Radii of Halo States in Light Nuclei Deduced from Their Asymptotic Behavior

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Much effort has been dedicated in recent years to the study of nuclei away from the valley of beta stability. A very interesting and puzzling phenomenon was the discovery of halo nuclei [1]. Presently, a definition of what precisely constitutes a halo nucleus does not exist, but a common characterization is that their structure is dominated by the last one (or two) nucleon(s) with a spatial distribution which is much larger than that of the nuclear matter distribution of the core. A common cause for a large spatial extent of the last nucleon is small binding energy, but Coulomb and centrifugal barriers are known to matter, and for some time there were even questions about possible unknown factors contributing to their unique structure, in particular after the discovery of two-neutron halo nuclei like ^{11}Li and ^{14}Be.

There are several ways to measure the spatial extent of these nuclear states, not all of them entirely equivalent. Two important characteristics of halo states are their increased interaction cross-sections (manifestation of an increased nuclear matter distribution) and the narrow momentum distributions of the last nucleon. The first type of measurements determine the halo radii from differences in the total reaction cross section between neighboring nuclei. As such they might be too inclusive, and less sensitive to the details of the halo states. For the second type of measurements, where the widths of the measured parallel momentum distributions are related to the size of the spatial wave function of the last nucleon, complications arise from the reaction model used, and therefore, most of these determinations of nuclear radii are model dependent.

Last year we proposed to use the asymptotic behavior of the outermost nucleon to determine the radii of halo states. The experimental asymptotic normalization coefficient (ANC) specifying the amplitude of the tail of the ^{8}B many-body wave function projected on the two body channel ^{7}Be+p, determined from transfer reactions [2], was used to calculate the rms radius for the ground state of ^{8}B [3] and it was shown to be a proton halo nucleus. We showed that for the case of halo nuclear states, the asymptotic region has the dominant contribution to observables favoring large distances from the core, like the mean square radius, and that therefore, the ANC is the quantity that can be best extracted from experiment and is the most relevant. In particular, we have shown that the use of the ANC gives a reliable and model independent experimental value for the rms radius of the ^{8}B halo. We also have used the technique to determine the radii of halo states in ^{13}C and ^{17}F [4]. The results do not depend on particular assumptions made about the configuration of the states, or on the shape or the parameters of the core-proton potentials, nor even on the assumption that such a potential (mean field) description is valid in the interior of the nucleus. This might become particularly important for light nuclei in which cluster phenomena are important, and for nuclei close to the drip lines, where major uncertainties about the mean field approach exist. This was due both to the large radial extent of the halo states and to the nature of the operator that favors contributions from larger distances.

We have applied the same procedure described above to a variety of nuclei. To see the influence of the three factors determining the halos we selected several nuclear states for which the ANC is known or can be determined from breakup or transfer reactions and determined their rms radii. These are either proton or neutron states, have different nucleon binding energies, different centrifugal barriers (*s, p* or *d* states) and different Coulomb barriers. The states under consideration are in the light nuclei ^{8}B, ^{17}F, ^{17}O, ^{11}Be, ^{13}C, ^{15}C, and ^{21}Na. First the ANCs were extracted from available one-nucleon transfer or breakup data. Then the same technique was applied to obtain the rms radii for the states under consideration. Most of the states are produced by the $2s_{1/2}$ orbital. When appropriate, the contribution of admixtures from other orbitals (mostly $1d_{5/2}$ for the nuclei here) was included, but not explicitly shown in Table I.

The halo rms radii (size of the orbital of the last nucleon) are compared for situations like:

^{8}B - proton state (Coulomb barrier), *p*-wave (centrifugal barrier), S_p=137 keV; ^{13}C* - neutron state, *s*-wave (no Coulomb, no centrifugal barrier), but larger binding: S_n=1,857 keV; ^{17}F - proton states (larger Coulomb), both *d* and *s*-wave (g.s. and first excited state, respectively) and smaller binding energy (S*p*=600 and 105 keV); ^{17}O 1/2^{+} - neutron state (no Coulomb barrier), *s*-wave (no centrifugal barrier), but better bound; ^{21}Na* 1/2^{+} - proton state (larger Coulomb barrier), no centrifugal barrier, but very small binding energy.

A detailed discussion of these results will be published.

Table I: Halo radii deduced from ANC.

Nucl	orbital	$S_{p(n)}$ (MeV)	C^2 (fm^{-1})	Ref.	r_h (fm)
^{8}B	$\pi 1p_{3/2}$	0.137	0.449(46)	2	4.18(22)
^{11}Be	$\nu 2s_{1/2}$	0.504	0.505(6)	5	6.26(46)
^{14}B	$\nu 2s_{1/2}$	0.970	1.09(2)	6	5.46(26)
^{13}C*	$\nu 2s_{1/2}$	1.857	3.65(49)	7	5.10(38)
^{15}C	$\nu 2s_{1/2}$	1.218	1.48(18)	8,9	5.62(68)
^{17}O*	$\nu 2s_{1/2}$	3.272	7.78	10	4.24
^{17}F	$\pi 1d_{5/2}$	0.600	1.08(10)	11	4.45(42)
^{17}F*	$\pi 2s_{1/2}$	0.105	6480(680)	11	5.56(33)
^{21}Na*	$\pi 2s_{1/2}$	0.007	6.8e33	12	5.12(38)

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