Nucleon density distribution in ^{9}C

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(Received 27 May 2014; published 20 June 2014)

Recently the measured proton-^{9}C elastic angular distribution at 300 MeV/nucleon had been analyzed within the Brueckner-Hartree-Fock framework. The Argonne v-18 internucleon potential was used to generate the reaction matrices which were then folded over ^{9}C density distributions obtained by using the relativistic mean-field model. The calculations yield a satisfactory agreement with the experimental data.

DOI: 10.1103/PhysRevC.89.067601 PACS number(s): 24.10.Ht, 21.10.Gv, 25.40.Cm, 27.20.+n

The discovery of a halo structure [1] in ^{11}Li, thick neutron skins, and expectations of new magic numbers triggered interest in the production and studies of a new variety of exotic nuclei with large neutron or proton excesses. This has led to a renewed interest in the studies concerning the unusual neutron and proton density distributions in these nuclei. Since the electron-scattering data from these unstable nuclei are not available, scattering from the hydrogen targets is one of the important tools for obtaining information about their density distributions.

In view of the above, 700-MeV proton-scattering experiments from neutron-rich isotopes were performed at the Schwerionen Synchrotron [2–4]. Furthermore, since the nucleon mean-free path in a nucleus is longest at around 300 MeV, the radioactive ion beam facility (elastic scattering of protons with radioactive ion beams) in Japan has embarked on the scattering experiments of exotic nuclei from protons at around 300 MeV/nucleon. Recently, Matsuda *et al.* [5] reported the measurement of the differential elastic scattering of ^{9}C from protons at 277–290 MeV/nucleon. To obtain the nucleon distributions in ^{9}C, they analyzed the experimental data by using a modified version of the model proposed by Murdock and Horowitz [6]. The *NN*-scattering amplitudes were modified to include density dependence in the coupling constants and meson masses in terms of four parameters. These parameters were determined by fitting the proton-^{12}C differential elastic cross section and polarization data at 300 MeV/nucleon. Since ^{12}C is a stable $N = Z$ nucleus its neutron distribution is expected to be similar to that of protons, which is relatively more reliably known as compared to the corresponding density distributions in the exotic nuclei. The medium modified-scattering amplitude thus fixed was then used for analyzing the proton-scattering data from ^{9}C. The differential elastic cross section of the proton-^{9}C (p-^{9}C) data was fitted by assuming a two-parameter Fermi distribution for both neutron and proton densities with different radii and diffuseness parameters. Thus four adjustable parameters were used to obtain a reasonable agreement with the angular distribution by hoping that reliable information with regard to matter distribution in ^{9}C could be obtained. Although they obtained a rms matter radius (2.43 fm), which is consistent (Tables III and IV of Ref. [5]) with the radii deduced from other experiments and the theoretical models [7,8], the proton and neutron distributions as obtained in Ref. [5] (shown in Fig. 1) are highly unphysical. In view of this they concluded that additional data are required to obtain a reliable density distribution in ^{9}C.

In view of the failure of the above approach to yield reasonable proton and neutron distributions, we have performed a reanalysis of the p-^{9}C data by using the Brueckner-Hartree-Fock (BHF) approach. It has been established that the optical potentials calculated by using the BHF approach are quite sensitive to the densities used [9–11]. Hence application of the BHF approach to analyze the proton-scattering data can be helpful in ascertaining a more appropriate density distribution for the target nuclei.

The BHF approach requires only two inputs: the realistic internucleon potential to calculate the reaction matrices (effective interaction) and the nucleon density distributions of the target required in the folding of the reaction matrices to obtain the nucleon-nucleus optical potential. We have used the Argonne v-18 internucleon potential [12] to obtain the effective interaction. The method of calculation is described in detail in Ref. [13]. The numerically calculated effective interaction was then folded over the proton and neutron densities calculated independently by using the well-established and reliable relativistic mean-field (RMF) theory [14] to obtain the nucleon-nucleus optical potential (OP). This OP was then used to predict or to calculate the observables. Thus there are no free parameters in this microscopic approach for obtaining the nuclear optical potential. The predictions of the BHF approach are thus sensitive to the density distributions used. Figure 1 shows the calculated RMF neutron and proton density distributions. It is important to note that our RMF densities for ^{9}C are very different from the corresponding ones obtained by Matsuda *et al*. [5]. We also show, in Fig. 1, our RMF neutron and proton densities for ^{12}C. It is important to note that the proton density distribution in ^{9}C is very different from that in ^{12}C. In view of this one should be cautious in assuming the same proton density distribution in different isotopes of a nucleus.

The calculated potential in the BHF approach was then used in a spherical optical model code to predict the observables. This procedure has been satisfactorily used in the past for

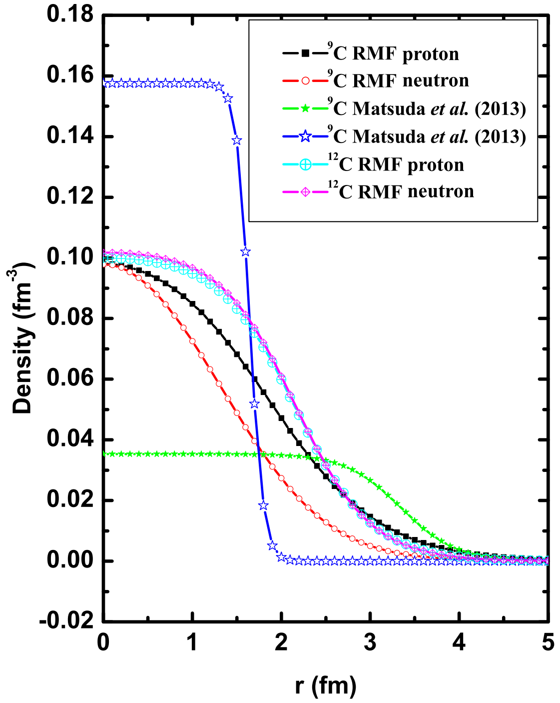

FIG. 1. (Color online) RMF proton and neutron density distributions in ^{9}C and ^{12}C. The two-parameter Fermi density distributions of Matsuda *et al.* [5] are also shown.

analyzing the proton-scattering data from stable as well as exotic nuclei [11,13–16]. To further test our approach we have first analyzed the p-^{12}C differential elastic cross section and analyzing power data at 300 MeV/nucleon. Figure 2 shows that the BHF approach satisfactorily reproduces the

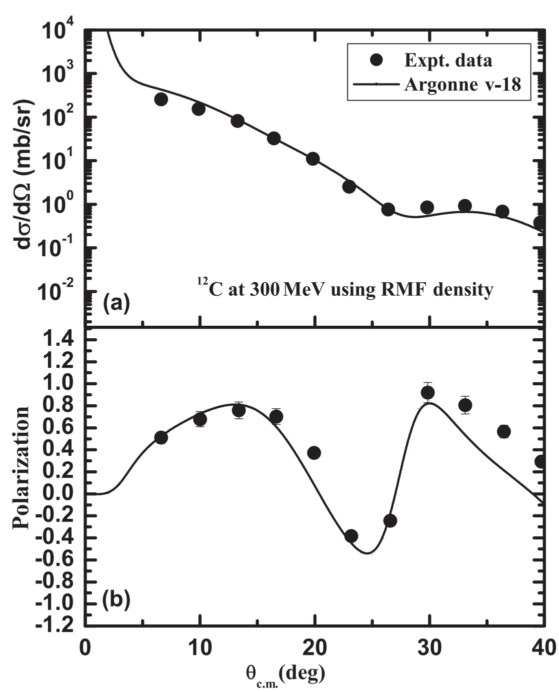

FIG. 2. Proton-^{12}C (a) differential cross section and (b) analyzing power at 300 MeV by using the RMF density in the BHF approach.

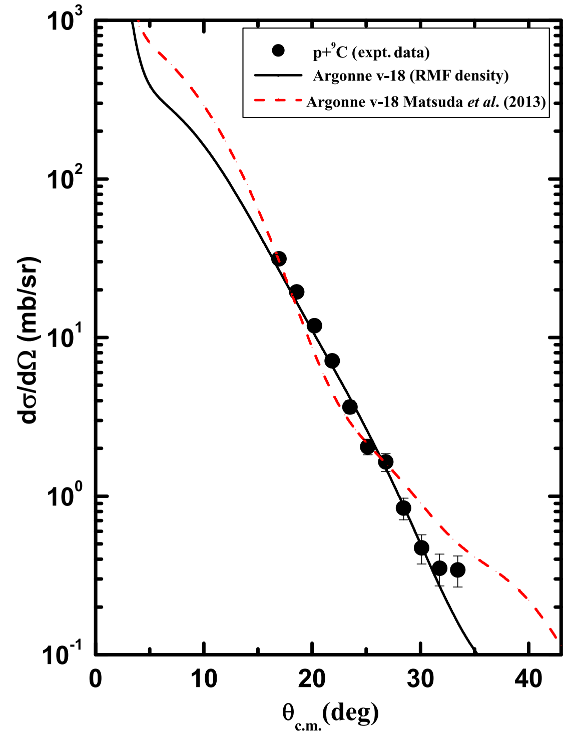

FIG. 3. (Color online) Differential elastic cross section for p-^{9}Ca scattering at 290 MeV by using densities from Matsuda *et al.* [5] and the RMF in the BHF approach.

experimental data at 300 MeV/nucleon. In Fig. 3 we show that our predictions for the p-^{9}C differential cross section reproduce well the experimental data. In Fig. 3 we also show our BHF results by using the two-parameter Fermi (2PF) density [5] distributions of Matsuda *et al.* The results indicate that the calculations are sensitive to the densities used. We note that our results with RMF densities are in better agreement than those obtained by using the 2PF densities [5]. Hence, it appears that the agreement obtained by adjusting the four parameters in Ref. [5] is model dependent. Since there are no free parameters in our analysis it seems that the RMF density distributions used here are a fair representation for the nucleon density distributions in^{9}C. The rms matter, proton radii, neutron radii, and skin thicknesses for the ^{9}C density used in the present Brief Report are listed in Table I. For comparison we have also listed the corresponding results reported by Matsuda *et al.* [5] and

TABLE I. The rms matter, proton radii (R_p), neutron radii (R_n), and binding energies (B.E.) for ^{9}C. RH refers to the relativistic Hartee-Fock approach, and MAMD refers to the multiple width antisymmetric molecular-dynamics results.

	(fm) R_p	(fm) R_n	Skin thickness (fm)	rms matter radii (fm)	B.E./nucl. (MeV)	Expt. B.E./nucl. (MeV)
RMF	2.684	2.164	0.52	2.522	4.82	4.34
Ref. [5]	3.345	1.647	1.698	2.43		
Ref. [17]				RH 2.58		
				MAMD 2.40		

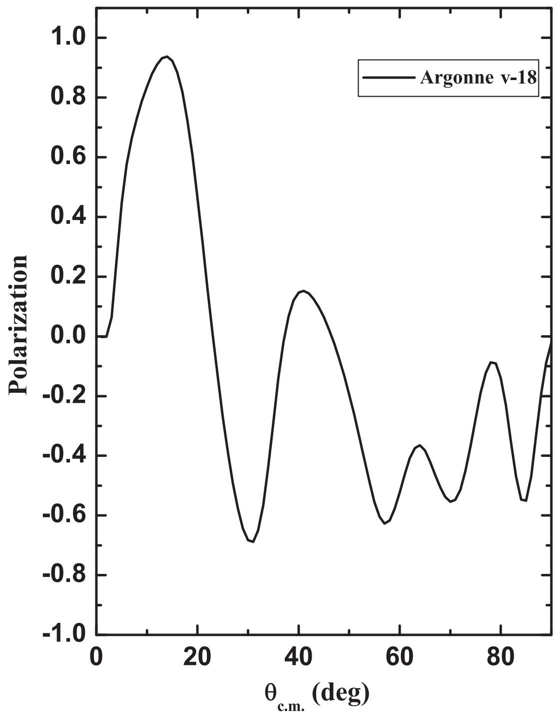

FIG. 4. Predicted analyzing power for p-^{9}C scattering at 290 MeV by using the Argonne v-18 *NN* interaction with the RMF density in the BHF approach.

the rms matter radius reported by Ref. [17]. We note that our matter radius is in close agreement with those of Refs. [5,17].

In Fig. 4 we show our BHF predictions for the analyzing power for proton scattering from p-^{9}C at 290 MeV/nucleon for comparison with the data expected to be available from future experiments. It is important to note that the predictions for the proton analyzing power from ^{9}C are very different from ^{12}C. Hence experimental data for the analyzing power are expected to give more reliable information with regard to nuclear matter distribution in ^{9}C.

It is important to mention that the inclusion of an additional contribution due to the phenomenological three-body forces (TBFs), such as Urbana IX [18] or the density-dependent three-nucleon interaction [19,20], leaves the calculated differential cross sections almost unaltered, and the analyzing power changes only marginally (for details refer to Refs. [21,22]). Therefore the conclusions of the present Brief Report would not be affected by the TBF.

It is satisfying to note that the BHF approach used in the present Brief Report with the RMF densities is able to provide a satisfactory agreement with the presently available experimental data for p-^{9}C. However to conclude that our RMF densities for ^{9}C provide an accurate description, we would require experimental data over a much wider angular region than is currently available.

One of the authors (W.H.) thankfully acknowledges the financial grant from DAE Project No. 2011/37P/16/BRNS.

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