The relativistic continuum Hartree-Bogoliubov description of charge-changing cross section for C, N, O and F isotopes postprint

Authors: S.Q. Zhang, J. Meng, S.-G. Zhou, J.Y. Zeng

Date: 2017-08-22T00:00:00+00:00

Abstract

The ground state properties including radii, density distribution and one neutron separation energy for C, N, O and F isotopes up to the neutron drip line are systematically studied by the fully self-consistent microscopic Relativistic Continuum Hartree-Bogoliubov (RCHB) theory. With the proton density distribution thus obtained, the charge-changing cross sections for C, N, O and F isotopes are calculated using the Glauber model. Good agreement with the data has been achieved. The charge changing cross sections change only slightly with the neutron number except for proton-rich nuclei. Similar trends of variations of proton radii and of charge changing cross sections for each isotope chain is observed which implies that the proton density plays important role in determining the charge-changing cross sections.

Full Text

Preamble

The Relativistic Continuum Hartree-Bogoliubov Description of Charge-Changing Cross Sections for C, N, O, and F Isotopes

J. Meng[1 3*], S.-G. Zhou[1 3], and I. Tanihata

[1]Department of Technical Physics, Peking University, Beijing 100871, China

[2]Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China

[3]Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China

The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako-shi, Saitama 351-0198, Japan

*e-mail: mengj@pku.edu.cn

(August 1, 2017)

Abstract

The ground-state properties—including radii, density distributions, and one-neutron separation energies—for C, N, O, and F isotopes up to the neutron drip line are systematically studied using the fully self-consistent microscopic Relativistic Continuum Hartree-Bogoliubov (RCHB) theory. With the proton density distributions thus obtained, the charge-changing cross sections for these isotopes are calculated using the Glauber model, achieving good agreement with experimental data. The charge-changing cross sections vary only slightly with neutron number except for proton-rich nuclei. Similar trends in the variation of proton radii and charge-changing cross sections are observed for each isotopic chain, implying that the proton density distribution plays an important role in determining the charge-changing cross sections.

PACS numbers: 21.10.Gv, 21.60.-n, 24.10.Cn, 25.45.De

Key words: Relativistic Continuum Hartree-Bogoliubov (RCHB) theory, charge-changing cross section, neutron-rich light nuclei, exotic nuclei

Introduction

Recent progress in accelerator and detection techniques worldwide has made it possible to produce and study nuclei far from the stability line—so-called "exotic nuclei." Measurements of interaction cross sections with radioactive beams at relativistic energies have revealed novel and entirely unexpected features, such as neutron halos and skins manifesting as rapid increases in the measured interaction cross sections for neutron-rich light nuclei [**?**, **?**]. Systematic investigations of interaction cross sections for isotopic or isotonic chains provide excellent opportunities to study density distributions across a wide range of isospin [**?**, **?**]. However, proton and neutron contributions are coupled in interaction cross section measurements, making definitive conclusions about differences in proton and neutron density distributions difficult without combined analysis of interaction cross sections and other experiments probing either protons or neutrons alone. The charge-changing cross section, defined as the cross section for all processes resulting in a change of atomic number for the projectile, provides an excellent opportunity for this purpose.

In Ref. [**?**], total charge-changing cross sections σ_{cc} for light stable and neutron-rich nuclei on a carbon target at relativistic energies were measured. In this Letter, we theoretically investigate σ_{cc} using the fully self-consistent and microscopic relativistic continuum Hartree-Bogoliubov (RCHB) theory combined with the Glauber model.

The RCHB theory [**?**, **?**, **?**], an extension of relativistic mean field (RMF) theory [**?**, **?**, **?**] incorporating Bogoliubov transformation in coordinate representation, satisfactorily describes ground-state properties for nuclei both near and far from the β-stability line, from light to heavy and superheavy elements, and provides understanding of pseudo-spin symmetry in finite nuclei [?, ?, ?, ?]. A remarkable success of RCHB theory is the self-consistent reproduction of the halo in ^{11}Li [?] and the prediction of giant halos [?]. In combination with the Glauber model, RCHB theory successfully reproduces interaction cross sections in Na isotopes [?]. These successes motivate us to apply RCHB theory to calculate charge-changing cross sections for C, N, O, and F isotopes (ranging from the β-stability line to the neutron drip line) on a ^{12}C target as reported in Ref. [?].

With density distributions provided by RCHB theory, total charge-changing cross sections can be calculated using the Glauber model and compared directly with data [?], as was done for interaction cross sections in Ref. [?]. Since the theory is fully microscopic and essentially parameter-free, we expect it to provide more reliable information on both proton and neutron distributions.

Theoretical Framework

We first study the ground-state properties of C, N, O, and F isotopes up to the neutron drip line, including single-neutron separation energies, density distributions, and radii. We then calculate total charge-changing cross sections using the Glauber model with densities obtained from RCHB calculations.

The basic ansatz of RMF theory is a Lagrangian density whereby nucleons are described as Dirac particles interacting via exchange of various mesons (the scalar sigma (σ), vector omega (ω), and isovector rho (ρ)) and the photon. The σ and ω mesons provide the attractive and repulsive parts of the nucleon-nucleon force, respectively, while the ρ meson provides the necessary isospin asymmetry. The scalar sigma meson moves in a self-interacting field with cubic and quadratic terms of strengths g_2 and g_3, respectively. The Lagrangian consists of free baryon and meson parts and an interaction part with minimal coupling, together with nucleon mass M and masses m_σ, m_ω, m_ρ (and coupling constants g_σ, g_ω, g_ρ) of the respective mesons:

$$L = \bar{\psi}(i\partial\!\!\!/-M)\psi+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma-U(\sigma)-\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu}+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu-\frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu}+\frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-g_\sigma\bar{\psi}\sigma\psi-g_\omega\bar{\psi}\omega\!\!\!/\psi-$$

For proper treatment of pairing correlations and correct description of scattering of Cooper pairs into the continuum in a self-consistent manner, the relativistic mean-field theory must be extended to RCHB [?, ?, ?]:

$$\begin{pmatrix} h-\lambda & \Delta \\ -\Delta^* & -h^*+\lambda \end{pmatrix}\begin{pmatrix} U_k(r) \\ V_k(r) \end{pmatrix} = E_k \begin{pmatrix} U_k(r) \\ V_k(r) \end{pmatrix}$$

where E_k is the quasiparticle energy, $U_k(r)$ and $V_k(r)$ are four-dimensional Dirac spinors, and h is the usual Dirac Hamiltonian $h = [\alpha \cdot p + V(r) + \beta(M + S(r))]$, with vector and scalar potentials calculated from:

$$V(r) = g_\omega \omega(r) + g_\rho \rho(r)\tau + e(1-\tau_3)A_\tau(r), \quad S(r) = g_\sigma \sigma(r)$$

The chemical potential λ is adjusted to give the proper particle number. The meson fields are determined self-consistently from the Klein-Gordon equations in the no-sea approximation.

The pairing potential Δ in Eq. (2) is given by $\Delta_{ab} = \sum_{cd} V_{abcd}\kappa_{cd}$, obtained from the pairing tensor $\kappa = U^* V^T$ and the one-meson exchange interaction V_{abcd} in the pp-channel. As in Refs. [?, ?, ?], V^{pp}_{abcd} in Eq. (5) is the density-dependent two-body force of zero range:

$$V(r_1, r_2) = V_0(1 + P^\sigma)\delta(r_1 - r_2)\left(1 - \frac{\rho(r)}{\rho_0}\right)$$

The ground state $|\Psi\rangle$ of an even-particle system is defined as the vacuum with respect to quasiparticles: $\beta_\nu|\Psi\rangle = 0$, with $|\Psi\rangle = \prod_\nu \beta_\nu|-\rangle$, where $|-\rangle$ is the bare vacuum. For odd systems, the ground state can be written as $|\Psi\rangle_\mu = \beta^\dagger_\mu \prod_{\nu\neq\mu} \beta_\nu|-\rangle$, where μ is the blocked level. Exchanging the quasiparticle creation operator $\beta^\dagger_\mu$ with the corresponding annihilation operator β_μ means replacing column μ in the U and V matrices by the corresponding column in the matrices V^*, U^* [?].

The RCHB equations (2) for zero-range pairing forces form a set of four coupled differential equations for the quasiparticle Dirac spinors $U(r)$ and $V(r)$, solved by the shooting method in a self-consistent manner [?]. Detailed formalism and numerical techniques of RCHB theory can be found in Ref. [?] and references therein.

In the present calculations, we follow the procedures in Refs. [?, ?, ?] and solve the RCHB equations in a box of size $R = 20$ fm with step size 0.1 fm. The parameter set NL-SH [?] is used, which is designed to describe both stable and exotic nuclei. The density-dependent δ-force in the pairing channel with $\rho_0 = 0.152$ fm^{-3} is employed, with its strength V_0 fixed by the Gogny force as in Ref. [?]. Contributions from the continuum are restricted within a cutoff energy $E_{\text{cut}} \sim 120$ MeV.

Results and Discussion

Systematic RCHB calculations have been carried out for C, N, O, and F isotopes. The one-neutron separation energies S_n predicted by RCHB and their experimental counterparts [?] for nuclei $^{11-22}$C, $^{13-24}$N, $^{15-26}$O, and $^{17-25}$F are shown in Fig. 1 [Figure 1: see original paper] as open and solid circles, respectively. For carbon isotopes, the theoretical one-neutron separation energies for $^{11-18,20,22}$C agree with data. The calculated S_n is less than 0 (-0.003 MeV) for the odd-A nucleus ^{19}C, which is experimentally bound, while for the experimentally unbound nucleus ^{21}C, the predicted S_n is positive. From the neutron-deficient side to the neutron drip line, excellent agreement is achieved for nitrogen isotopes. Like other relativistic mean-field approaches, RCHB calculations overestimate binding for ^{25,26}O, which are unstable experimentally. For fluorine isotopes, S_n in $^{17,26-29}$F are overestimated, in contrast to the underestimated value in ^{18}F. The neutron drip-line nucleus is predicted to be ^{30}F. Overall, RCHB theory reproduces S_n data well, considering it is a microscopic, nearly parameter-free model. Some discrepancies between calculations and empirical values for certain isotopes may be due to deformation effects neglected in this study.

The proton density distributions predicted by RCHB for nuclei $^{10-22}$C, $^{12-24}$N, $^{14-26}$O, and $^{16-25}$F are given in Fig. 2 [Figure 2: see original paper] on a logarithmic scale. Changes in density distributions for each isotopic chain occur only in the tail or central region as the proton number remains constant. Since density must be multiplied by $4\pi r^2$ before integration to yield proton number or radii, large changes in the center are less significant. What matters most is the density distribution in the tail region. Compared with neutron-rich isotopes, proton distributions in less neutron-rich nuclei have higher central density, lower density in the intermediate region ($2.5 < r < 4.5$ fm), and a larger tail in the outer region ($r > 4.5$ fm), giving rise to increased r_p and σ_{cc} for proton-rich nuclei as seen below.

The neutron and proton root-mean-square (rms) radii predicted by RCHB for nuclei $^{10-22}$C, $^{12-24}$N, $^{14-26}$O, and $^{16-25}$F are given in Fig. 3 [Figure 3: see original paper]. Neutron radii increase steadily for nuclei in each isotopic chain, while proton radii remain almost constant with neutron number for each chain except for proton-rich nuclei.

To compare charge-changing cross sections σ_{cc} directly with experimental measurements, we use the proton densities $\rho_p(r)$ of the target ^{12}C and the C, N, O, and F isotopes obtained from RCHB (see Fig. 2 [Figure 2: see original paper]). Cross sections are calculated in the Glauber model using free nucleon-nucleon cross sections [?] for protons and neutrons, respectively. The total charge-changing cross sections σ_{cc} for nuclei $^{10-22}$C, $^{12-24}$N, $^{14-26}$O, and $^{16-25}$F on a carbon target at relativistic energies are given in Fig. 4 [Figure 4: see original paper]. Open circles show RCHB combined with Glauber model results, while available experimental data [?] are shown as solid circles with error bars. Agreement between calculated and measured values is excellent.

Charge-changing cross sections vary only slightly with neutron number except for proton-rich nuclei, indicating that proton density plays an important role in determining σ_{cc}. A gradual increase in cross section is observed toward the neutron drip line, though large experimental error bars preclude definitive conclusions. Clearly, RCHB theory combined with the Glauber model provides reliable descriptions of both interaction cross sections and charge-changing cross sections. Comparison of Fig. 4 [Figure 4: see original paper] with Fig. 3 [Figure 3: see original paper] reveals similar trends in the variation of proton radii and charge-changing cross sections for each isotopic chain, again implying that proton density plays an important role in determining charge-changing cross sections.

Summary

In summary, we have systematically studied ground-state properties of C, N, O, and F isotopes using the microscopic RCHB theory, where pairing and blocking effects are treated self-consistently. Calculated one-neutron separation energies S_n agree well with available experimental values, with some exceptions likely due to neglected deformation effects. Glauber model calculations for total charge-changing cross sections using RCHB densities show good agreement with measured cross sections on ^{12}C targets. An important conclusion is that, contrary to common expectation, the proton density distribution is relatively insensitive to the proton-to-neutron ratio, remaining almost unchanged from stability to the neutron drip line. The influence of deformation, neglected in this study, is of interest, and more extensive studies extending to deformed cases are in progress.

This work was partly supported by the Major State Basic Research Development Program under Contract Number G2000077407 and the National Natural Science Foundation of China under Grant Nos. 10025522, 19847002, and 19935030.

References

[1] I. Tanihata, Prog. Part. Nucl. Phys., 35 (1995) 505.
[2] P.G. Hansen, A.S. Jensen, and B. Jonson, Ann. Rev. Nucl. Part. Sci. 45 (1995) 591.
[3] T. Suzuki, et al., Phys. Rev. Lett. 75 (1995) 3241.
[4] J. Meng, I. Tanihata and S. Yamaji, Phys. Lett. B419 (1998) 1.
[5] L.V. Chulkov, et al., Nucl. Phys. A674 (2000) 330.
[6] J. Meng, Nucl. Phys. A635 (1998) 3.
[7] J. Meng, and P. Ring, Phys. Rev. Lett. 77 (1996) 3963.
[8] J. Meng, and P. Ring, Phys. Rev. Lett. 80 (1998) 460.
[9] B.D. Serot and J.D. Walecka, Adv. Nucl. Phys. 16, 1 (1986).
[10] P-G. Reinhard, Rep. Prog. Phys. 52, 439 (1989).
[11] P. Ring, Prog. Part. Nucl. Phys. 37, 193 (1996).
[12] J. Meng, K. Sugawara-Tanabe, S. Yamaji, P. Ring and A. Arima, Phys. Rev. C58 (1998) R628.
[13] J. Meng, K. Sugawara-Tanabe, S. Yamaji and A. Arima, Phys. Rev. C 59 (1999) 154.
[14] J. Meng, and I. Tanihata, Nucl. Phys. A 650 (1999) 176-196.
[15] J. Meng, and N. Takigawa, Phys. Rev. C61 (2000) 064319.
[16] P. Ring and P. Schuck, The Nuclear Many-body Problem, Springer Verlag, Heidelberg (1980).
[17] M. Sharma, M. Nagarajan and P. Ring, Phys. Lett. B312 (1993) 377.
[18] G. Audi, and A.H. Wapstra, Nucl. Phys. A565 (1993) 1.
[19] L. Ray, Phys. Rev. C 20 (1979) 1857.

Figures

[Figure 1: see original paper] The one-neutron separation energies S_n for nuclei $^{11-22}$C, $^{13-24}$N, $^{15-26}$O, and $^{17-25}$F from RCHB theory (open circles) and experiment (solid circles).

[Figure 2: see original paper] The proton density distributions predicted by RCHB for nuclei $^{10-22}$C, $^{12-24}$N, $^{14-26}$O, and $^{16-25}$F on a logarithmic scale.

[Figure 3: see original paper] The neutron and proton rms radii predicted by RCHB for nuclei $^{10-22}$C, $^{12-24}$N, $^{14-26}$O, and $^{16-25}$F.

[Figure 4: see original paper] The total charge-changing cross sections σ_{cc} for nuclei $^{10-22}$C, $^{12-24}$N, $^{14-26}$O, and $^{16-25}$F on a carbon target at relativistic energy. Open circles show RCHB results and solid circles with error bars represent experimental data.

Note: Figure translations are in progress. See original paper for figures.