Study of low energy proton capture resonances in ^{14}N

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Abstract: Several proton capture resonances in ^{14}N have been studied theoretically using partial wave analysis technique. Most of the results agree well with available experimental data. The analysis has been extended to indicate that one of the resonances with uncertain spin may need a change in the assignment.

1. INTRODUCTION

Study of radiative low energy proton capture reactions has several important implications in nuclear astrophysics. Experimental data on the capture cross sections at stellar energies are essential for studying primordial nucleosynthesis. The measurements at stellar energies are difficult as the direct capture cross-sections are very low. Usually data measured at higher energies are extrapolated to lower energies, which may fail if there are low energy resonances. The astrophysical capture reaction rate is thus greatly affected by the capture resonances at the stellar energies.

The partial wave analysis technique for studying nuclear radiative capture resonances is well-established. This analysis is also useful to search for new resonances and to predict their quantum numbers. In the present work, various experimentally observed resonances [1] in ^{14}N are reproduced reasonably well using this theory. Spectroscopic factors for these states have also been estimated. Some of the deviations of the theoretical results from data are discussed for future scopes.

2. THEORETICAL APPROACH

2.1. The Code

The code **wspot** [2] has been utilized for the partial wave analysis. This program utilizes Woods-Saxon potential as the phenomenological one-body potential. It provides well-accepted results for the properties of bound-state and continuum single-particle wavefunctions. The parameters of the potential are chosen to have a best fit of nuclear single-particle energies and nuclear radii. This potential is composed of the sum of a spin-independent central potential, a spin-orbit potential, and the Coulomb potential. The code thus provides single-particle energies and single-particle radial wavefunctions for the bound states of Woods-Saxon potential with quantum numbers n_r, l and j. It also calculates the nucleon scattering cross-sections for given l and j values.

2.2. The Parameters

The set of parameters used for the Woods-Saxon potential are V_0 (central part)= −53 MeV, V_1 (central part – isospin dependent= −30 MeV and V_{so} (spin-orbit)= 22 MeV for the potential strengths, and r_o (radius parameter–central) = r_{so} (radius parameter–spin-orbit) = 1.25 fm and a_o (diffuseness–central)= a_{so} (diffuseness – spin-orbit)= 0.65 fm for geometry. The radius for the Coulomb term is smaller with r_c = 1.20 fm.

2.3. Determination of phase shifts

The code **wspot** [2] is used to calculate the energies and widths of the capture resonance states [1]. An incident particle is captured to form a metastable bound state which subsequently decays by emission of gamma or by release of a particle. For a given (l, j) value the program calculates the phase shift δ(E) and the scattering cross section σ(E) as a function of energy. The cross-section can be expressed as:

$$\sigma_{\text{total}} = \frac{4\pi}{k^2}\sum_{l=0}^{l_{\max}}(2l+1)\sin^2\delta_l$$

2.4. Determination of energies of resonant levels and their widths

By varying the energy of the incoming particle the relative phase of the inner and outer wavefunctions are changed. The energy E_0 where the amplitude of inside and outside wavefunctions match, cross-section has maximum value. This energy E_0 is known as a resonance energy. Only one partial wave ‘l’ is necessary to have the occurrence of a resonance state corresponding to the energy E_0 where $\delta_l = \pi/2$. The width of the resonance (Γ) is determined from the energy (E), where cross-section reduces to half of a central value $(E-E_0) = \pm\Gamma/2$.

E_x (MeV)	E_R (MeV)		V_N factor	Width (Γ) (keV)		Spectro-scopic Factor ($\Gamma^{expt}/\Gamma^{theo}$)	Single Particle Orbital
	Expt [1]	Theo		Expt [1]	Theo		
7.966 (2^-)	0.416	0.411	0.933	<0.37	0.212	1.74	$1d_{5/2}$ (l=2)
8.062 (1^-)	0.512	0.515	0.972	23 (1)	66.8	0.34	$2s_{1/2}$ (l=0)
8.620 (0^+)	1.07	1.07	0.703	3.8 (3)	124	0.03	$1p_{1/2}$ (l=1)
8.776 (0^-)	1.226	1.074	0.914	410 (20)	475	0.86	$2s_{1/2}$ (l=0)

Table 1: Comparison of experimental and theoretical features of the low energy resonance states at different excitation energies (E_x) in ^{14}N.

2.5. Inputs needed to identify a resonance

The energy range that could be populated in the compound nucleus by capture of the incoming projectile by the target nucleus is determined by the energy given in the input and the Q value of the reaction. The incoming particle energy necessary to populate a resonant state is known as resonance energy (E_r).

The resonances which are already identified in a particular nucleus can be reproduced to get an idea of the spectroscopic purity of the state. For a particular choice of l and j, the depth of the central potential is varied (normalized) by a factor such that the resonance energy is determined correctly. The ratio of widths of the resonance obtained in experiment over theory provides a measure of the spectroscopic factor of that particular state.

By fixing a particular depth of the potential as estimated from reproducing known resonances – unknown resonances can be also identified which corresponds to a specific single particle orbit (l,j).

3. RESULTS AND DISCUSSION

3.1. Study of known proton capture resonances in ^{14}N

The Q value for the reaction $^{13}C+p \rightarrow ^{14}N+\gamma$ is 7550 keV. The ground state spin of ^{13}C is $1/2^{-}$. The known resonances [1] have been reproduced by varying the potential depths. The single particle orbits are chosen keeping in mind the spin assignment in ^{14}N, as well as the earlier information of the l value. The results are shown in Figure 1 and Table 1. Figure 1 shows the features of different resonances in ^{14}N. In Fig 1a, the variation of the normalization factor of the potential to choose the best value for reproducing the experimental resonance energy is demonstrated for a particular case. In Fig 1b, the resonance at 8062 keV (1^{-}), reported to be originated from l=0, has been shown to be reproduced by the l=2 contribution. However in Table 1, the spectroscopic factor has been calculated for l=0 contribution only. Figs 1c and d show the features for other resonances.

The results show quite good agreement with the experimental data. However, except for the 0- state at 8776 keV, the spectroscopic factors for the other states do not appear to be realistic. The normalization factors for the potential corresponding to different shells and l values are consistent. For $d_{5/2}$ and $s_{1/2}$ orbitals, the normalization is less than 1 (~0.91-0.97), whereas for $p_{1/2}$, it needs 30% reduction (~0.7), indicating that the resonance energies are under predicted with full strength of the potential. However, in Fig.1 b, while reproducing the resonance (1^{-}) with $d_{3/2}$, the resonance energy is over predicted resulting in a normalization value > 1 (~1.35).

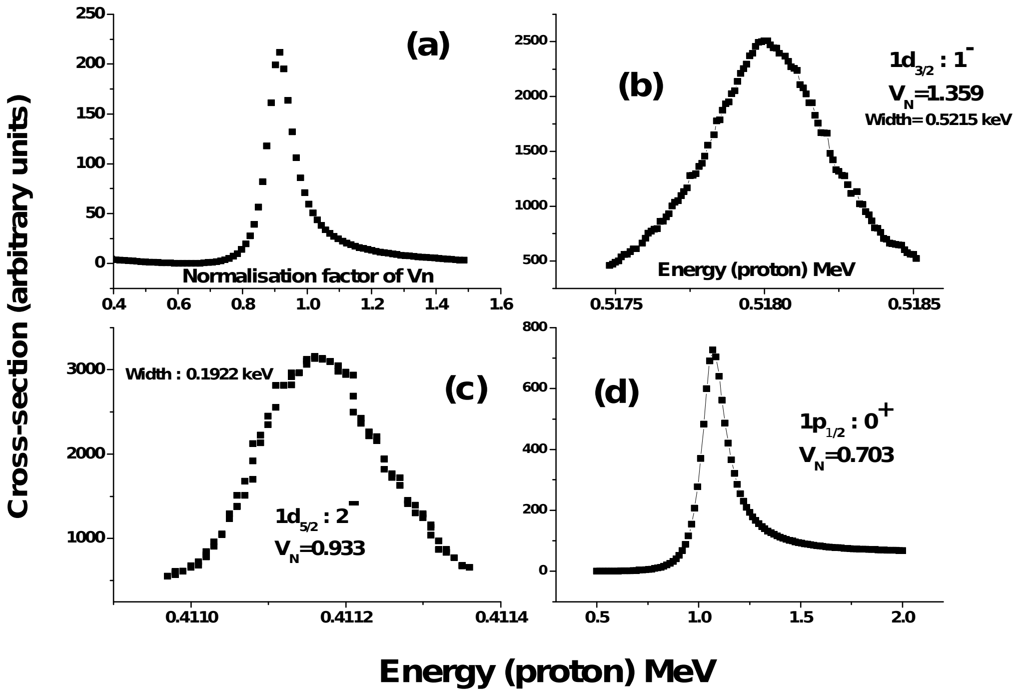

Figure 1: Theoretical results for different resonances. See text for details.

3.2. Comments on resonance states with relatively higher spins

In the present work, no excitation of the target has been considered. With this assumption, having a resonance with spin >3 (4) with negative (positive) parity at low energies (E_r< 1000 keV) is unlikely as those will need coupling with l=4 (5) partial wave, i.e *g* (*h*) orbitals. However, such states have been reported in literature [1].

Thereafter, with normalization around 0.91 as obtained for $d_{5/2}$ for known resonances, the energies are varied and a resonance is obtained at E_R~0.8 MeV (Fig. 2). The energy almost matches with an observed state at 8490 keV with a tentatively assigned spin of (4^-). However, having two close-by resonances with same l is also doubtful. This spin assignment therefore needs to be revalidated experimentally.

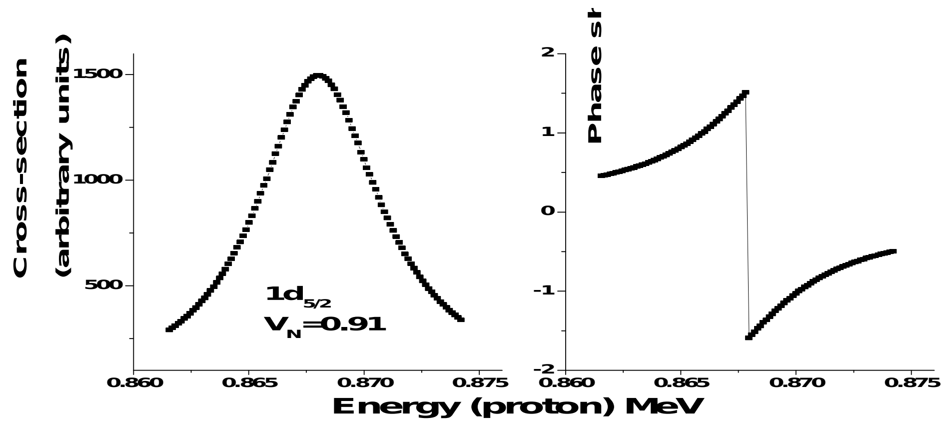

Figure 2: The resonance at E_r~0.866 MeV

4. CONCLUSION

Several proton capture resonances in ^{14}N have been studied theoretically using partial wave analysis technique. Most of the results agree well with available experimental data. The spectroscopic factors are determined. The analysis has been extended to indicate that one of the resonances with uncertain spin may need a change in the assignment.

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