EMPIRICAL STUDY OF THE SUBSHELL CLOSURE AT N=40

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Perhaps the most exciting phenomenon identified to date in the neutron-rich Ni isotopes is the indication for a subshell closure at N=40 in ^{68}Ni (Z=28). This was suggested from early transfer studies [1] and reinforced by the observation [2] of a high excitation energy of the first 2^+ state and a pronounced similarity with the excitation spectrum of ^{90}Zr. However, recent spectroscopic data on some Zn [3] and Fe [4] isotopes with neutron number around N=40, point toward a development of collectivity, possibly involving deformation, and thus do not support the existence of a strong subshell closure at N=40.

The presence of a shell gap in the single-particle spectrum gives rise to "discontinuities" in several properties for the nucleus with the closed shell, as compared to the neighboring nuclei. We have examined several possible indications for a subshell gap in the case of ^{68}Ni using the existing information on energy levels and masses.

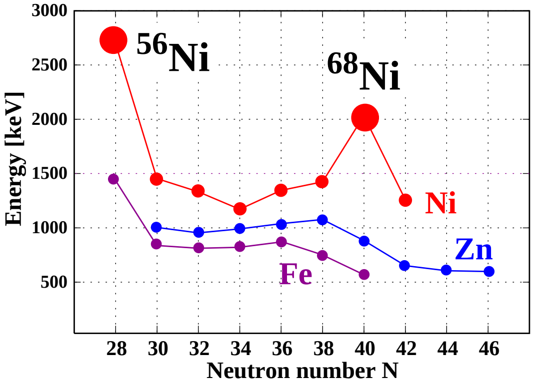

Figure 1: Systematic behavior of the excitation energy of the first 2^+ state in the even Ni (Z=28), Zn (Z=30) and Fe (Z=26) isotopes. The neutron shell- and subshell-closures at N=28 and N=40 are indicated. The data are taken from Refs. [4-6]

The excitation energy of the first excited 2^+ state $E(2_1^+)$ in the Ni isotopes rises by more than 500 keV between ^{66}Ni and ^{68}Ni [2]. This is a strong indication of an N=40 subshell closure, and also the most pronounced empirical evidence in its favor. The information has been completed with the recent observation [5] of an excitation energy $E(2_1^+)$ in ^{70}Ni very similar to that of ^{66}Ni. The relevant data are summarized in Fig. 1. As mentioned, the behavior of the $E(2_1^+)$ values in the even Zn (Z=30) and Fe (Z=26) isotopes, shown for comparison in Fig. 1, is intriguing. A clear difference in $E(2_1^+)$ can be observed for N=40, as compared to N=38, but this time the energy is lower than the one of the preceding nucleus. Nevertheless, the first excited 2^+ state in the "two-proton particle" Zn or "two-proton hole" Fe isotopes is expected to be of predominant proton nature. The effect of, for example, changes in the proton single-particle energies on the excitation of the 2_1^+ state cannot be easily disentangled from the effect of the neutron subshell closure on the same state.

A pronounced drop in the two-neutron separation energies S_{2n} is expected immediately after a neutron shell closure. The effect of a *subshell* closure on the S_{2n} values is less pronounced, and mainly gives rise to a change of the slope of the separation energies. A more sensitive quantity is the derivative of S_{2n} as a function of mass. The behavior of the derivative is reflected by the differential quantity $S_{2n}(A)$-$S_{2n}(A+2)$.

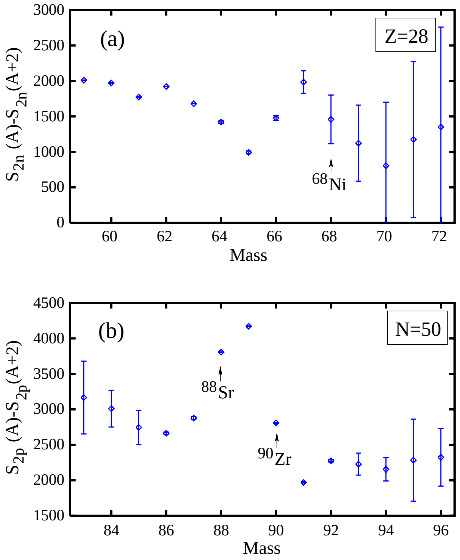

Figure 2: (a) Differential two-neutron separation energies in the Ni isotopes, S_{2n}(A)-S_{2n}(A+2). (b) Similar for the two-proton separation energies in the N=50 isotones. The data are taken from the evaluation of Ref. [7].

The differential two-neutron separation energies of the Ni isotopes are shown in Fig. 2(a). For comparison, the similar quantity calculated from the two-proton separation energies is shown in Fig. 2(b) for the N=50 isotones, which cross the Z=40 subshell closure in ^{90}Zr. The two-neutron and two-proton separation energies are taken from the evaluation of Ref. [7]. Similar effects can be noticed at the crossing of N=40 in the Ni isotopes, as at the crossing of Z=40 in the N=50 isotones. The magnitude of the effect is larger in the N=50 isotones, but this might be due to a somewhat different single-particle spectrum, giving rise to an additional gap between the pair of orbitals $2p_{3/2}$, $1f_{5/2}$ and the orbital $2p_{1/2}$, as well as additional binding of ^{88}Sr. The errors on the adopted separation energies become very large just in the region of interest for ^{68}Ni. Additional effort for precise mass measurements may provide a clear signature for subshell effects at N=40.

Another quantity which can show discontinuities at the crossing of a shell closure is the pairing gap Δ. A good estimate for the neutron pairing gap from the experimental neutron separation energies is [8]:

$$\Delta_n = -1/4\left\{S_n(N-1,Z) - 2S_n(N,Z) - S_n(N+1,Z)\right\},$$

for even N values, or the same quantity with opposite sign for odd N values. The neutron pairing gap in the Ni isotopes, extracted from the adopted S_n values [7], is shown in Fig. 3. A minimum value for the experimental gap is found for ^{68}Ni. The "V-shaped" behavior and the reduced value of the pairing gap for ^{68}Ni indicates the presence of a gap in the single-particle spectrum. Unfortunately, due to the large experimental errors on the separation energies, the errors in Δ_n become large precisely in the interesting region (after ^{68}Ni). In order to investigate in more detail the information which can be extracted from the experimental pairing gaps, we have calculated this quantity in a standard BCS approach with a constant pairing force. The neutron single-particle energies from ^{57}Ni were used as a starting point for the Ni isotopes with N>28. The pairing strength was adjusted to reproduce the experimental pairing gap in ^{59}Ni. For the isotopes with N<28, the orbital $1f_{7/2}$ was added, and the pairing strength was determined from the experimental pairing gap in ^{54}Ni. Some variation of the single-particle energies was allowed for the

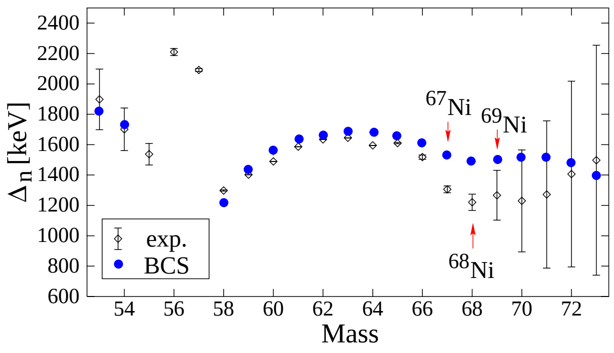

Figure 3: Experimental neutron pairing gap in the Ni isotopes (open diamonds), calculated with the method given in Ref. [8]. The pairing gap obtained in a standard BCS approach is plotted as filled circles. The nuclear masses are taken from the evaluation of Ref. [7].

heavier isotopes (N>28), and determined from a best qualitative description of the experimental data. We point out the fact that the "V-shape" is qualitatively reproduced by the simple BCS approach and is due to the existence of a gap in the single-particle spectrum (around 3 MeV in this calculation). However, the low value of Δ_n in ^{68}Ni cannot be quantitatively reproduced in the BCS approach, when the single-particle energies and pairing strength from the lighter isotopes are extrapolated to N=40. The discrepancy is visible in Fig. 3, despite the large experimental errors.

Information from both one-neutron stripping and pick-up is available for ^{59,61,63}Ni, and from one-neutron stripping for ^{65}Ni [6]. From comparison of the spectroscopic factors for the same state obtained in stripping and in pick-up, the occupation probability for a given single-particle orbital can be determined. The distribution of neutron particles in the major shell N=28--50 points toward a substantial subshell gap at N=40. The occupancy of the $1g_{9/2}$ orbital, extracted from experiment, is consistent with zero.

In conclusion, the behavior of the excitation energy E(2_1^+), differential neutron separation energies, and pairing gap in the Ni isotopes, are consistent with a good subshell closure at N=40. Furthermore, no major differences were observed in the behavior of the two-neutron separation energies at N=40 compared to that of the two-proton separation energies at Z=40. The study points toward similar subshell gaps at both neutron and proton numbers equal to 40.

References

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