Study of Pairing Correlations in Neutron-rich Nuclei

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Introduction

There has been large effort for investigating nuclear ground and excited state properties in terms of the self-consistent mean-field approximation. This description of the atomic nucleus can account for the bulk properties such as masses, radii or shape of nuclei. An approximation of closed shell magic nuclei can be provided by the Hartree-Fock method. For the description of open shell nuclei the pairing correlations forms an essential ingredient. The semi-empirical mass formula displays pairing correlations of nucleons through binding energy differences for even-even, odd-even, and odd-odd nuclei.The pairing effects are usually described by the Hartree-Fock plus BCS (HFBCS) or Hartree-Fock- Bogoliubov (HFB) methods [1].

The odd-even staggering (OES) of nuclear binding energy implies that the masses of odd nuclei are larger than the two nearby even nuclei. A systematic odd-even staggering in nuclear binding energy has already been identified in nuclear physics. This is associated with the phenomenon of pairing correlation. It plays an important role in many-body nuclear mean field theory. In case of neutron-rich nuclei, the study of OES effects induced by pairing reveals various exotic phenomena[2]. In the present study we have made an attempt to investigate the influence of pairing interactions in neutron-rich isotopes Ta, W, Re, Os and Pt.

Theory

For nuclei with N > Z, the pair correlated state consists of neutron (nn) and/or proton (pp) pairs coupled to angular momentum J = 0 and isospin T = 1. For nuclei with N ≈ Z, the protons and neutrons near the Fermi surface occupy identical orbitals, which allows pairs consisting of a neutron and a proton (np). The np pairs can couple to angular momentum J = 0 and isospin T = 1 (isovector) or they can couple to J = 1 and T = 0 (isoscalar)[2]. Pairing energies in even-even, even-odd and odd-odd neutron-rich nuclei are studied within the Skyrme-Hartree-Fock-Bogoliubov approach, with the density-dependent pairing interaction. The Skyrme HFB equations are solved by assuming axial and reflection symmetry. These symmetries make the HFB matrix block-diagonal. This makes HFBTHO an ideal tool [3] for large-scale calculations in cases where axial and reflection symmetries are sensible assumptions.

The theoretical calculations are difficult for odd mass nuclei since their presence breaks the time reversal symmetry. An approximation to the exact blocking called Equal Filling Approximation (EFA) can be used in this case. The unpaired nucleon is assumed to occupy half in a given orbital and half in its time reversal partner in EFA, by preserving the time reversal symmetry. Here we use the Hartree-Fock-Bogoliubov(HFB) theory of nuclei in the co-ordinate representation and solve the HFB equation for the Skyrme effective interaction[4]. The HFB method is employed to include the description of short-range pairing correlations.

The HFB equation is given by

$$\begin{pmatrix} (h-\lambda) & \Delta \\ -\Delta^* & -(h-\lambda)^* \end{pmatrix} \begin{pmatrix} U_n \\ V_n \end{pmatrix} = E_n \begin{pmatrix} U_n \\ V_n \end{pmatrix} \quad (1)$$

The solution of the HFB equation is obtained in a given complete set of basis wave functions that conserve axial symmetry and

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parity for the two basis sets of wave functions - cylindrically symmetric deformed harmonic oscillator (HO) and transformed harmonic oscillator (THO). This method provides a choice for nuclear structure calculations in weakly bound systems. The program uses axial Transformed Harmonic Oscillator single-particle basis to expand the quasiparticle wave functions[3]. It iteratively diagonalizes the Hartree-Fock- Bogoliubov Hamiltonian based on the Skyrme forces and zero-range pairing interaction until the self-consistent solution is achieved.

Calculations were performed with the same basis and integration characteristics. The pairing channel was parameterized by a density-dependent delta-pairing force with mixed volume and surface features, of the general type equation

$$V_{pair}^{(n,p)}(\mathbf{r}) = V_0^{(n,p)}\left(1 - \frac{1}{2}\frac{\rho_0(\mathbf{r})}{\rho_c}\right)\delta(\mathbf{r\text{-}r'}) \quad (2)$$

where $V_0^{(n,p)}$ is the pairing strength for neutrons and protons, $\rho_0(\mathbf{r})$ is the isoscalar local density and ρ_c is the saturation density. η takes the value 1, 0 and 1/2 for surface, volume and mixed pairing, respectively.

Results and Discussion

From the given results we can see that the pairing gap (Δ) and the quadrupole deformation (β) of varius nuclear isotopes decreases with increasing neutron number. There appears an increase in total energy with neutron number. We can also notice that the neutron pairing gap of all nuclei are greater than the proton pairing gap. Here we have compared quadrupole deformation, total energy, neutron and proton Fermi energy, neutron and proton pairing gap of stable nuclear isotopes with those of neutron rich isotopes. From these we can infer that the change in pairing energy of different nuclear isotopes can have significant influence on the Fermi energy, total energy and quadrupole deformation.

Table 1: Results of mean field calculations

Nuclei	β	E_{total}	$E_{F(n)}$	$E_{F(p)}$	Δ_n	Δ_p
^{180}Ta	0.154	-1424.296	-7.169	-7.256	1.145	0.542
^{181}Ta	0.153	-1434.795	-6.951	-7.577	1.125	0.536
^{187}Ta	0.144	-1470.743	-6.261	-8.815	0.962	0.401
^{188}Ta	0.143	-1470.505	-6.054	-9.072	0.922	0.401
^{180}W	0.155	-1438.669	-7.486	-6.348	1.127	0.390
^{182}W	0.152	-1453.125	-7.244	-6.884	1.104	0.388
^{183}W	0.150	-1456.565	-7.237	-7.100	1.102	0.395
^{184}W	0.149	-1467.112	-7.001	-7.412	1.068	0.385
^{186}W	0.146	-1480.611	-6.750	-7.931	1.016	0.382
^{187}W	0.145	-1481.065	-6.618	-8.175	0.974	0.381
^{188}W	0.143	-1493.588	-6.483	-8.440	0.952	0.377
^{189}W	0.142	-1493.502	-6.266	-8.694	0.909	0.375
^{190}W	0.141	-1506.025	-6.194	-8.936	0.886	0.370
^{185}Re	0.148	-1463.211	-7.233	-7.185	1.078	0.396
^{187}Re	0.145	-1473.497	-7.040	-7.213	1.002	0.256
^{191}Re	0.139	-1500.056	-6.463	-8.211	0.865	0.232
^{192}Re	0.138	-1499.878	-6.243	-8.424	0.833	0.208
^{184}Os	0.149	-1465.540	-7.778	-5.734	1.090	0.215
^{187}Os	0.145	-1484.436	-7.522	-6.495	1.050	0.249
^{188}Os	0.144	-1495.129	-7.269	-6.771	0.993	0.170
^{189}Os	0.143	-1498.979	-7.274	-7.004	0.995	0.232
^{190}Os	0.141	-1509.150	-6.990	-7.277	0.924	0.145
^{193}Os	0.137	-1522.582	-6.448	-7.992	0.816	0.047
^{194}Os	0.136	-1535.411	-6.352	-8.250	0.787	0.123
^{195}Os	0.135	-1534.759	-6.063	-8.477	0.713	0.047
^{196}Os	0.134	-1547.550	-6.002	-8.705	0.729	0.139
^{194}Pt	0.137	-1536.399	-7.171	-6.444	0.846	0.285
^{199}Pt	0.130	-1562.458	-6.167	-7.624	0.661	0.281
^{200}Pt	0.130	-1575.648	-6.107	-7.873	0.683	0.281
^{201}Pt	0.128	-1574.212	-5.800	-8.104	0.627	0.283
^{202}Pt	0.127	-1587.293	-5.760	-8.351	0.655	0.284

References

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