Nuclear halo structure from quasielastic charge-exchange reactions *

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Neutron and proton densities in the nuclear periphery are investigated within (p,n) charge-exchange isobar transitions. For this purpose we have developed parameter-free optical potentials [1)] with a detailed treatment of the *in-medium* t_τ part of the effective interaction. Non local coupled-channel Lane equations are solved to obtain the scattering observables. The use of conventional proton and neutron densities significantly underestimates Fermi (forward-angle) cross-sections in agreement with findings by various other groups. However, we have found model-independent densities which provide a remarkable improvement in the description of the quasielastic scattering data. The densities obtained are consistent with recent measurements at CERN in studies of the neutron-to-proton halo factor f(r)=$Z\rho_n/N\rho_p$ with antiprotons [2)]. These findings provide an alternative way to investigate the nuclear periphery, and may also help to solve the long-standing puzzle of the underestimated Fermi cross section in (p,n) charge-exchange phenomena.

1. INTRODUCTION

An issue of prominent interest in recent nuclear research has been the formation of neutron halo structures in various neutron-rich nuclei. Due to its nature, this phenomenon is a clear manifestation of the isospin degrees of freedom of the interacting nucleons in the nuclear medium. Since the nucleon-nucleon interaction discriminates among the different isospin states of the two nucleon system, its use within an *in-medium* microscopic approach for nucleon-nucleus collisions serves as a means to explore the proton and neutron densities of the target ground state. In particular, (p,n) charge-exchange reactions provide a rich and interesting arena for exploring neutron-to-proton density differences.

The study of (p,n) charge-exchange reactions in the intermediate energy range has been a subject of considerable attention during the past two decades. These reactions are of great value in understanding the isovector modes of excitations of the nucleus. At beam energies above 100 MeV, nucleon charge-exchange reactions can be considered as a one step process thus allowing a rather clean separation of the nuclear structure

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from the underlying nucleon-nucleon effective interaction. In spite of these advantageous considerations, no microcopic effort has been able to satisfactorily describe the differential cross-section data without phenomenological adjustments *a posteriori*[1].

2. FRAMEWORK

The optical potential for nucleon scattering and charge-exchange reactions may be written in momentum space as:

$$\langle \mathbf{k}'\nu'\mu' \mid U \mid \mathbf{k}\nu\mu\rangle = \sum_{m,m',n,n'} \int\int d\mathbf{p}' d\mathbf{p} \langle F \mid \psi^\dagger_{\frac{1}{2}m',\frac{1}{2}n'}(\mathbf{p}')\overline{\psi}_{\frac{1}{2}m,\frac{1}{2}n}(\mathbf{p}) \mid I\rangle \langle \mathbf{p}'m'n', \mathbf{k}'\nu'\mu' \mid t \mid \mathbf{p}\,m\,n, \mathbf{k}\,\nu\,\mu\rangle_A . \tag{1}$$

Here t is the NN t-matrix; ν and μ denote the initial spin and isospin projections of the projectile and

$\overline{\psi}_{\frac{1}{2}m,\frac{1}{2}n}(\mathbf{p}) = (-)^{\frac{1}{2}-m+\frac{1}{2}-n}\psi_{\frac{1}{2}-m,\frac{1}{2}-n}(\mathbf{p})$

where $\psi_{\frac{1}{2}-m,\frac{1}{2}-n}(\mathbf{p})$ annihilates a nucleon with momentum $\mathbf{p}$ and spin and isospin projections $-m$ and $-n$ respectively. The choice of the pair (μ,μ') is determined by the reaction being considered.

Our study focuses on quasielastic scatering to the isobaric analog state. Considering explicitly the isospin degrees of freedom for the scattering waves in the form of outgoing proton and neutron wavefunctions, we obtain a non-local version of the coupled-channel Lane equations for incoming protons,

$$\begin{pmatrix} \Psi_p \\ \Psi_n \end{pmatrix} = \begin{pmatrix} \phi_p \\ 0 \end{pmatrix} + \begin{bmatrix} G_p U^{(s)}_{pp} & G_p U_{px} \\ G_n U_{nx} & G_n U_{nn} \end{bmatrix} \begin{pmatrix} \Psi_p \\ \Psi_n \end{pmatrix} . \tag{2}$$

Here we denote by G_p (G_n) the Green functions for charged (uncharged) outgoing particles. Furthermore, U^s_{pp} represents a short-range interaction where the point-Coulomb interaction has been subtracted from the hadronic-plus-Coulomb contribution, i.e. $U^{(s)}_{pp} = (U_H + U_{Ch}) - U_{Pt}$. This coupled-channel integral equation is solved using standard numerical methods. The primary input in these equations is the optical potential which we obtain following a current version of the full-folding optical model approach to nucleon scattering [2,3]. Here we account thoroughly for the Fermi motion of the target nucleons. The effective interaction in the form of isospin-symmetric nuclear matter g matrix, is treated fully off-shell. An essential ingredient in these parameter-free constructions is the nuclear density of the target. However, intermediate-energy applications for ^{48}Ca(p,n) and ^{90}Zr(p,n) substantially underestimate the Fermi cross section, with only marginal differences in the scattering observables when considering conventional alternative representations of the nuclear densities.

3. APPLICATIONS AND CONCLUSIONS

In order to explore this difficulty we have devised model-independent densities which, once folded with the *in-medium* effective interactions, generate an optical potential. These model-independent representations of the density have the general form

$$\rho_{p,n}(r) = \rho^\circ_{p,n}(r)(1 + \tfrac{1}{2}\xi_{p,n}(r))^2 , \tag{3}$$

where $\rho^{\circ}_{p,n}(r)$ is a reference density taken from a reasonable model (3pF, 3pG, etc.) and $\xi_{p,n}(r)$ is a dressing function constructed from an N-knot spline. The value of ξ at each of the selected knots becomes a searchable parameter. We have allowed variations of both proton and neutron densities in order to fit in the best possible way the measured cross sections from quasielastic charge-exchange experiments. For physical consistency we have constrained the full proton densities to the measured charge r.m.s radius from electron scattering experiments (and the volume integrals of ρ_n and ρ_p to give N and Z respectively).

In Fig. 1 we show results for the iterative search in the case of ^{48}Ca(p,n) at 160 MeV.

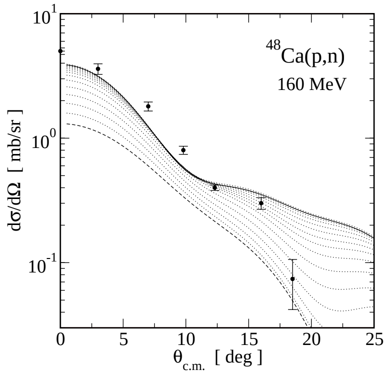

Figure 1. Differential cross-section for ^{48}Ca(p,n) quasielastic scattering at 160 MeV. The data are taken from Ref. [4]. The solid curve corresponds to the last iteration.

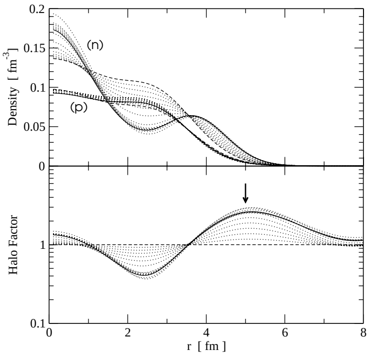

Figure 2. Evolution of the proton (p) and neutron (n) point densities (upper frame), and halo factor (lower frame) in search of the best fit of the measured forward-angle differential cross section. Results from the last iteration are shown with solid curves.

Each curve represents the calculated differential cross-section for a given density. In Fig. 2 we represent the corresponding proton (p) and neutron (n) densities, and respective halo factor defined as $f(r) = Z\rho_n(r)/N\rho_p(r)$. It is interesting to observe the manifestation of a halo structure at a distance near 4 fm. Indeed, a close examination of the obtained results indicates a peripheral halo factor of 2.3, in good agreement with values reported in Ref. [5]. Another quantity of interest in the characterization of neutron halos is the nuclear skin, defined as the difference between the neutron and proton r.m.s. radii. We obtain 0.52 fm for this quantity, which is much larger than conventional reported values.

Here we have focused on variations in the proton and neutron densities; a closer examination of these results may require additional constraints from the elastic channel, a closer scrutiny of the isovector strength and/or the inclusion of higher order effects such as asymmetric nuclear matter effective interactions.

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