Density distribution investigation through the geometrical structure for the $^{27}$S halo nucleus

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Abstract. $^{27}$S was predicted as a proton halo nucleus in the $2s_{1/2}$ state due to the abnormally large protons root mean square radius. The presence of weakly bound ($S_{2n} = 0.90(20)$ MeV) two valence protons in the $^{27}$S nucleus strongly supported this prediction. The core density, matter density, and halo density for this nucleus ($^{27}$S) have been investigated in this study. The geometrical halo structure has been used for different parameter calculations to investigate these density distributions since sufficient experimental data are not available for this $^{27}$S nucleus. The parameters’ values were calculated easily following this geometrical structure. Gaussian-Gaussian (GG) distribution has been applied to investigate these densities. In our present study, the $^{27}$S nucleus was investigated as a $2-p$ halo nucleus due to its low valence two-protons separation energy (0.90 MeV). The $2-p$ halo $^{27}$S nucleus was described having ($^{25}$Si) + p + p configuration. These measured parameters’ values were then used to investigate the Gaussian-Gaussian (GG) density distributions. MATLAB computational software was also used for these distribution investigations. From these density distributions, a maximum density of 1.042%, 1.001%, and 0.4789% at the centre of the nucleus was obtained for the core density ($\rho_c$), matter density ($\rho_m$), and halo density ($\rho_h$), respectively. The presence of longer tails on the halo and matter distributions also support the prediction as a two-proton halo nucleus.

1. Introduction

The $^{27}$S nucleus is located at the proton-drip line in the nuclear landscape, and the nucleus is a proton halo candidate. In 1996, this candidature was confirmed and the $^{27}$S nucleus is a proton halo nucleus based on the mean-square radius of proton for the $2s_{1/2}$ state [1]. The low separation energy of the two-valence protons on the $^{27}$S nucleus emphasizes the two-proton ($2-p$) halo nucleus demand [2,3]. In addition, its root mean square (rms) halo radius ($R_h$) is larger than the rms core radius ($R_c$) and rms matter radius ($R_m$). Considering the two-proton halo configuration of the nucleus $^{27}$S, we have focused our work on the nuclear density distributions ($\rho_c$, $\rho_m$, and $\rho_h$) of this nucleus. The Gaussian-Gaussian (GG) density distributions depend on the rms core, matter and halo radii [4]. However, there is a lack of sufficient experimental data to study the nuclear properties, especially the density distributions for the $^{27}$S nucleus [5]. Therefore, to investigate these density distributions, we have calculated the density parameters such as distance between core and centre of mass of two valence protons, half distance of...
the two-valence protons, distance between two-valence protons, etc. using a geometrical halo structure.

We have calculated the nuclear density distributions ($\rho_c$, $\rho_m$ and $\rho_h$) for the nucleus $^{27}$S theoretically using MATLAB computational software in our present work.

2. Theoretical Frameworks

The simplest shell-model structure consists of $2s_{1/2}$ valence orbital, which is filled up by two protons for $Z = 16$, and the $1d_{3/2}$ valence orbital which is filled up by protons for $Z = 14$ and neutron number $N = 11$ [2]. For this shell-model, the $^{25}$Si nucleus was considered as the core of the halo nucleus $^{27}$S. To study the density distributions of the halo nucleus ($^{27}$S), we have applied a geometrical structure for the halo nucleus since this geometrical structure was used for the study of the $^6$He two-neutron structure [6]. The core nucleus was considered inside a cluster core model (CCM). The geometrical structure for this core and the valence two-proton are shown in Figure 1.

![Figure 1. The geometrical structure for the $^{27}$S halo nucleus.](image)

Through this geometrical structure, all parameters for the core ($^{25}$Si) and $^{27}$S nucleus can be determined based on the following:

- The distance $\rho_c$ between the nuclear centre of mass and the core centre is [7]:
  \[
  \rho_c = \left( \frac{R_{sm}^2}{A_c} - \frac{R_m^2}{A} \right)^{1/2}
  \]
  where, $R_{sm}$ is rms matter radius of the core ($^{25}$Si) nucleus, $R_m^2$ is the rms matter radius of $^{27}$S, $R_{sm}^2$ is the rms radius of the $^{25}$Si nucleus and $A_c$ is the mass number of the $^{25}$S.

- The core radius of the centre of mass $R_c$ is:
  \[
  R_c = \left( R_{sm}^2 + \rho_c^2 \right)^{1/2}
  \]

- The vector $R_{2p}$ joining the nuclear centre of mass and the midpoint of the line connecting the two halo protons is determined from the balancing condition:
  \[
  A_c \rho_c = A_h R_{2p}, \text{where } A_c = 25, \ A_h = 2
  \]
• The distance $R_{c-2p}$ from the core centre to the two halo protons is:

$$R_{c-2p} = \rho_c + R_{2p}$$  \hspace{1cm} (4)

• The distance $R_{p-p}$ between the two halo neutrons is given by:

$$R_{p-p} = 2R_{dip}, \text{ where } R_h^2 = R_{2p}^2 + R_{dip}^2$$  \hspace{1cm} (5)

• The rms halo radius of the $^{27}$S nucleus is [7]:

$$R_h = \left(\frac{1}{2} \left( (A_c + 2)R_m^2 - A_c R_{sm}^2 \right) \right)^{1/2}$$  \hspace{1cm} (6)

where, from Equation (3) to Equation (5) are taken from the Ref. [6].

Moreover, the Gaussian-Gaussian (GG) density distributions equations for $\rho_c$, $\rho_m$ and $\rho_h$ can be written as [4][6]:

$$\rho_{core(halo)}(r) = \left(\frac{3}{2\pi \rho_c^{(h)}}\right)^{3/2} \exp\left(-\frac{3r^2}{2\rho_c^{(h)}}\right)$$  \hspace{1cm} (7)

and,

$$\rho_m(r) = \frac{1}{A} [N_{core}\rho_{core}(r) + N_{halo}\rho_{halo}(r)]$$  \hspace{1cm} (8)

where $N_{core}$ and $N_{halo}$ are the number of nucleons in the core and halo respectively and $A$ is the mass number of the halo nucleus. $r$ is the radial distance from the centre of the nucleus’ core to infinity. We have carried out all calculations including the core, matter and halo distribution calculations etc. through the MATLAB codes.

3. Result and discussion

Using Equations (1) – (6) through the geometrical halo structure, we obtained the calculated values tabulated in Table 1. From these measurements, the rms core, halo, and matter radii of the $^{27}$S nucleus were determined 3.1632 fm, 4.0994 fm, and 3.2347 fm respectively. Using these rms radii in Equations (7) and (8), the core density, halo density, and matter density were calculated. These density distributions are shown in Figure 2.

| Nucleus | Parameter Name | Parameters | Parameter Values |
|---------|----------------|------------|-----------------|
| $^{25}$Si | Matter radius | $R_{sm}$ | 3.1553 |
|         | Distance between core and centre of mass | $\rho_c$ | 0.2232 |
| $^{27}$S | Core radius | $R_c$ | 3.1632 |
|         | Matter radius | $R_m$ | 3.2347 |
|         | Distance between centre of mass and the mid-point of two valence protons | $R_{2p}$ | 2.7900 |
|         | Halo radius | $R_h$ | 4.0994 |
|         | Half distance of the two-valence protons | $R_{dip}$ | 3.0035 |
|         | Distance between two-valence protons | $R_{p-p}$ | 6.0071 |
The maximum density values of 1.042%, 1.001%, and 0.4789% are noted at the centre of the nucleus respectively for the core density, matter density, and halo density which are shown in Figure 2.

![Density Distributions for the $^{27}$S Halo Nucleus](image)

**Figure 2.** GG density distributions for the $^{27}$S halo nucleus.

4. Conclusion
The $^{27}$S nucleus core density ($\rho_c$) is at maximum for all $\rho_c$, $\rho_h$ and $\rho_m$ and all neutrons are distributed in the nucleus’ core. Furthermore, the matter density ($\rho_m$) is less than $\rho_c$ and the tail of the proton halo density ($\rho_h$) is larger than $\rho_c$ and $\rho_m$. This indicates that the protons are distributed at larger radius from the nucleus centre and exist outside the core of the nucleus. Ultimately, $\rho_h$ has the smallest density at the core of the $^{27}$S nucleus and the tail of this density is at the largest up to 7 fm in radius which indicates that the protons are lying further away from the nucleus’ core. The nucleons’ distribution at further distances and the halo density distribution’s large tail show that the $^{27}$S nucleus is a proton-halo nucleus.

5. References
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