^{147}Tb and proton single particle states near $Z = 64$

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Proton single particle level spacings near $Z = 64$ are deduced from an analysis of low-lying levels in ^{145}Eu, using a pairing force as the residual interaction. Two forms for the pairing force are explored. Using this spectrum, high spin states in ^{144}Sm, ^{146}Gd, and ^{148}Dy are calculated and compared with known experimental values when possible. The low-lying states in ^{143}Pm and ^{147}Tb are also calculated. The need for experimental data on ^{147}Tb is emphasized.

[NUCLEAR STRUCTURE $Z \approx 64$, proton single particle states, pairing force, high spin states.]

The observation[1] that the first excited state of ^{146}Gd is $I^\pi = 3^-$, rather than the nearly universal 2^+, suggests that there are large gaps in the single particle spectra; for both protons at $Z = 64$ and neutrons at $N = 82$. A gap of ~4 MeV is expected for $N = 82$. However, the gap at $Z = 64$ is expected to be considerably smaller, ~2 MeV. This proton gap is defined by the energies of the $d_{5/2}$ and $h_{11/2}$ single particle orbitals. The lowest energy state in ^{146}Gd with $I^\pi = 8^-$ is found at 3.18 MeV. In the absence of residual interactions, this excitation energy would be identical with the $d_{5/2}$-$h_{11/2}$ spacing. As noted by Blomqvist,[2] the difference between 3.18 and ~2 MeV attests to the important role of residual interactions in ^{146}Gd and the neighboring nuclides.

In this communication, we address the question of how well the proton excitations near $Z = 64$ can be understood with one choice of single particle energy levels, assuming a pairing force as the residual interaction. To this end we have analyzed both odd mass and even mass nuclides in this region. We compare the proton level spacings extracted from this analysis of experimental data with proton single particle spectra obtained with a Woods-Saxon single particle potential, in order to get some idea of the reasonableness of these spacings. We present Woods-Saxon levels for two different choices of the spin-orbit radius $R_{s.o.}$, namely, $R_{s.o.} = R_0$ and $R_{s.o.} = 0.75\,R_0$. The latter choice is motivated by the fact that this value provides an optimum description for proton single particle level spacings in the Pb and actinide regions.

We compare the proton pairing interaction constant extracted from our analysis with values obtained from similar analyses of the rare earths and actinides. As well as considering a constant pairing force, we use a state dependent pairing force with larger pairing matrix elements for the high spin states, to get some idea of the effects of the choice of pairing interaction on our analysis.

Specifically, we report a calculation of proton spectra for nuclides with $Z = 61$ through $Z = 66$, using a pairing force as the residual interaction. We have carried out calculations with a conventional pairing force of the form

$$G(i,j) = G_p^0, \tag{1a}$$

as well as with a state dependent pairing force of the form

$$G(i,j) = G_p' f(i) f(j), \tag{1b}$$

where $f(i)$ and $f(j)$ are numerical factors that may be different from 1. All of the calculations were done using a program based on the method of correlated quasiparticles.[3] In this method one includes the correlations arising from particle number conservation that are neglected in the Bardeen-Cooper-Schrieffer (BCS) approximation. We have used the excitation energies of the low-lying states[4] in ^{145}Eu and the excitation energy of the 10^+ state[1] in ^{146}Gd to determine the appropriate proton single particle spectrum and the proton pairing interaction strength in this mass region. A separate calculation was carried out for each state, i.e., blocking was fully taken into account in our calculations. The energy of the 10^+ state in ^{146}Gd is quite sensitive to the pairing interaction strength and somewhat less sensitive to the single particle level spacings. For the levels in ^{145}Eu, the level spacings are the more crucial feature.

In Fig. 1, we display the proton single particle level spacings obtained from our analysis, using pairing interactions of the form of Eqs. (1a) and (1b). For the interaction of Eq. (1b), we chose $f(h_{11/2}) = 1.2$, $f(g_{7/2}) = 1.1$, and $f(i) = 1$ for all other orbitals. In addition to the levels shown in Fig. 1, we also included the $g_{9/2}$ hole state and the $f_{7/2}$ and

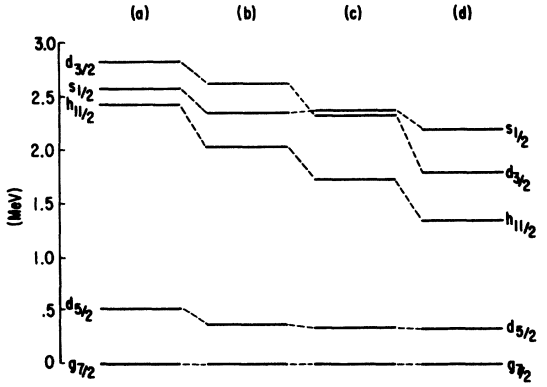

FIG. 1. Proton single particle states near $Z=64$: (a) Level spacings obtained from analysis of ^{145}Eu, using the interaction of Eq. (1a); (b) level spacings obtained from analysis of ^{145}Eu, using the interaction of Eq. (1b); (c) level spacings obtained from momentum dependent Woods-Saxon potential setting $r_{\text{Spin Orbit}}=r_0$; (d) level spacings obtained from momentum dependent Woods-Saxon potential setting $r_{\text{Spin Orbit}}=0.75r_0$.

$i_{13/2}$ particle states at energies of -4.58 MeV, $+6.55$ MeV, and $+6.85$ MeV respectively. These levels are far from the Fermi surface and their exact positions are not crucial. We have included these levels so as to have ~30 doubly degenerate levels. This allows us to compare the value of G_p^0 with values obtained in the analysis of the actinides[5] using the same program.

In addition to the proton single particle spacings obtained from the analysis of ^{145}Eu, we also show in Fig. 1 proton single particle spectra obtained with a momentum dependent Woods-Saxon potential[6]. We have carried out the Woods-Saxon calculation with two choices of spin-orbit radius $r_{s.o.}=r_0$ and $r_{s.o.}=0.75r_0$. The choice $r_{s.o.}=0.75r_0$ gives a poor fit to the spacings deduced from ^{145}Eu; the $d_{5/2}$-$d_{3/2}$ spacing appears to be much too small. The choice $r_{s.o.}=r_0$ agrees somewhat better with the ^{145}Eu spacings, especially for the spacings deduced from the interaction of Eq. (1b). The $d_{5/2}$-$h_{11/2}$ spacing obtained from ^{145}Eu is 1.9 MeV with Eq. (1a) in extremely good agreement with the 1.8 MeV estimate[2] of Blomqvist. This value is ~0.6 MeV smaller than the value obtained in Ref. 7. The main reason for this discrepancy is that it was not possible to consider shifts in λ in their analysis. Our calculations show that there is a large shift in λ, the chemical potential, when the blocked level is above the $Z=64$ gap relative to its position when the blocked level is below the $Z=64$ gap.

The values of the pairing strengths we find in our calculations are

$$G_p^0=0.170 \text{ MeV}, \tag{2a}$$

$$G_p'=0.147 \text{ MeV}. \tag{2b}$$

This value of G_p^0 is considerably smaller than we had anticipated. Assuming an ~$(1/A)$ dependence

TABLE I. Comparison of calculated and observed high spin states in ^{144}Sm, ^{146}Gd, and ^{148}Dy. B.L. denotes blocked level.

B.L. 1	B.L. 2	B.L. 3	B.L. 4	I^π max	$E^{\text{expt.}}$	calc. E (1a)	calc. E (1b)
			^{144}Sm				
$d_{5/2}$	$h_{11/2}$	···	···	8^-	3.37	3.36	3.30
$g_{7/2}$	$h_{11/2}$	···	···	9^-	3.46	3.61	3.59
$h_{11/2}$	$h_{11/2}$	···	···	10^+	···	4.51	4.34
$d_{5/2}$	$d_{5/2}$	$g_{7/2}$	$h_{11/2}$	13^-	5.36	5.53	5.52
$d_{5/2}$	$g_{7/2}$	$g_{7/2}$	$h_{11/2}$	14^-	5.72	5.97	5.89
$d_{5/2}$	$g_{7/2}$	$h_{11/2}$	$h_{11/2}$	16^+	6.82?	6.71	6.51
			^{146}Gd				
$d_{5/2}$	$h_{11/2}$	···	···	8^-	3.18	3.18	3.22
$g_{7/2}$	$h_{11/2}$	···	···	9^-	3.42	3.58	3.57
$h_{11/2}$	$h_{11/2}$	···	···	10^+	3.86	(3.86)	(3.86)
$d_{5/2}$	$d_{5/2}$	$h_{11/2}$	$h_{11/2}$	14^+	5.89	5.94	5.94
$d_{5/2}$	$g_{7/2}$	$h_{11/2}$	$h_{11/2}$	16^+	6.40	6.38	6.32
$d_{5/2}$	$h_{11/2}$	$h_{11/2}$	$h_{11/2}$	16^-	···	6.96	6.78
			^{148}Dy				
$d_{5/2}$	$h_{11/2}$	···	···	8^-	···	3.37	3.33
$g_{7/2}$	$h_{11/2}$	···	···	9^-	···	3.76	3.71
$h_{11/2}$	$h_{11/2}$	···	···	10^+	2.92	2.92	3.21
$d_{5/2}$	$h_{11/2}$	$h_{11/2}$	$h_{11/2}$	16^-	···	5.72	5.91
$g_{7/2}$	$h_{11/2}$	$h_{11/2}$	$h_{11/2}$	17^-	···	6.18	6.30
$h_{11/2}$	$h_{11/2}$	$h_{11/2}$	$h_{11/2}$	16^+	···	6.49	6.56

TABLE II. Comparison of calculated and observed states in ^{143}Pm and ^{147}Tb.

I^π	$E^{expt.}$	calc. E (1a)	calc. E (1b)
	^{143}Pm		
$\frac{5}{2}^+$	0.00	0.00	0.00
$\frac{7}{2}^+$	0.271	0.24	0.28
$\frac{11}{2}^-$	0.960	1.10	1.03
$\frac{3}{2}^+$	{1.056, 1.403}	1.40	1.40
$\frac{1}{2}^+$	1.173	1.24	1.16
	^{147}Tb		
$\frac{5}{2}^+$	...	0.27	0.00
$\frac{11}{2}^-$	...	0.00	0.03
$\frac{1}{2}^+$	...	0.11	0.08
$\frac{3}{2}^+$	...	0.30	0.29
$\frac{7}{2}^+$	...	0.63	0.36

of G_p^0, and the value obtained in the analysis of actinide proton levels, we estimate $G_p^0 \simeq 0.2$ MeV. Also, the detailed analysis of the rare earths by Ogle *et al.*[8] suggests $G_p^0 \simeq 0.19$ MeV.

In Table I, we show the calculated excitation energies for seniority 2 ($S=2$) and $S=4$ high spin states in ^{144}Sm, ^{146}Gd, and ^{148}Dy. Where possible, we compare with the measured energies [1,9-11] of the states of highest spin that can be formed from the relevant configuration. The agreement between calculation and experiment is quite good for ^{144}Sm and ^{146}Gd. As yet there are not many data on high spin states in ^{148}Dy. The excitation energies calculated with Eqs. (1a) and (1b) used as the interaction are similar, with the exception of the $I^\pi = 10^+$ state in ^{148}Dy.

In Table II, we present calculated and measured[4,12] energies for $S=1$ states in ^{143}Pm and ^{147}Tb. The calculated values agree well with the measured ones in ^{143}Pm.

The most interesting nuclide in this region is ^{147}Tb. Here the calculations suggest that all of the proton single particle orbitals that occur between $Z=50$ and $Z=82$ will be found well below 1 MeV. Unfortunately, little is known at this time experimentally about ^{147}Tb, other than the existence of a low-lying isomer. This feature is consistent with both calculated spectra. Based on the available experimental data, the most probable assignments[12] are a ground state spin of $\frac{5}{2}^+$ and a low-lying $\frac{11}{2}^-$ isomer. This is the sequence obtained with the interaction of Eq. (1b). Also, the positions of the $d_{3/2}$ and $s_{1/2}$ orbitals in the $Z \approx 64$ region are not well established experimentally. It appears that a careful study of ^{147}Tb would place these levels as well.

The determination of the low energy spectrum of ^{147}Tb will provide a most remarkable view of the underlying proton spherical shell structure—in a nuclide that is halfway between major proton shells. It is hoped that this spectrum will suggest an explanation for the weak proton pairing interaction strength in this region.

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