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Is there np pairing in $N=Z$ nuclei?

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The binding energies of even-even and odd-odd $N=Z$ nuclei are compared. After correcting for the symmetry energy we find that the lowest $T=1$ state in odd-odd $N=Z$ nuclei is as bound as the ground state in the neighboring even-even nucleus, thus providing evidence for isovector np pairing. However, $T=0$ states in odd-odd $N=Z$ nuclei are several MeV less bound than the even-even ground states. We associate this difference with the $T=1$ pair gap and conclude from the analysis of binding energy differences and blocking arguments that there is no evidence for an isoscalar (deuteronlike) pair condensate in $N=Z$ nuclei.

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Soon after the interpretation of superconductivity in terms of a condensate of strongly correlated electron pairs (Cooper pairs) by Bardeen, Cooper, and Schrieffer (BCS) [1] a similar pairing mechanism was invoked for the nucleus [2] to explain, for example, the energy gap in even-even nuclei and the magnitudes of moments of inertia. For almost all known nuclei, i.e., those with $N>Z$, the ''superconducting'' state consists of neutron (nn) and/or proton (pp) pairs coupled to angular momentum zero and isospin $T=1$. However, for $N=Z$ nuclei Cooper pairs consisting of a neutron and a proton (np) may also occur due to the near degeneracy of the proton and neutron Fermi surfaces (protons and neutrons occupy the same orbitals). The np pair can couple to angular momentum $J=0$ and isospin $T=1$ (isovector), or, since they are no longer restricted by the Pauli exclusion principle, they can couple to $T=0$ (isoscalar) and angular momentum $J=1$ or $J=J_{\max}$ [3], but most commonly the maximum value [4]. Charge independence of the nuclear force implies that for $N=Z$ nuclei, $T=1$ np pairing should exist on an equal footing with $T=1$ nn and pp pairing. Whether there also exists strongly correlated $T=0$ np pairs, i.e., a deuteronlike pair condensate, has remained an open question. Early theoretical works [5] discussed the competition between $T=0$ and $T=1$ pairing within the BCS framework. Recent works have focused on the solutions of schematic (or algebraic) [6,7] and realistic shell models [8], as well as on the properties of heavier $N=Z$ nuclei [9], and the effects of rotation [10,11].

There are many experimental observables (signatures) supporting the existence of a condensate of nn and pp pairs, but few have been discussed for the case of an np pair condensate. Recently, Vogel [12] (following the work of Janecke [13]) used experimental binding energies (BE) and excitation energies to study the role of $T=1$ pair correlations and the symmetry energy in $N\approx Z$ nuclei and showed that for odd-odd nuclei the two contributions are essentially equal causing the observed near degeneracy of $T=0$ and $T=1$ states in odd-odd $N=Z$ nuclei. In this Rapid Communication we present an independent analysis of experimental binding energies of $N=Z$ nuclei and the relative excitation energies of the lowest $T=0$ and $T=1$ states in self-conjugate ($N=Z$, $T_z=0$) odd-odd nuclei. We use, for the first time, the observed BE differences to exclude the presence of a significant $T=0$ deuteronlike pair condensate in $N=Z$ nuclei, even though the $T=0$ interaction is an important component of the nuclear force. As expected from charge independence and in agreement with Ref. [12] this same analysis provides evidence for the existence of strong $T=1$ np pairing in $N=Z$ nuclei. The relative excitation energies of the lowest $T=0$ and $T=1$ states in odd-odd $N=Z$ nuclei are then understood within a simple model that includes full $T=1$ pairing and a symmetry energy term.

Let us start by recalling that pairing effects can be isolated by studying differences in binding energies [14]. Particularly, the difference

$$BE_{\text{even-even}}-BE_{\text{odd-odd}}\approx\Delta_p+\Delta_n\approx 2\Delta \tag{1}$$

is used as a measure of the pair gap, Δ, for both protons and neutrons.[1] Implicit in Eq. (1) is the assumption that the ground states have the same isospin, which is the case for nuclei with $N\neq Z$ since they are *maximally aligned* in isospace, i.e., $T=T_z=\frac{1}{2}(N-Z)$ [14]. Equation (1) is also true when comparing $T=0$ states in even-even and odd-odd $N=Z$ nuclei.

The difference in binding energy between $T=0$ states, given by

$$BE_{ee}(N,Z)-\frac{(BE_{oo}(N-1,Z-1)+BE_{oo}(N+1,Z+1))}{2}, \tag{2}$$

is shown in Fig. 1, where the binding energies are from Ref. [15]. Taking the average in Eq. (2) removes the smooth variations due to volume, surface, and Coulomb energies, and any remaining differences can then be attributed to shell and/or pairing effects. The extra binding of the even-even nuclei is clearly seen in Fig. 1 and it follows remarkably well the known $1/A^{1/2}$ dependence [14] for the $T=1$ pair gap. It would then appear natural to associate the observed BE dif-

[1]There is usually a correction term due to the residual np interaction. This term is of order $20/A$ MeV and we will not consider it here.

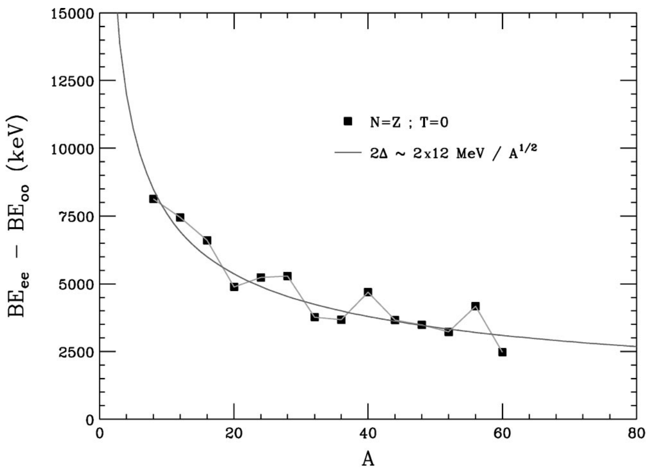

FIG. 1. The difference in binding energy between even-even and odd-odd nuclei. Squares correspond to $T=0$ states in $N=Z$ nuclei ($T=0$ is the ground state for $N=Z$ even-even nuclei and for $N=Z$ odd-odd nuclei with $A<40$). This difference is interpreted as a measure of the $T=1$ pair gap, Δ. The solid line shows the conventionally adopted smooth dependence of Δ on A ($\Delta \sim 12/A^{1/2}$ MeV).

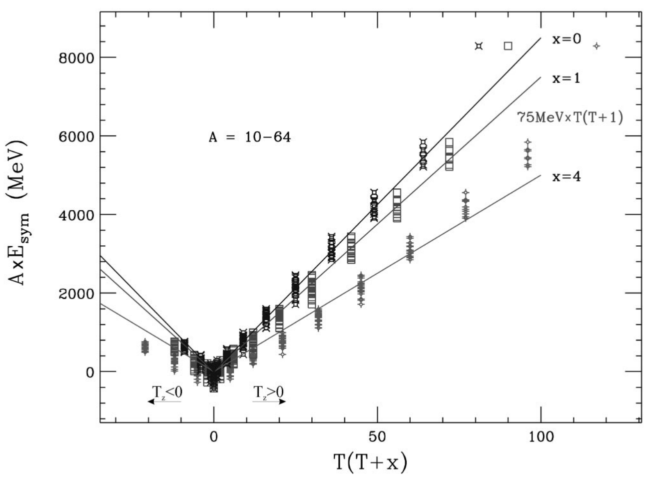

FIG. 2. The symmetry energy, $E_{\rm sym}=-BE_{\rm sym}=E_{\rm exp}-E_{\rm vol}-E_{\rm surface}-E_{\rm Coulomb}$, for nuclei in the range $A=10-64$ as a function of $T(T+x)$, as discussed in the text; where, $E_{\rm vol}=-15A$ MeV, $E_{\rm surface}=17A^{2/3}$ MeV, and $E_{\rm Coulomb}=0.7(Z^2/A^{1/3})$ MeV. Lines are to guide the eye.

ferences between the lowest $T=0$ states in $N=Z$ nuclei with the full $T=1$ pair gap, and therefore Fig. 1 suggests that $T=0$ pairs do not contribute significantly to the pair correlation energy in $N=Z$ nuclei. The $T=0$ states in odd-odd $N=Z$ nuclei then behave like those in any other odd-odd nucleus where the extra *n* and *p* block the $T=1$ pairing to the same degree as any ''standard'' two-quasiparticle state. Note, if the ground states of $N=Z$ even-even nuclei contained an appreciable contribution from $T=0$ correlated pairs (i.e., there was a deuteronlike condensate) then the addition of a $T=0$ np pair would not give rise to a gap with a magnitude comparable to that of the full ($2\times12/A^{1/2}$ MeV) $T=1$ pair gap, on the contrary, the gap for the $T=0$ states would have to be smaller. Indeed, for the situation where the ground state of an $N=Z$ nucleus is a condensate of deuteronlike pairs the average binding energy of the two odd-odd $N=Z$ neighbors is similar to that of the even-even nucleus and the observed gap, Eq. (2), would be very close to zero since the pairing energy is proportional to the number of deuteronlike pairs.

Is it possible that only $T=1$ pairing is important for these $N=Z$ nuclei? If np $T=1$ pairs form a correlated state, the lowest $T=1$ state in self-conjugate odd-odd nuclei should be as bound as that of the neighboring even-even ground state and thus the BE difference is ~ 0. However, in applying Eqs. (1) or (2) to determine the binding energy difference for $T=1$ states we need to include a symmetry energy term because of the different isospins (i.e., $T=1$ in odd-odd $N=Z$ nuclei and $T=0$ for the ground state of even-even $N=Z$ nuclei). A detailed discussion on the symmetry term is given in Refs. [14,16]. Here, we extract the symmetry energy ($E_{\rm sym}=-BE_{\rm sym}$) by plotting the experimental binding energies of several nuclei in the range $A=10-64$, as shown in Fig. 2, after subtracting volume, surface, and Coulomb terms. They are plotted as a function of $T(T+x)$, for three cases: (1) $x=4$, corresponding to the SU(4) Wigner supermultiplet expression [17], (2) $x=1$, i.e., $T(T+1)$, and (3) $x=0$, giving a T^2 approximation. While any of these choices can be used, the $T(T+1)$ expression provides a better account of the experimental data, as discussed in Refs. [12,13]. In our analysis we use a symmetry energy given by $E_{\rm sym}=(75/A)T(T+1)$ MeV which represents an average neglecting the effects of shell structure and pairing.

The binding energy difference between the lowest $T=1$ state in odd-odd $N=Z$ nuclei and the $T=0$ ground state in neighboring even-even $N=Z$ nuclei is presented in Fig. 3 (squares). If the only difference between the even-even ground state and the odd-odd $T=1$ state were the symmetry term, then the difference in binding energy is given by the upper solid line. That is, the symmetry energy of the $T=1$ state $(75/A)T(T+1)=150/A$ MeV subtracted from the binding energy of the even-even nucleus provides the correct reference to which the odd-odd $T=1$ states should be compared.

In addition, it is also possible to use the even-even $T=1$ ($T_z=-1,1$) isobaric analog states as a ''local'' reference, rather than the global expression $(75/A)T(T+1)$ MeV. After correcting for the Coulomb energy, the binding energies of the isospin triplet are very similar, often within a few hundred keV. The average binding energies of the even-even $T=1$ ($T_z=-1,1$) isobaric analog states, relative to the even-even $T=0$ ground state, are also shown in Fig. 3 (dotted line). These values are extremely close to those of the corresponding $T=1$, $T_z=0$ state in the odd-odd nucleus. Since (i) the binding energy difference between the $T=1$, $T_z=0$, (odd-odd) and $T=0$, $T_z=0$ (even-even) states is described by the symmetry energy term only, and (ii) the $T=1$ ($T_z=-1,1$) states are the ground states of the even-even isobaric analogs, then the binding energy difference $(BE_{ee}(T=0)-BE_{oo}(T=1))$ cannot be associated with a difference in

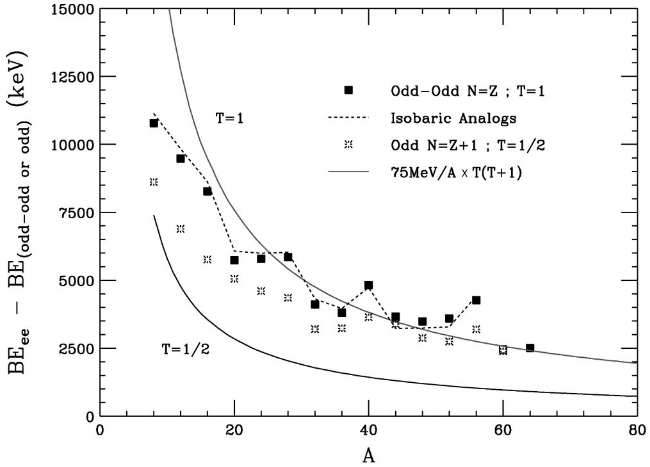

FIG. 3. The difference in binding energy between even-even and odd-odd $N=Z$ nuclei. The $T=1$ states in odd-odd $N=Z$ nuclei (squares) are compared with the $T=0$ ground states in neighboring even-even nuclei. The upper solid line represents the energy difference due to the difference in isospins ($T=1$ and $T=0$). The dotted line was obtained from an average energy of $T=1$ isobaric analog states (see text). The isospin correction term is seen to account for the observed binding energy difference. The difference in binding energy is also shown for odd nuclei, $N=Z+1$ (stars), compared with the even-even neighbor and the corresponding symmetry energy is given by the lower solid curve.

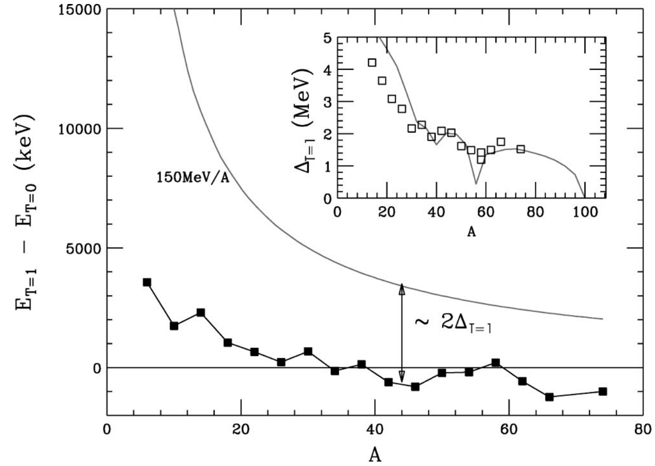

FIG. 4. The difference in level energies between $T=1$ and $T=0$ states in odd-odd $N=Z$ nuclei. For $A<40$ these nuclei have $T=0$ ground states, except ^{34}Cl, above this mass they have $T=1$ ground states, except ^{58}Cu. The solid line represents the isospin correction term $\Delta E_{\rm sym}=150/A$ MeV and corresponds to the expected energy difference between $T=1$ and $T=0$ states if the only difference between these states were due to the isospin correction. Inset: Squares denote the effective $\Delta_{T=1}$ gap derived from the relative excitation energies of the $T=0$ and $T=1$ states in odd-odd $N=Z$ nuclei after correcting for the isospin difference as illustrated in the main figure. The solid line shows the result of a simple BCS calculation (see text for details).

pairing. Rather, it is due to the difference in isospin for which the smooth overall behavior is given by the symmetry energy.

These results (Fig. 3) indicate that the lowest $T=1$ state in a self conjugate odd-odd nucleus is as bound as the neighboring even-even $N=Z$ ground state (after correcting for the symmetry energy). In other words, there is no difference in pairing, and just as the addition of an nn or pp pair to an even-even nucleus does not block pair correlations, neither does the addition of an np $T=1$ pair in $N=Z$ nuclei. However, as expected, adding a single n or p to the even-even core does reduce the pair energy and results in a binding energy difference in excess of the symmetry energy, as seen by the fact that the data points (stars in Fig. 3) for an odd nucleus ($N=Z+1$) lie higher than the symmetry energy expected for a $T=1/2$ nucleus (lower solid curve in Fig. 3). In view of the charge independence of the nuclear force these results are not too surprising, indeed isobaric analogues were used by Janecke [13] to extract the pairing term in a semi-empirical mass formula. Nevertheless, it is important to discuss the $T=1$ states within the framework of this analysis since it enables a consistent picture to be developed which favors the existence of full (i.e., nn, pp, and np) isovector pairing correlations in $N=Z$ nuclei with little if any room for a condensate of deuteronlike pairs.

We now consider the relative energies of the $T=0$ and $T=1$ states in odd-odd $N=Z$ nuclei (for a similar discussion see also Ref. [12]). If there were no np pairing of any type ($T=0$ or $T=1$) the $T=1$ state should lie above the $T=0$ state at an excitation energy given by the symmetry term. However, the analysis of the experimental data presented above shows strong evidence for the existence of $T=1$ np pair correlations, and at the same time no evidence for $T=0$ correlated pairs. The $T=1$ states should then lie at a lower energy than that given by the symmetry term, and if the $T=1$ pairing energy were sufficiently large, the $T=1$ state may lie lower than the $T=0$ state. The experimental energy differences are shown in Fig. 4 along with the expected contribution from the symmetry energy. The energy separation between the states of different isospin is clearly less than that predicted by the symmetry term. This is consistent with the pairing arguments presented above, and suggests that whether the $T=0$ or $T=1$ state is lower depends largely on the relative magnitudes of the symmetry and pairing energies. We further note that while the near cancellation of the symmetry and pairing terms (for $T=1$ compared with $T=0$) appears to be accidental we cannot rule out, at this time, a deeper physical origin.

Assuming the reduced separation is only due to the effects of pairing then, in the language of the BCS model and taking the symmetry term into account, the $T=0$ state in the odd-odd $N=Z$ nucleus can be interpreted as a two-quasiparticle excitation (''broken-pair'' with seniority 2) relative to the $T=1$ correlated pair state ($J=0$, seniority 0). In complete analogy with Eq. (1) we have

$$(BE_{T=1}-BE_{\rm sym})-BE_{T=0}\approx 2\Delta_{T=1}, \tag{3}$$

or,

$$E_{\rm sym}-(E_{T=1}-E_{T=0})\approx 2\Delta_{T=1}, \tag{4}$$

in terms of the difference between the excitation energies of the lowest $T=1$ and $T=0$ state in the same $N=Z$ odd-odd nucleus. It is important to realize that the situation is different in an even-even $N=Z$ nucleus. In this case the $T=0$ ground state has $J=0$, seniority 0, while the $T=1$ state has seniority 2 since it is the isobaric analogue of the ground states in the neighboring odd-odd ($T_z=\pm 1$) nuclei. Therefore, the energy difference ($E_{T=1}-E_{T=0}$) is now the sum and not the difference of the symmetry energy (150/A MeV) and the $T=1$ pairing gap ($24/A^{1/2}$ MeV).

The effective gap ($\Delta_{T=1}$) extracted using Eq. (4) is presented in the inset to Fig. 4, together with the result of a BCS calculation that includes nn, pp, and np $T=1$ pairs. For the BCS calculation we adopted standard single-particle levels from a spherical Nilsson potential and a pairing strength of 20/A MeV. This figure illustrates that the magnitude of $2\Delta_{T=1}$ extracted from experiment using Eq. (4) compares favorably with that obtained from a BCS calculation using a realistic spectrum of single-particle levels. While the gap (difference in binding energy) is not necessarily related only to a pairing interaction [18], the agreement is remarkable. Due to the presence of shell gaps the simple BCS model gives a characteristic oscillation in Δ. In this calculation, the single-particle levels were truncated at $N=Z=50$, which led to an artificial quenching of Δ at $A=100$. The reversal of the favored isospin from $T=1$ to $T=0$ at ^{58}Cu coincides with it being one np pair above the $N=Z=28$ shell closure and, within the pairing interpretation given here, this reversal occurs because the shell gap reduces the magnitude of the $T=1$ pair gap. For heavier nuclei, $A>60$, the $T=1$ state is favored and we would expect that this is likely to remain the case until the $N=Z=50$ shell gap is reached, where for ^{98}In ($N=Z=49$) the ground state may well revert to $T=0$ once more. The competition between pairing and symmetry energy was also discussed in Ref. [4]. In this work, semiempirical fits to the binding energies suggested that for odd-odd $N=Z$ nuclei beyond the $1f_{7/2}$ shell, pairing correlations will result in $T=1$ ground states.

In summary, we have argued that binding energy differences indicate that the lowest $T=1$ states in odd-odd $N=Z$ nuclei are as bound as their even-even neighbors, which provides strong evidence for the presence of isovector np pairing. We have then shown by simple arguments, and for the first time, that there is no similar evidence to support the existence of np isoscalar (deuteronlike) pair correlations even though the $T=0$ channel is an important part of the nuclear force. The fact that the nucleus does not appear to favor the formation of a $T=0$ condensate may be related to the destructive influence of the spin-orbit interaction and the reduced number of $J>0$ pairs compared with $J=0$. Finally, we considered the relative excitation energies of the lowest $T=0$ to $T=1$ states in odd-odd $N=Z$ nuclei and, as also discussed by Vogel [12], concluded that the intriguing switch from $T=0$ to $T=1$ ground states in odd-odd $N=Z$ nuclei arises from a competition between the symmetry energy and full isovector pairing correlations (without the need to include an isoscalar pair condensate). For $A>40$, $T=1$ pairing wins over the symmetry energy and the $J=0^+$ state becomes the ground state except, possibly, near closed shells where the static pairing correlations are expected to be reduced.

Future experiments on heavier $N=Z$ nuclei to determine the binding energies and the relative excitation energies of $T=1$ and $T=0$ states (in odd-odd nuclei), as well as studies of their high-spin rotational properties, are clearly important to provide further information on the role of pairing correlations in $N=Z$ nuclei.

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