Michigan State University

National Superconducting Cyclotron Laboratory

STRUCTURE AND REACTIONS OF DRIP-LINE NUCLEI

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P. G. HANSEN

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P.G. Hansen
National Superconducting Cyclotron Laboratory
and
Department of Physics and Astronomy
Michigan State University, East Lansing MI 48824-1322

1. Introduction

Secondary radioactive beams produced at intermediate-energy heavy-ion accelerators have in a short time span added a new dimension to the research on nuclear species at the limits of particle stability, and new detection techniques have made it possible to study reactions caused by incident beams of as little as one particle per second. Imminent developments such as the M.S.U. Coupled-Cyclotron Facility [1] are expected to extend the range and to permit the observation of many previously inaccessible species. For a perspective on the progress in this area we only need to go about fifteen years back to a time when it had just become possible to study the radioactivity of rare nuclear species such as ^{11}Li. In presenting early experiments with secondary beams produced in fragmentation James Symons [2] said "... In the introduction to this paper we questioned the applicability of high-energy heavy-ion accelerators to this field. Our experience at the Bevalac leads us to believe that this question does indeed have a positive answer. If the physics interest justifies it, then high-energy heavy-ion beams can certainly be expected to play a role in the study of nuclei at the limits of stability." At the time, very few, if any, realized how prophetic this remark was.

In the present paper the interpretation of the longitudinal-momentum distributions from the nuclear fragmentation of single-nucleon halos is discussed. It is pointed out that these measurements, at least for the cases studied so far, directly reflect the halo wave function, and that there is no direct contribution from the reaction mechanism. This is an important difference from the radial momentum distributions, for which diffractive processes play an important role.

Let me mention in passing that while final-state interactions seem relatively unimportant for the cases to be discussed in the following, they are essential for understanding the continuum states in ^{10}Li. The latter are, in turn, the key to understanding the three-body system ^{11}Li. The importance of this aspect was first identified by Barranco et al. [3], and the influence of both nn and n-^{9}Li final-state interactions has been the subject of an interesting series of papers by Garrido et al. [4].

2. Stripping and Diffraction Dissociation of Nuclear Halos

It has commonly been assumed that the longitudinal momentum distributions of the core fragment in reactions such as (^{11}Be, ^{10}Be) and (^{8}B, ^{7}Be) on light targets represented the true momentum distribution of the halo state. This would imply that experiments on a single-nucleon halo measured the square of the Fourier transform of the total wave function. A series of papers [5-10] have now shown that the information actually obtained is more specific and, in fact, more interesting. The essential point is that the reactions that remove the halo nucleon can only sample the halo proper, i.e. the region of space outside of the nuclear core. The core-target collisions at small impact parameters lead to other exit channels, mainly complex fragmentation reactions. When this geometrical selection is taken into account, the calculations agree well with the measured [11-13] momentum widths and cross sections.

Owing to a number of favorable circumstances, the analysis of dissociation reactions of halo states is much simpler than that of the more familiar deep-inelastic reactions of other intermediate-energy ions. First of all, the weakly bound and spatially extended halo states can be approximated by a wave function ψ_0 based on a single-particle potential-well model. The reactions producing a fast core fragment have contributions from two reaction channels, and because the beam velocity is much higher than that of the halo nucleon, both can be treated in the sudden approximation. In the first channel, referred to as nucleon stripping (or absorption), the halo nucleon has interacted strongly with the target and disappears from the beam. In the second channel, referred to as diffraction dissociation, the nucleon and the core fragment move forward with essentially beam velocity.

The high projectile energies, 0.5-12 GeV, imply that the collision may be described in terms of a classical impact parameter, so that the dissociation reactions are characteristic of impact parameters greater than $b_{min}=R_C+R_A$, defined as the sum of the (energy-dependent) core and target interaction radii. The high energy also means that the eikonal approximation is applicable, so that the target trajectory is a straight line and the range of the nuclear interaction (which does not have to be weak) is of the order of the target radius R_a. The result is that the wave function of the halo state remains unchanged throughout all space except for a region corresponding roughly to a cylinder of radius R_a The more detailed dependence is taken into account by the choice of the profile function, but the results [5-10] are not strongly dependent on the details and they agree well with each other and with experiments.

3. Results for Parallel-Momentum Distributions

As a transparent illustration [5] we cite here a simple model valid for large target radii. In this, the profile function is approximated by a planar cut-off parallel to the beam direction and tangential to the target surface, a model originally due to Glauber. Assume further that the total spatial wave function appropriate for a halo neutron in an s state is a Yukawa, so that the corresponding intrinsic momentum distribution along the z axis is a one-dimensional Lorentzian

$$\frac{dW}{dp_z} = \frac{\Gamma}{2\pi}\frac{1}{(\Gamma^2/4 + p_z^2)}$$

where the width $\Gamma=(8\mu S_n)^{1/2}$ is defined in terms of the reduced mass and the neutron separation energy. Exploiting that the Fourier transform of the severed wave function can be expressed analytically [14], it is found after integration over the x and y momentum components that the momentum distribution in the z direction equals the intrinsic one given above multiplied by the correction factor

$$C_1(w) = \frac{1}{2}\int_0^{\pi/2} \cos(\vartheta)\exp\left[-2w/\cos(\vartheta)\right] d\vartheta$$

where the parameter is defined as $w = b_l(\Gamma^2/4+p_z^2)^{1/2}/\hbar$, expressed in terms of the distance b_l from the center of the halo system to the cutoff plane. The usual definition of the impact parameter corresponds to $b=R_T+b_l$, where R_T is the effective target radius. For the value of $b_l = 0$ (not realizable in experiments) half of the halo wave function would be removed and the distribution would be unchanged in shape. The actual minimum value of b_l is given by the core radius, about 2.5 fm, and larger values of the impact parameter lead to increasingly narrow distributions. For the case of ^{11}Be there is good agreement the experimental findings, essentially for two reasons, (i) the Yukawa is, apart from a normalization factor, identical to the exact solution in the region sampled, and (ii) the target radius is comparable to the decay length of the wave function.

A better approximation [8], exact for small target radii, is to assume that the wave function inside the reaction zone may be replaced by its value along the axis of the target trajectory as seen from the halo's coordinate system. For neutron halos this approximation leads to convenient analytical expressions. The corresponding momentum distributions for halo protons were calculated numerically with a Woods-Saxon single-particle wave functions In both cases the differential cross sections can be estimated by integrating over impact parameter. Results obtained with this model are shown in Fig. 1. For the case of ^{11}Be there is good agreement between the experimental parallel momentum width [11] and the calculation. In view of the strong dependence on impact parameter that underlies this result, it must be considered a numerical coincidence that the distribution corresponding to the total wave function has a very similar width. This is underscored by the fact that the plateau at 80-160 MeV/c is entirely absent in the momentum distribution of the localized wave function. To see why this is so, we note that the high momentum components in the wave function in momentum space are the counterpart of the inner lobe peaking at 0.7 fm in the spatial wave function. This is a region of space that is not sampled in the experiment. For the case of ^{11}Be, the absence of an outer plateau is presumably too weak an effect to be observable, but it is likely that it could be discernible in the momentum distributions from stripping of *s*-state proton halos in the light phosphorus isotopes [15].

For the case of ^{8}B, the calculated intrinsic parallel-momentum width corresponding to the total wave function is 153 MeV/c. The calculated value of 75 MeV/c obtained when the selection due to localization [8] is taken into account agrees well with the experimental value [12] of 81±6 MeV/c. The apparent discrepancy between the widths of the total momentum distribution and that of the experiment originally led to the claim [12] that an interpretation in terms of single particle model was not possible.

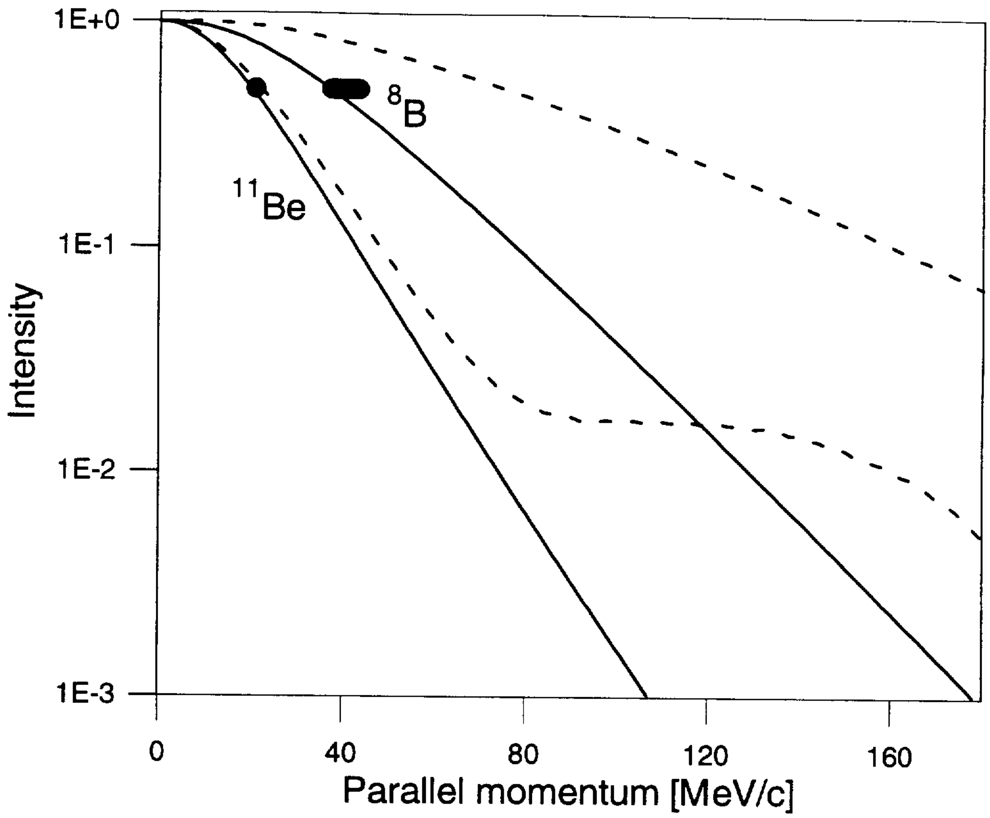

Fig. 1

The parallel momentum distributions of the core fragment from the single-nucleon stripping reactions of ^{11}Be ($s_{1/2}$ ground state) and ^{8}B ($p_{1/2}$ ground state). The dashed lines are those of the total momentum wave functions and the full-drawn lines correspond to the external spatial part selected in the stripping reaction. The shaded areas are the measured [11,12] values of the half width at half maximum.

The experiments underlying Fig. 1 do not distinguish the stripping and diffraction-dissociation mechanisms and analyses such as the two sketched above assume that the final-state interaction between the nucleon and the core fragment is negligible. Hencken et al. [10] find that this is indeed a valid approximation for ^{11}Be, for which a similar conclusion was reached in Coulomb-excitation experiments [14], where plane-wave and Woods-Saxon final states gave almost identical results. On the other hand, Barranco et al. [9] using a simpler model for ^{11}Be find that the final-state interactions increase the full width at half maximum of the parallel-momentum distribution to 79 MeV/c for diffraction dissociation as compared with 49 MeV/c for the stripping reaction.

An independent verification of the estimates given here is provided by the measured cross sections. The calculated ^{11}Be cross section of 316 mb at 41 MeV/u is roughly one third of the free-nucleon value and agrees well with the experimental value [14] of 290±40 mb. The ^{8}B cross sections are calculated as 111 mb at 40 MeV/u and 54 mb at 1471 MeV/u are roughly one tenth of the free-nucleon values and are qualitatively in good agreement with the measured [16,12] values of 80±15 and 94±4 mb, respectively. The overall agreement must be considered satisfactory, but it is probably worth noting that the tendency of the model [8] must be to underestimate the widths and, more so, the cross sections. This tendency will be most pronounced for the case of ^{8}B for which the external wave function falls off rapidly. The cross sections and longitudinal-momentum widths agree well with a more refined recent calculation with a profile function calculated from an optical model and a microscopic Glauber model [10] at low and high energies, respectively. In this calculation it is interesting to see that the stripping and diffraction-dissociation cross sections come out identical at low energies, just as for a black-disc model, whereas the former is far bigger at high energies. The reaction and elastic cross sections for free nucleons behave in the same way.

The interpretation given here suggests, contrary to what is often assumed, that the longitudinal momentum distributions measured with a light target should not be affected appreciably by the acceptance of the spectrometer. Basically this may be seen from the uncertainty principle, which allows an exact measurement of the momentum along the z-axis for a precisely known (x,y) coordinate. For an infinitesimal target it follows that all information about the original momentum in the xy plane will be destroyed by the measurement. For a small target the radial momentum distribution of the neutron in the approximation leading to the expressions above becomes proportional to $[J_1(k_r R_a)/k_r R_a]^2$, the usual diffraction pattern, depending only on the radius of the target. This means that the wave function at the moment of the collision takes a form that factorizes, so that the k_z distribution will not be changed by an incomplete detection of the k_x and k_y components.

4. Concluding Remarks

The parallel momentum distributions of the heavy fragment in processes such as (^{11}Be,^{10}Be) and (^{8}B,^{7}Be) on light targets reflect the halo wave function in a localized region outside of the nuclear core. When this is taken into account, the calculated longitudinal momentum widths and reaction cross sections are in good agreement with the experiments. The transverse momentum components and also the momentum distributions of the halo nucleon(s) provide interesting complementary information [17].

The author appreciated interesting discussions with many colleagues during the Argonne Conference on Nuclear Structure at the Limits, and comments made by Henning Esbensen and Enrico Vigezzi have been taken into account in this written version of my presentation.

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