Inelastic scattering studies of ^{16}C reexamined

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Previous inelastic scattering experiments populating the 2_1^+ state in ^{16}C using ^{208}Pb and liquid hydrogen targets have been reanalyzed. Exploiting the different sensitivities of the two probes for the neutron and proton distributions, the neutron and proton deformation lengths and transition strengths have been derived by means of distorted wave calculations. The determined $B(E2)$ value is consistent with the results of lifetime measurements while the large difference in the neutron and proton transition strengths shows relatively enhanced neutron excitations.

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The ^{16}C nucleus has been in the forefront of both experimental and theoretical nuclear structure studies in the past years because of several reasons. Its extended neutron distribution was suggested from a reaction cross section measurement [1]. Another interesting phenomenon in the chain of carbon isotopes, opposite deformations between protons and neutrons [2], which inspired several experimental works, was proposed in the mid-1990s by antisymmetrized molecular dynamics (AMD) calculations. In addition, an anomalously long lifetime of the first 2^+ excited state and a corresponding hindered $E2$ strength was measured by the recoil shadow method in RIKEN [3]. Similar small $B(E2)$ values and a strong dominance of neutron over proton excitations were concluded by analyzing the angular distribution of ^{16}C nuclei inelastically scattered on a ^{208}Pb target [4]. This picture seemed to be confirmed by a proton inelastic scattering measurement in inverse kinematics [5]. In turn, several theoretical attempts have been made to interpret this feature [6–13]. This year, the results of two new experiments aimed at redetermining the lifetime of the first 2^+ excited state have become available. RIKEN has come up with revised data [14] and Lawrence Berkeley National Laboratory has reported a value close to theirs [15]. These studies suggest a shorter lifetime and a corresponding larger $B(E2; 0^+_{\text{g.s.}} \to 2^+_1)$ between 10–20 e^2 fm^4.

Here, we present a reanalysis of the inelastic scattering experiments populating the 2_1^+ state using ^{208}Pb [4] and hydrogen targets [5]. Due to the small charge of the carbon nuclei, the scattering on the ^{208}Pb target at intermediate energy cannot be considered as a pure Coulomb process; both charge and mass deformations play a role in the excitation. Since the Pb and H targets probe the neutron and proton distributions with different sensitivities, both mass and charge, and consequently, the neutron and proton deformation lengths δ_n and δ_p can be extracted by comparing the integrated cross sections of the two processes in a simultaneous way. In this Brief Report, we describe the analysis, which uses only the previously determined total, integrated cross sections, and the results on ^{16}C.

As a first step, a pair of neutron and proton deformation lengths has been chosen. These are in the following correspondence with the matter and Coulomb deformation lengths for the two probes ($\delta_M^{Pb}, \delta_M^{pp}, \delta_C^{Pb} = \delta_C^{pp} = \delta_p$):

$$\left(Z \cdot b_p^{Pb} + N \cdot b_n^{Pb}\right) \cdot \delta_M^{Pb} = N \cdot b_n^{Pb} \cdot \delta_n + Z \cdot b_p^{Pb} \cdot \delta_p, \quad (1)$$

$$\left(Z \cdot b_p^{pp} + N \cdot b_n^{pp}\right) \cdot \delta_M^{pp} = N \cdot b_n^{pp} \cdot \delta_n + Z \cdot b_p^{pp} \cdot \delta_p, \quad (2)$$

where $b_n^{Pb}, b_p^{Pb}, b_n^{pp}$, and b_p^{pp} are the neutron and proton sensitivity parameters, which are not independent of each other. For low-energy proton scattering (<50 MeV), $(\frac{b_n}{b_p})^p = 3$ and for low-energy neutron scattering $(\frac{b_n}{b_p})^n = 1/3$ [16]; thus $b_n^p = 0.75$, $b_n^n = b_p^p = 0.25$. The Pb probe contains both protons and neutrons, and its sensitivity parameters were derived assuming they depend on the N/A and Z/A ratios and the nn, pp, np interactions: $b_n^{Pb} = b_p^n \frac{Z}{A} + b_n^n \frac{N}{A} = 0.447$; $b_p^{Pb} = b_p^p \frac{Z}{A} + b_n^p \frac{N}{A} = 0.553$.

$\delta_{M,C}^{Pb}, \delta_{M,C}^{pp}$ are the input parameters in the coupled channel code ECIS97 [17] which is used to retrieve calculated cross sections σ_{cal}^{Pb} and σ_{cal}^{pp}. The difference between the calculated and experimental cross sections has been quantified in a χ^2 value so we ended up with a set of data ($\delta_n, \delta_p, \chi^2$). This procedure was repeated with varied initial (δ_n, δ_p) parameters and the results are visualized in a contour plot of χ^2 values (Fig. 1). From this figure, the neutron and proton deformation lengths can easily be determined at $\delta_n = 1.37 \pm 0.12$ (stat) fm, $\delta_p = 0.90 \pm 0.13$ (stat) fm. The corresponding proton and neutron transition strengths are calculated with the following formulas:

$$B(E2; 0^+_{\text{g.s.}} \to 2^+_1)/e^2 = M_p^2 = \left(\frac{3}{4\pi} \cdot Z \cdot \delta_p \cdot R\right)^2 \quad (3)$$

$$M_n^2 = \left(\frac{3}{4\pi} \cdot N \cdot \delta_n \cdot R\right)^2 \quad (4)$$

at 15.2 ± 4.4 (stat) fm^4 and 98 ± 17 (stat) fm^4, respectively.

In the ECIS calculations, the standard collective form factors have been applied. For the Pb target, the optical model parameters (OMP) from a previous measurement of the ^{17}O + ^{208}Pb reaction [18] have been taken while the global phenomenological parameter set $CH89$ [19] have been used for the hydrogen run. By switching from $CH89$ to Becchetti-Greenlees [20] parametrization and from the OMP

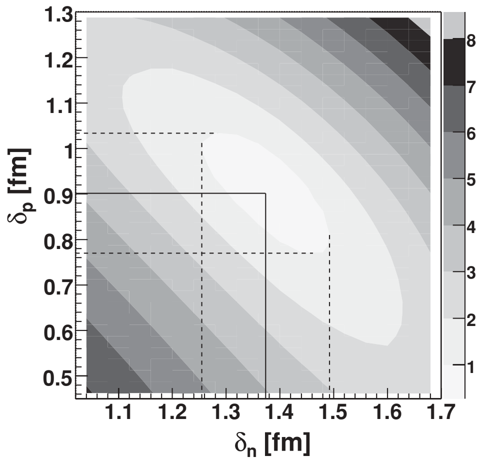

FIG. 1. Contour plot of reduced χ^2 values in function of the neutron and proton deformation lengths (δ_n, δ_p). The mean values of δ_n and δ_p together with their error bars are indicated by solid and dashed lines, respectively.

of the $^{17}O + ^{208}Pb$ reaction to that of the $^{12}C + ^{208}Pb$ [21], the total systematic uncertainties due to OMP choice have been determined at $\Delta\delta_n = 0.095$ fm, $\Delta\delta_p = 0.13$ fm, $\Delta M_n = 14$ fm^4, $\Delta M_p^2 = 4.4$ fm^4. Another source of uncertainty comes from the sensitivity parameters of the probes. They are not precisely known, therefore, the dependence of the final data on them has been tested by introducing a 20% change in the $(\frac{b_n}{b_p})^{pp}$ ratio, which alters the $(\frac{b_n}{b_p})^{Pb}$ value consequently. This resulted in the following systematic errors: $\Delta\delta_n = 0.025$ fm, $\Delta\delta_p = 0.025$ fm, $\Delta M_n = 3.6$ fm^4, $\Delta M_p^2 = 0.8$ fm^4.

The presently determined $B(E2) = 15.2\,e^2$ fm^4 value is close to the results coming from the two new lifetime measurements of 13.0 ± 1.0 (stat)± 3.5 (syst) e^2 fm^4 [14] and $20.8 \pm 3.7\,e^2$ fm^4 [15] and they are consistent with each other taking into account the error bars. However, they are much smaller than $82.3\,e^2$ fm^4 which is expected using a global fit by Raman [22] based on the Grodzins rule [23]. On the other hand, our extracted neutron strength of 98 fm^4 is about 6 times larger than the proton one, which shows the dominance of neutron over proton excitations in ^{16}C nucleus. This phenomenon, i.e., the $0^+_{g.s.} \rightarrow 2^+_1$ transition is a nearly pure neutron excitation, is not new. As was discussed in several earlier works [4,14,24,25], it might be related to the idea that ^{16}C can be considered as a $\nu(sd)^2$ coupled to an inert ^{14}C core.

Finally, it is worth noting that these new results on δ_n and δ_p differ from those extracted by our earlier analysis of the angular distribution of the $^{208}Pb + ^{16}C$ reaction [4]. There, the uncertainty of the experimental differential cross section data varied with the angular bins having an average error of 8.3%. By increasing the individual, relative error bars in the bins with the same relative amount to an average error of 11.7%, the discrepancy, which is most likely due to the underestimation of the systematic errors in the previous work, can be resolved. Namely, the angular distribution curve with the present δ_n and δ_p deformation lengths fits the experimental data with a χ^2 value similar to that of the earlier paper.

Summarizing our studies, we have simultaneously reanalyzed the $^{208}Pb, ^1H + ^{16}C$ inelastic scattering reactions populating the first 2^+ excited state in ^{16}C in the framework of distorted wave calculations. From this, the neutron and proton deformation lengths and consequently the transition strengths have been extracted focusing only on the total, integrated cross sections. The determined $B(E2)$ value is consistent with the results of other experiments. An enhanced contribution of neutron over proton excitation in the $0^+_{g.s.} \rightarrow 2^+_1$ transition, suggested in previous studies [4,14,24,25], has been confirmed.

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