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One-neutron halo structure by the ratio method

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ABSTRACT

We present a new observable to study halo nuclei. This new observable is a particular *ratio* of angular distributions for elastic breakup and scattering. For one-neutron halo nuclei, it is shown to be independent of the reaction mechanism and to provide significant information about the structure of the projectile, including binding energy, partial-wave configuration, and radial wave function of the halo. This observable offers new capabilities for the study of nuclear structure far from stability.

Nuclear halos are one of the most striking phenomena revealed through the study of extreme states of matter. Their discovery became possible through the development of radioactive beams in the mid 80s [1]. Measured reaction cross sections along an isotopic chain are seen to increase dramatically as the limits of stability are approached as compared with more bound neighboring isotopes. This observation implies that near the end of an isotopic chain (the drip-line), where the neutron number is much larger than the proton number, adding one or two neutrons to a well-bound core may produce a nucleus with a radius much larger than that of its core, suggesting a halo picture for these valence neutrons [2,3].

The halo phenomenon is believed to arise from the combination of a very low separation energy of the valence particles and the absence of a strong repulsive barrier. For example, this may appear for neutrons loosely bound to a core in an *s* orbital. The result is a highly delocalized wave function and a considerable probability of finding the valence particles outside the range of their binding interaction to the core, well into the classically forbidden region. It is less likely to find nuclear halos on the proton drip-line or in orbitals involving large angular momentum, as the Coulomb or centrifugal barriers hinder the development of the extended wave function. Halo structures have also been observed experimentally in other fields such as atomic and molecular physics [4]. Extreme examples of halo states are Efimov states, an area generating intense activity in molecular physics [5].

These qualitative features of halo states are fairly well established, but ever since the discovery of halo nuclei [1], it has been a challenge to reconcile this picture with the strongly interacting many-fermion structure of real nuclei. On the experimental side much of the difficulty arises because halo nuclei tend to be unstable against the weak interaction and therefore cannot be prepared as a target. Plans are being made to use electron scattering from trapped radioactive ions [6] or from a beam [7] of these exotic species to measure their charge distribution. So far all the available evidence for their structure is obtained indirectly mostly through the measurements of nuclear reactions, such as breakup [8], elastic scattering [9], or knockout [10].

Collisions between a one-neutron halo nucleus and a target can be described as three-body processes in which a projectile P, seen as a valence neutron n loosely bound to a core c, impinges on a target T. Various theoretical models have been developed to solve the corresponding Schrödinger equation (see Ref. [11] for a review). These models have improved our understanding of the reaction process. They have shown that the mechanisms involved in collisions of loosely-bound nuclei are more complex than initially thought and that extracting information about nuclear structure from reaction measurements is not as straightforward as hoped [12]. Moreover, reaction calculations depend on optical potentials, which describe the interaction between the projectile

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constituents and the target. These potentials are often unknown. This is especially true for the interaction of the core and the target as there exist little—if any—data to constrain this potential, the core being usually itself radioactive. The uncertainties related to the choice of these potentials hinder the quantitative analysis of experimental data [13]. An observable that is less dependent on the reaction process and that reveals more information about the structure of the projectile is clearly needed. In this Letter, we present such an observable.

In this framework, the structure of the projectile is described by the internal Hamiltonian

$$H_0 = \frac{p^2}{2\mu_{cn}} + V_{cn}(\mathbf{r}), \tag{1}$$

where μ_{cn} is the c-n reduced mass, $\mathbf{r}$ is the relative c-n coordinate, and $\mathbf{p}$ the corresponding momentum. The c-n potential V_{cn} is adjusted to reproduce properties of the projectile, such as its binding energy and some of its excited levels. In partial wave ljm, the eigenstates of H_0 of energy E are denoted by $\phi_{ljm}(E)$ (l is the c-n orbital angular momentum, j is the total angular momentum resulting from the coupling of l with the neutron spin, and m is the projection of j). For $E < 0$ they are normed to unity and correspond to bound states of the projectile. For $E > 0$, they describe the continuum spectrum, i.e. the projectile broken up into c and n. They are normalized as $\langle \phi_{ljm}(E) \mid \phi_{l'j'm'}(E')\rangle = \delta_{ll'}\delta_{jj'}\delta_{mm'}\delta(E-E')$. The interactions of the projectile fragments c and n with the target are simulated by the optical potentials V_{cT} and V_{nT}, respectively. Within this framework the study of reactions involving one-neutron halo nuclei reduces to solving the three-body Schrödinger equation with Hamiltonian

$$H = \frac{P^2}{2\mu} + H_0 + V_{cT}\left(\mathbf{R} - \frac{m_n}{m_P}\mathbf{r}\right) + V_{nT}\left(\mathbf{R} + \frac{m_c}{m_P}\mathbf{r}\right), \tag{2}$$

where μ is the P-T reduced mass, m_n is the mass of the valence neutron, and m_c that of the core ($m_P = m_c + m_n$). Variable $\mathbf{R}$ is the P-T relative coordinate and $\mathbf{P}$ the corresponding momentum. The Schrödinger equation corresponding to Hamiltonian (2) must be solved with the condition that the impinging projectile is initially in its ground state ϕ_0.

Recently, within the dynamical eikonal approximation (DEA) [14,15,11], angular distributions for the elastic scattering and elastic breakup of one-neutron halo nuclei have been studied [16]. This analysis shows that both processes exhibit very similar features, suggesting that the loosely-bound projectile is scattered similarly whether it remains in its ground state or is broken up. This result can be explained within the Recoil Excitation and Breakup (REB) model [17,18]. In this model, a simple solution of the three-body Schrödinger equation is obtained by neglecting V_{nT} and the excitation energy of the projectile (i.e. using the adiabatic—or sudden—approximation). In the REB limit the elastic-scattering cross section in direction $\Omega = (\theta, \phi)$ in the P-T center-of-mass rest frame is exactly factorized into the product of an elastic-scattering cross section for a pointlike projectile $(d\sigma/d\Omega)_{pt}$ and a form factor describing the extension of the halo [17,18].

The REB model can also describe the angular distributions for excitation of the projectile to any of its states [18,19]. The corresponding cross sections also factorize into a reaction-dynamics part and a projectile-structure part. In particular, this can be performed for the breakup of the projectile, i.e. its excitation at an energy E in the c-n continuum with its center of mass scattered in direction Ω. To the extent that the small difference in magnitude between the outgoing momenta for elastic scattering and breakup can be neglected, the pointlike cross section $(d\sigma/d\Omega)_{pt}$ is identical in the expression of both processes. This particular feature explains why the angular distributions for elastic scattering and breakup are so similar [16]. It also leads to the main new idea introduced here. It is exactly $(d\sigma/d\Omega)_{pt}$ that contains the undesired dependence on the P-T relative motion and its sensitivity to V_{cT}. Therefore, a ratio of breakup to elastic-scattering angular distributions would naturally remove this dependence and provide information pertaining only to the halo structure. In addition, this observable, being the ratio of two cross sections, would not depend on their absolute normalizations, which is particularly attractive from an experimental point of view.

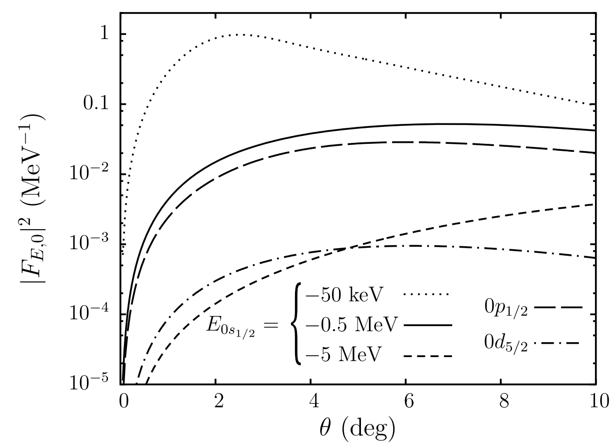

Fig. 1. Form factor $|F_{E,0}|^2$ for ^{11}Be impinging on Pb at 69 MeV/nucleon. Its sensitivity to the projectile binding energy and partial-wave configuration is illustrated.

The same factorization is obtained for the ratio of any linear combination of angular distributions. We have found it optimal to consider the ratio of the angular distribution for elastic breakup at one definite c-n relative energy E, to the sum of the angular distributions for elastic and inelastic scattering and for elastic breakup at all c-n energies

$$\frac{d\sigma_{sum}}{d\Omega} = \frac{d\sigma_{el}}{d\Omega} + \frac{d\sigma_{inel}}{d\Omega} + \int \frac{d^2\sigma_{bu}}{dE\,d\Omega}\,dE. \tag{3}$$

Using the closure relation for the states of the projectile, this ratio is approximated at the REB limit by

$$\left(\frac{d^2\sigma_{bu}/dE\,d\Omega}{d\sigma_{sum}/d\Omega}\right)_{REB} = \left|F_{E,0}(\mathbf{Q})\right|^2, \tag{4}$$

where the form factor reads

$$|F_{E,0}|^2 = \sum_{ljm}\left|\int \phi_{ljm}(E,\mathbf{r})\phi_0(\mathbf{r})e^{i\mathbf{Q}\cdot\mathbf{r}}\,d\mathbf{r}\right|^2, \tag{5}$$

with $\mathbf{Q} = (m_n/m_P)(\mathbf{K} - \mathbf{K}')$ corresponding to the fraction m_n/m_P of the momentum transferred from the incoming $\hbar\mathbf{K}$ to the outgoing $\hbar\mathbf{K}'$ momenta between the center of mass of the c-n pair and the target. We show below by comparison with more exact calculations that the REB approximations can be justified in realistic cases. Assuming this temporarily we discuss the structure information that can be extracted from $|F_{E,0}|^2$.

To illustrate the general properties of $|F_{E,0}|^2$, we consider ^{11}Be as a projectile. Reactions involving this archetypal one-neutron halo nucleus have been extensively studied both theoretically and experimentally. In particular its angular distributions for breakup on Pb and C targets have been precisely measured at about 70 MeV/nucleon [20]. Figs. 1 and 2 depict $|F_{E,0}|^2$ at $E = 0.1$ MeV for ^{11}Be impinging on lead at 69 MeV/nucleon as a function of the azimuthal angle θ up to 10°. The form factor (5) is initially computed for the c-n potential developed in Ref. [13], in which the