest a comparison for all experimentally known $T = 1, 2$ MED in the sd shell. This is shown in Fig. 5 by the full line. Qualitative agreement within expected deviations due to neglected Coulomb contributions is found for $A = 18$–28 and especially for $A = 34$–38. The largest deviations are found for $A = 18$ ($T = 1$), 24 ($T = 2$), 30 ($T = 1$) and 32 ($T = 2$) with even a wrong sign in the two latter cases. It is noted that the dedicated calculation of Coulomb shifts in Ref. [24] fails to reproduce the experiment except for $A = 28$ ($T = 2$). Introducing an empirical Coulomb correction to the proton $d_{5/2}$ and $d_{3/2}$, $J = 2, 4$ TBME improves agreement at the beginning and end of shell but does not cure the $A = 24, 30, 32$ discrepancy. This and the inspection of the wave functions for the corresponding mirror pairs suggest that the deviations are of structural origin, as the $Z, N = 14$ gaps are crucial in all critical cases, the $A = 30$, $T = 1$ mirrors additionally depend on the $Z, N = 16$ gaps. An isospin symmetric monopole correction obviously will not influence the MED. Moreover, due to the symmetry of the model space in protons and neutrons, any isospin asymmetric modification (which necessarily changes only the $T = 1$ TBME) that shifts a proton (neutron) SPE in the lower half of the shell will have the same effect in the upper half, however with the difference that the corresponding nuclei lie on different sides of the $N = Z$ line. Therefore, any MED improvement in the upper sd shell ($A = 30, 32$) will inevitably deteriorate the agreement in the lower shell ($A = 18$–24) and vice versa. The midshell mirror pair $A = 28$ however, which exhibits the only $T = 2$ positive MED, will remain virtually unchanged. This value was recently measured [18] and is intriguingly well reproduced in all approaches.

To get better insight in the underlying structure, we have therefore in an empirical approach introduced different ad hoc corrections in the lower sd shell between the $Z = 8$, $N = 8$ and $A = 28$ isobar lines and the upper shell triangle bordered by the $Z = 20$, $N = 20$ and the $A = 28$ lines.

- In the lower mass triangle $A = 16$–28 the proton gap at $N = 8$ and $Z = 14$ (Si) was reduced by 200 keV. In addition, the proton $d_{5/2}^2$ TBME were quenched by 5% to improve the USD^m (and USD) agreement for ^{18}Ne, which introduces another reduction of the proton gap by monopole drift summing up to a total reduction in the full shell calculation of 0.32 MeV relative to its mirror neutron gap at $Z = 8$ (O) and $N = 14$.
- In the higher mass triangle $A = 28$–40 the neutron gap at $Z = 20$ (Ca), $N = 14$ was reduced by 900 keV while the $Z = 14$ (Si), $N = 20$ proton gap was increased by 300 keV to further improve the agreement shown in Fig. 4. The full calculation was done with a final reduction of 0.74 MeV of the ^{34}Ca neutron gap relative to ^{34}Si. Note that the MED are only sensitive to the gap difference.

The results are shown in Fig. 5 by short and long dashed lines for the lower and upper shell, respectively. The excellent agreement proves the sensitivity of the MED to the experimentally unknown proton gap at $Z = 14$, $N = 8$ (^{22}Si) and the neutron gap at $N = 14$, $Z = 20$ (^{34}Ca), making MED useful probes for shell structure in experimentally inaccessible regions. The substantial reduction of the $d_{5/2}$–$s_{1/2}$, $N = 14$ gap in ^{34}Ca is corroborated by the experimental evidence in its isotone ^{32}Ar of a reduced $\nu d_{5/2}$ occupation as seen in neutron knockout reactions [32]. The origin of the reduction must be sought in the approaching dripline and gradual coupling to the continuum. The assumption of a constant ad hoc shift in the upper (lower) sd shell is therefore only a crude approach. The effect of cross-shell excitations from the adjacent $0p$ and $1p0f$ shells would be symmetric in isospin and influences the absolute excitation energies only. The quenching of the $d_{5/2}^2$ interaction in the lower shell, needed to reproduce the MED, can be taken as first evidence for the reduced overlap of the protons involved due to coupling to the continuum. Further experimental evidence would come from a measurement of the $I^\pi = 2^+$ excitation energy in ^{20}Mg, yielding the $A = 20$ MED which is predicted to be negative in the present approach.

In conclusion, the energy for the $I^\pi = 2_1^+$ state of ^{36}Ca, the heaviest $T = 2$ nucleus with an observed γ-decay, was determined to be 3015(16) keV. The extremely large mirror energy difference relative to ^{36}S can be understood with an isospin symmetric USD based interaction using experimental proton and neutron SPE from the $A = 17$, $T = 1/2$ isospin doublet, which account empirically for the one-body part of Thomas–Ehrman and/or Coulomb effects. The results are consistent with a monopole driven shell structure scenario and the expectation that Ca isotopes below $N = 16$ develop another "island of inversion". From the systematics of $T = 1$ and $T = 2$ MED in the sd shell a reduction of the $Z = 14$ gap in the $N = 8$ isotones and the $N = 14$ gap in the $Z = 20$ Ca isotopes relative to their mirror gaps N, $Z = 14$ in $Z = 8$ O isotopes and $N = 20$ isotones is inferred. In view of the considerable reduction of the $Z = 20$ shell gap relative to the $N = 20$ gap in ^{36}Ca and ^{36}S, respectively, the onset of inversion may start at $N = 14$ in ^{34}Ca already.

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