O Isotopes: Drip line within Relativistic Mean Field plus BCS Approach

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Experimental and theoretical studies of exotic nuclei with extreme isospin values present one of the most active areas of research in nuclear physics. Experiments with radioactive nuclear beams provide the opportunity to study very short-lived nuclei with very large neutron to proton ratios N/Z. Recent experiments with radioactive nuclear beams (RNB) have provided the facilities to study drip line nuclei and the nuclei beyond the drip line [1]. More recently, heaviest bound isotope of O, ^{24}O, has been observed experimentally and established as a doubly magic drip line nucleus [2, 3]. In the present investigations we have employed relativistic mean-field plus BCS (RMF + BCS) approach [4, 5] to study drip line characteristic of O isotopes.

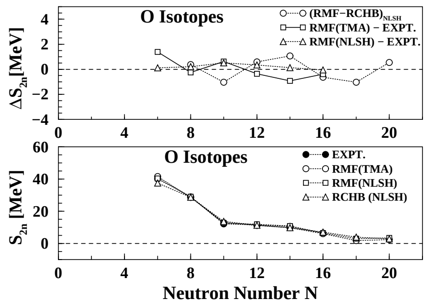

FIG. 1: Lower panel: RMF results for S_{2n} for the $^{12-28}$O isotopes obtained with the TMA (open circles) and the NL-SH (open squares) are compared with RCHB calculations of Ref. 7 carried out with the NL-SH force (open triangles). Available experimental data[7] (solid circles) are also shown for the purpose of comparison. Upper panel: Difference in the RMF+BCS results, RCHB results and available experimental data[7]

In the lower panel of Fig. 1 we have shown the two neutron separation energy S_{2n} for the O isotopes calculated by RMF+BCS calculations employing the TMA and the NL-SH forces. Results have also been shown along with those obtained in the RCHB [6] approach for the purpose of comparison. It is seen from the figure that the calculations using two different force parameters, the TMA and the NL-SH Lagrangian, yield almost similar results. Also, it is observed that the results for the NL-SH force using the RCHB approach and the present RMF+BCS calculations are quite close to each other. The upper panel depicts the difference between the results obtained using the RMF+BCS and the RCHB approaches. The difference is indeed small, a maximum difference is seen for ^{18}O and it is less than 1 MeV. It is further seen that the calculated results for S_{2n} are in good agreement with the experimental data. The upper panel depicts the difference between the experimental and calculated values. The maximum difference is about 1.5 MeV. The calculated two neutron drip line is found to occur at $N = 20$ in both the RMF+BCS and the RCHB calculations. However, in contrast it is experimentally [8] observed to occur at $N = 16$. The discrepancy between the theoretical prediction and the experimental data is found almost in all the mean field calculations employing both relativistic as well as non-relativistic approaches. A better insight into the position of the neutron drip line can be gained by looking at the dependence of the neutron single particle states around the Fermi level as a function of increasing neutron number N. This has been shown in fig. 2 for the bound neutron $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ states, as well as for the unoccupied $2p_{3/2}$, $2p_{1/2}$ and $1f_{7/2}$ states lying in the continuum. It is seen

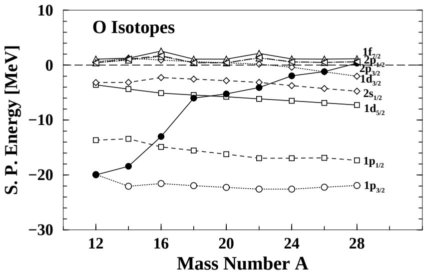

FIG. 2: Variation of the neutron single particle energies for the O isotopes.

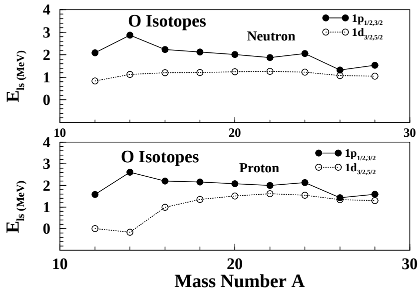

FIG. 3: Variation of the spin-orbit splitting energy E_{ls} for the neutron (upper panel) and proton (lower panel) doublets $(1p_{1/2}, 1p_{3/2})$ and $(1d_{3/2}, 1d_{5/2})$ in the O isotopes.

from fig. 2 that with increasing neutron number N, the bound states near the Fermi level, for example, $1d_{3/2}$ and $2s_{1/2}$ etc. have a tendency to come down in energy. For $N \leq 14$ the crucial $1d_{3/2}$ state remains unbound and lies close to other unbound states $2p_{3/2}$, $2p_{1/2}$, and $1f_{7/2}$, while the neutron Fermi energy increases with increasing neutron number N. Around $N = 16$, the $1d_{3/2}$ state comes down to become bound, whereas the other neighboring states $2p_{3/2}$, $2p_{1/2}$, $1f_{7/2}$ and $1g_{9/2}$ continue to remain unbound. With further addition of two neutrons, at $N = 18$, the $1d_{3/2}$ state becomes even more bound while the neutron Fermi energy approaches to zero. For $N = 20$, the Fermi energy becomes positive and the $1d_{3/2}$ state is fully occupied. This results in a stable ^{28}O isotope, the heaviest one. Beyond this the neutron Fermi energy becomes positive and any further addition of neutrons makes the isotope unstable. Thus the essential point for the position of the neutron drip line is that beyond $A = 24$, the $1d_{3/2}$orbital is slightly too bound and that the continuum states $2p_{3/2}$, $2p_{1/2}$, $1f_{7/2}$ and $1g_{9/2}$, though close to zero energy, remain entirely unoccupied. As shown in fig. 3, a study of N dependence of the spin-orbit splitting energy $E_{ls} = (E_{nlj=l-1/2} - E_{nlj=l+1/2})/(2l+1)$ of the spin-orbit doublet $1d_{3/2}$ and $1d_{5/2}$ indicates that the neutron doublet splitting energy is slightly reduced beyond $A = 24$ and, therefore, the $1d_{3/2}$ orbital is pushed down and accommodates further addition of 4 neutrons. From the above discussion it appears that for the neutron rich O, the pairing interaction beyond $A = 24$ is not strong enough to populate the positive energy states near the Fermi level, for example, $2p_{3/2}$, $2p_{1/2}$ and $1f_{7/2}$ etc., to make the isotopes heavier than $A = 24$ unstable. This discrepancy between the theoretical results and the measurements for the two neutron drip line in the O isotopes is found in most of the mean field calculations and needs further investigations.

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