EPJ Web of Conferences **107**, 08006 (2016)
DOI: 10.1051/epjconf/201610708006

Prediction of reaction cross section for p-Cr

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Abstract. Nuclear matter densities and charge radii for even $^{46-62}$Cr isotopes have been calculated using relativistic Hartree-Bogoliubov model based on density-dependent meson-exchange relativistic energy density functional. The calculated root-mean-square charge radii agree well with corresponding data and the kink at N=28 is reproduced by the calculation. The calculated target matter densities are folded with the Jeukenne, Lejeune, and Mahaux-Bruyéres inter-nucleon interaction to obtain semi-microscopic optical model potentials for incident protons of 65 MeV on even $^{46-62}$Cr isotopes. The elastic scattering differential cross sections calculated using the proton optical potentials reproduce corresponding data for stable isotopes. The optical model potential parameters required for prediction of differential and total reaction cross sections for unstable even isotopes have been obtained.

1 Introduction

The structure and reactions of nuclei close to drip lines and their role in the understanding of nuclear ground state properties has been a topic of experimental and theoretical interest. The total reaction cross section (σ_R) is an important observable and plays a crucial role in both optical and statistical model calculations. A definite correlation exists between nuclear charge radii ($\langle r_c{}^2\rangle^{1/2}$) and σ_R. Knowing $\langle r_c{}^2\rangle^{1/2}$, this correlation can be employed to make predictions of σ_R for nuclei, especially those that lie far from the stability line [1, 2]. Limited experimental information about both $\langle r_c{}^2\rangle^{1/2}$ [3] and σ_R [4] for neutron-deficient and neutron-rich nuclei in the region Z=20 − 28 are available, with most studies having been performed on stable nuclei. If the structure of nuclei involved in the reaction is accurately known, the reactions can be analyzed with scattering theory. The elastic scattering calculation using folding optical model has been known to be successful when radial matter densities are obtained from well-established structure models (relativistic or nonrelativistic) and microscopic, spherical nucleon-nucleus optical model potentials based on different approximations or effective forces are robust [5, 6]. For the predictions to hold, there must be no or few adjustable parameters in the model. Such an analysis would be able to predict the reaction observables successfully. In the present work, nuclear ground-state properties have been calculated for even $^{46-62}$Cr isotopes. The σ_R has been predicted by studying the p-Cr elastic scattering using folding optical model.

The nuclear ground state properties are calculated in the framework of relativistic Hartree-Bogoliubov (RHB) model [7] based on density-dependent meson-exchange (DD-ME2) relativistic energy density functional [8] for even Cr isotopes. The ground state properties are compared to the corresponding available data. The target radial matter densities calculated in RHB framework, have been used in the semi-microscopic optical model to obtain the proton optical potentials for even Cr isotopes. The Jeukenne-Lejeune-Mahaux-Bruyeŕes (JLMB) energy- and density-dependent nucleon-nucleon interaction [9] are folded with the target radial matter densities. The resulting real and imaginary parts of the folded optical potential are used to compute the differential and reaction cross sections for 65 MeV-proton elastic scattering off even $^{46-62}$Cr isotopes.

The RHB model and ingredients required for calculation of nuclear ground state properties as well as results of calculation for even Cr isotopes are included in Sec. 2. A brief description of semi-microscopic folded optical model are presented in Sec. 3. The results of calculation of cross section observables for (p, p) scattering at 65 MeV off even Cr isotopes are also given in the same section.

2 Relativistic Hartree-Bogoliubov model

The RHB model based on self-consistent mean-field and relativistic (covariant) energy density functionals has been effective in explaining nuclear structure over a range of isotopes: stable to drip-line [10, 11]. In RHB model, an effective Lagrangian describes the nucleus as a system of Dirac nucleons which interact by means of electromagnetic fields and meson (isoscalar scalar σ, isoscalar vector ω, and isovector vector ρ) exchange. In the mean-field approximation, meson field operators are replaced by their expectation values in the nuclear ground state. A

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Article available at http://www.epj-conferences.org or http://dx.doi.org/10.1051/epjconf/201610708006

medium dependence required for quantitative treatment of nuclear matter and finite nuclei, has been introduced by assuming a density-dependence for the meson-nucleon couplings. The relativistic density-dependent energy density functional (DD-ME2) [8] that provides a good description has been considered here. The energy density functional parameters for the DD-ME2 set have been obtained by treating the pairing correlations in the Bardeen-Cooper-Schrieffer (BCS) constant-gap approximation with empirical pairing gaps (5-point formula) [7]. The particle-particle channel of the effective nucleon-nucleon interaction is described by a separable finite-range pairing force [7]. The RHB equation is solved in the configuration space of harmonic oscillator wave functions with appropriate symmetry, while the densities are obtained in coordinate space. The wave functions in configuration space are generated by diagonalization of the RHB matrix equation. The density matrix obtained is then transformed to coordinate space, and the resulting vector and scalar densities are used to calculate the potentials. In the case of nuclei with axial symmetry, the solution of the Helmholtz equations for the meson fields is obtained by expanding in a harmonic oscillator basis. The solution of the relativistic mean-field equations are described in Ref. [12]. The calculation has been carried out for describing ground state properties of nuclei and the details are reported in Ref. [1]. In the present work, RHB model [7] combined with the successful DD-ME2 [8] has been employed for the calculation of ground state properties for Cr nuclei, as described below. The calculation is denoted as DIRHB in this article.

2.1 Ground state properties

The nuclear ground state properties such as binding energies, two neutron separation energies, proton, neutron and charge radii as well as matter densities have been calculated for the even $^{46-62}$Cr isotopes and compared with experimental values, where available. The difference between the DIRHB calculated binding energies for even Cr isotopes and the corresponding experimental data [13] is plotted in Fig. 1. The calculated binding energies for even Cr isotopes are found to agree within 1% of the corresponding data. Further, experimental values of two neutron separation energies [13] are reproduced by DIRHB calculations.

The $\langle r_c^2\rangle^{1/2}$ calculated by DIRHB are shown in Fig. 2 for even isotopes of Cr. For comparison, the corresponding spherical droplet model [14] estimates for $\langle r_c^2\rangle^{1/2}$ (normalized to N=28 data) are also shown in Fig. 2. The DIRHB calculated $\langle r_c^2\rangle^{1/2}$ agrees well with the corresponding data [3]. Data for $\langle r_c^2\rangle^{1/2}$ are available only for the stable even isotopes ^{50,52,54}Cr [3]. Both DIRHB calculated and experimental $\langle r_c^2\rangle^{1/2}$ show lower values for ^{52}Cr (N=28), as expected. Calculations have also been carried out for neutron-deficient (^{46,48}Cr) and neutron-rich (^{56,58,60,62}Cr) nuclei. The DIRHB calculation for $\langle r_c^2\rangle^{1/2}$ shows a change of slope at N=30 (^{54}Cr) and then increases smoothly for neutron-rich isotopes. In the neutron-deficient region, both calculation and experiment indicate an increase in $\langle r_c^2\rangle^{1/2}$ as neutrons are removed from N=28, contrary to the decrease expected from the droplet model. It is also seen that as neutrons are removed from closed-shell nuclei, ^{52}Cr, the calculated $\langle r_c^2\rangle^{1/2}$ increases smoothly up to ^{48}Cr followed by a change in slope at N=24. The behavior of $\langle r_c^2\rangle^{1/2}$ in Cr isotopes is similar to that in the Ti isotopic chain [1] and is correlated with change in quadrupole deformation [15]. As expected, DIRHB shows maximum deformation for the mid-shell nucleus, ^{48}Cr. It would be interesting to verify the calculation of nuclear charge radii by performing isotope shift and hyperfine structure measurements using laser spectroscopy for unstable Cr isotopes.

Further, the L=0 projected and renormalised DIRHB point proton and neutron density distributions for even

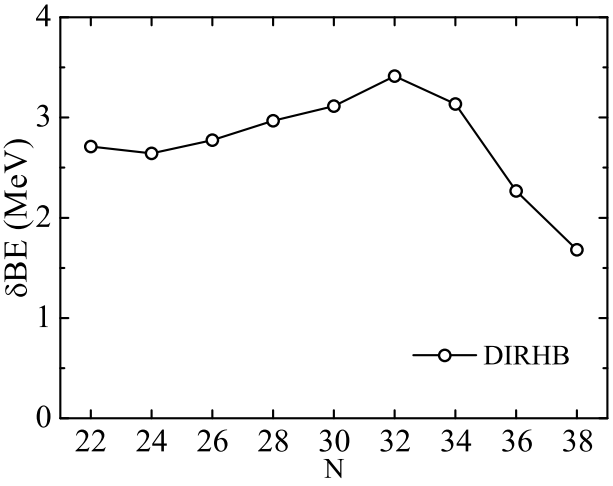

Figure 1. The difference between DIRHB calculated and the corresponding experimental [13] binding energies for even Cr isotopes.

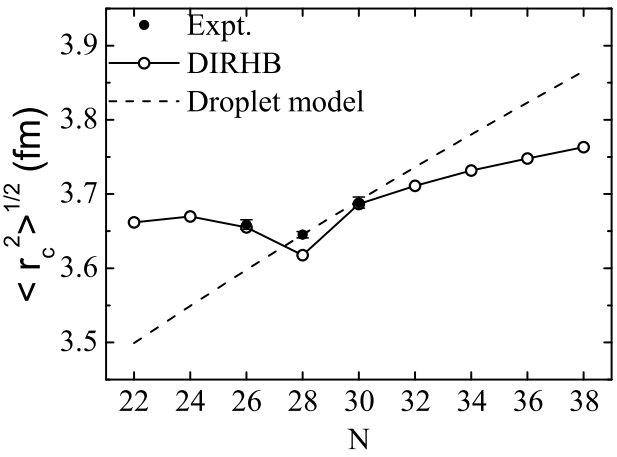

Figure 2. The DIRHB calculated root-mean-square charge radii ($\langle r_c^2\rangle^{1/2}$) for even Cr isotopes. The corresponding data [3] are shown by solid circles. The spherical droplet model estimate (normalized to N=28 data) for even Cr isotopes are shown by dashed lines.

$^{46-62}$Cr are calculated and used as inputs to the semi-microscopic folded optical model calculation as described below.

3 Semi-microscopic Optical Model

It is known that the folding model associates the elastic scattering cross section with the structure of nuclei. There is a definite correlation between $\langle r_c^2\rangle^{1/2}$ and σ_R. Once $\langle r_c^2\rangle^{1/2}$ and nuclear matter density distributions are accurately calculated, the correlation can be utilized to make predictions of σ_R for proton scattering from target nuclei. This is particularly useful for unstable nuclei for which very little information on cross sections are available. For the calculation of cross section for nuclei that lie far from stability, microscopically calculated potentials are effective. An extended semi-microscopic JLM potential [9] derived from Brückner-Hartree-Fock approximation based on Reid's hard core nucleon-nucleon interaction has become available recently. A new parameterization has been obtained and the resulting potential is referred to as JLMB [9]. The JLM interaction is energy- and density-dependent as well as spin-independent in nuclear matter. An improved local density approximation is obtained to make JLM interaction, that is applicable for nuclear matter, usable for finite nuclei. Both the real and imaginary parts of the central potential are obtained in this approach. In JLMB, the deformed complex spin-orbit potential has been calculated phenomenologically [9] in the full Thomas form [9]. Other nucleon-nucleon interactions [16, 17] that are successful and based on different approximations or effective forces can also be used. In the present work, the optical model potential (OMP) is calculated by folding the DIRHB densities with the JLMB interaction using the code MOM (Microscopic Optical Model) [9]. The OMP obtained has the real and imaginary parts of the microscopic central as well as phenomenological spin-orbit potential. These are used in the code ECIS [18] to estimate the differential ($d\sigma/d\Omega$) and reaction cross sections for elastic scattering of protons of 65 MeV incident on even Cr isotopes. The detailed description of the analysis is given in Ref. [1]. In spite of the fact that most of the Cr isotopes considered here, except N=28, are deformed and with evidence of collectivity [19, 20], the coupled channel effects were not required to be considered. This is because these effects are not important for higher proton energies (65 MeV) considered in this work.

3.1 Cross sections

The $d\sigma/d\Omega$ and σ_R values for proton scattering from even Cr isotopes are calculated using the semi-microscopic optical model potential. An overall renormalization is required for the calculated optical model potential to provide a good description of data. Searches on renormalization constants for real and imaginary parts of the central (λ_V and λ_W) and spin-orbit ($\lambda_{V_{so}}$ and $\lambda_{W_{so}}$) potentials were performed to obtain minimum χ^2 values in fitting $d\sigma/d\Omega$ data [21] for stable isotopes. The $\lambda_{W_{so}}$ obtained was negligible for stable isotopes and hence not used in the analysis. To keep the number of parameters in the prediction of σ_R to a minimum, $\lambda_{V_{so}}$ was fixed at 88 (average value for stable isotopes) for all isotopes. Thus, the number of parameters in the prediction of σ_R was reduced to two *viz.*, λ_V and λ_W. A two-parameter search on λ_V and λ_W was carried out with $\lambda_{V_{so}}$=88 fixed, which gave a good fit to

Table 1. Best fit values of renormalization constants for real and imaginary parts of the central (λ_V and λ_W) and real spin-orbit ($\lambda_{V_{so}}$) potentials, for protons of 65 MeV elastic scattering from stable even Cr isotopes. The corresponding total reaction cross sections (σ_R) are also given.

A	λ_V	λ_W	$\lambda_{V_{so}}$	$\sigma_R^{calculated}$ (mb)
50	0.88	0.70	88	741
52	0.98	0.98	88	810
54	0.84	0.70	88	826

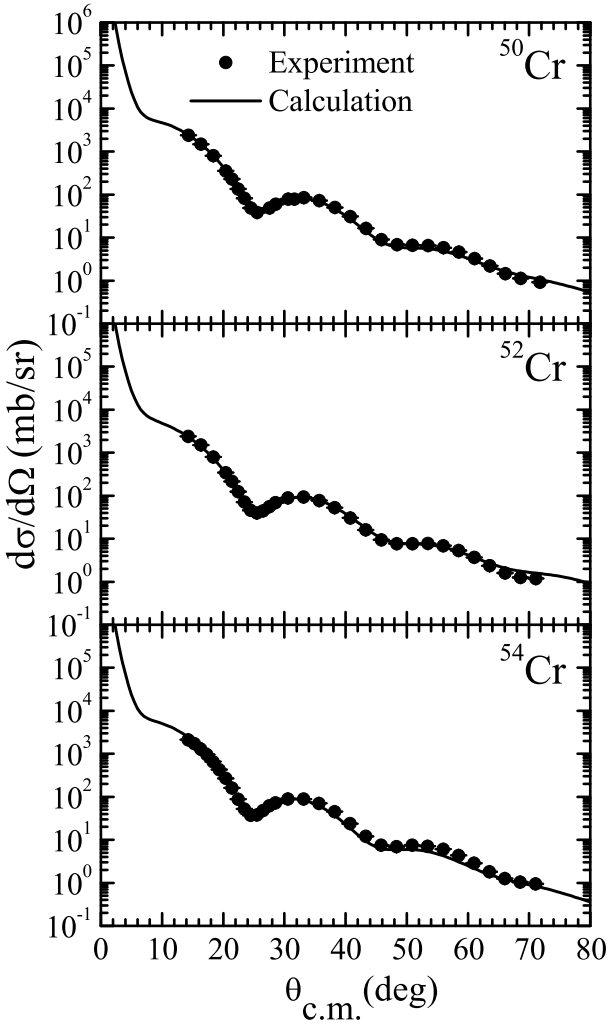

Figure 3. The elastic scattering differential cross section ($d\sigma/d\Omega$) calculated using the best fit values of λ_V, λ_W and $\lambda_{V_{so}}$, for protons with incident energy of 65 MeV scattering from stable even Cr isotopes. The corresponding data [21] are also plotted.

the $d\sigma/d\Omega$ data [21]. These values of λ_V and λ_W, with $\lambda_{V_{so}}$=88, are referred to as best fit values and are given in Table 1. The λ_V values obtained for all even stable isotopes have a small A dependence. For the closed-shell nucleus ^{52}Cr, λ_V and λ_W are close to unity. The calculated elastic scattering differential cross section for protons of 65 MeV incident on stable even Cr nuclei are plotted in Fig. 3. It is seen clearly from the figure that the calculated $d\sigma/d\Omega$ agree quite well with the data [21]. The calculated $d\sigma/d\Omega$ shapes have similar behavior for all stable isotopes. The minima in $d\sigma/d\Omega$ are shifted slightly to lower angles with the increase in neutron number. The corresponding calculated σ_R obtained from the best fit analysis for stable Cr isotopes are given in Table 1. It is seen that the calculated σ_R increases as a function of mass number, as expected. There are no measured values of σ_R for protons of incident energy 65 MeV scattering off stable and unstable Cr nuclei. The present prediction can be verified by performing cross-section measurements in inverse kinematics for unstable nuclei with Cr isotopes as projectiles and an hydrogen target in available radioactive ion-beam facilities.

To make predictions of $d\sigma/d\Omega$ and σ_R for unstable isotopes, a least-squares fit needs to be carried out for λ_V and λ_W as a function of A for stable isotopes. The variation of λ_V and λ_W obtained from best fit for stable isotopes exhibit a dependence on A. These renormalization constants are then extrapolated and are used for calculation of $d\sigma/d\Omega$ and σ_R for neutron-deficient and neutron-rich isotopes.

4 Summary

Nuclear ground state properties such as binding energies, two neutron separation energies, proton, neutron and charge radii as well as matter densities have been calculated within RHB approach using DD-ME2 interaction, for the even $^{46-62}$Cr. The DIRHB calculations agree well with data, where available. Both calculation and experiment show a kink in $\langle r_c^2\rangle^{1/2}$ at the N=28 shell closure. Prediction of $\langle r_c^2\rangle^{1/2}$ are made for neutron-deficient and neutron-rich Cr isotopes. Using calculated target matter densities and JLMB interaction, a folding model analysis has been carried out. Resulting OMPs are used to calculate cross sections for 65 MeV-protons scattering from even $^{46-62}$Cr isotopes. The elastic scattering $d\sigma/d\Omega$ show good agreement with data. The OMP parameters that are required for prediction of $d\sigma/d\Omega$ and σ_R for unstable even isotopes have been obtained. The correlation between nuclear charge radius and total reaction cross section has been utilized to make predictions of σ_R for stable and unstable Cr isotopes.

Acknowledgements

M.H. wishes to express gratitude to Profs. T. Nikšić and D. Vretenar for guidance in the calculation of nuclear ground state properties. S.K. acknowledges support by Raja Ramanna fellowship from Department of Atomic Energy, Government of India.

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