Pis'ma v ZhETF, vol.67, iss.5, pp.296 - 301

POSSIBLE APPROACH TO THE HALO SIZE DETERMINATION FROM FRAGMENTATION REACTIONS

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Submitted 4 February 1998

It is shown that in the distribution of the sum of the observed transverse momenta **q** of the core-fragment and the halo nucleons in the case of "elastic" break-up of exotic halo-nuclei there should exist a dip at **q**=0, the width of which may be a measure of the halo size.

PACS: 25.60.+v, 25.70.Mn, 27.20.+n

Exotic neutron- or proton-halo nuclei, discovered recently [1,2], are new interesting nuclear objects studied extensively nowadays. One of the main characteristics of these nuclei is the size of the halo, which may be several times larger than that of the nuclear core. To determine the halo size, different methods were used, such as measurement of interaction cross sections [3], low-energy and intermediate-energy elastic proton scattering [4,5], pion double-charge exchange reactions [6], measurement of fragment momentum distributions [7,8], and some others. Nevertheless, the results obtained are subject to different sources of uncertainties, and give somewhat different results. To our opinion, the overall nuclear size may be determined most accurately by the method of intermediate-energy proton elastic scattering [5]. As for determination of the sizes of the halo and of the core by this method, the results obtained depend on the nuclear model used.

Investigations of the structure of exotic nuclei were carried out last years most of all by the method of nuclear fragmentation. The fragmentation of exotic nuclei, which are loosely bound nuclear systems, occurs mainly as "elastic" break-up [9] or as a "stripping" reaction [10]. The observed momentum distributions of the fragments reflect to some extent the internal nucleon distributions of the studied nuclei. The width of these distributions contain, in principle, information on the halo size. Thus, in fragmentation of ^{11}Li nuclei at 800 MeV/u [7] there were observed two components in the transverse momentum distribution of the ^{9}Li fragments. It was supposed that a broad component of this distribution is due to a neutron knock-out from the ^{11}Li core, while a narrow component is due to a knock-out of neutrons from the ^{11}Li halo. The narrow width of the last component agrees with a relatively large size of the ^{11}Li halo. Later, a very narrow width in the angular distribution of neutrons from fragmentation of ^{11}Li nuclei at 29 MeV/u was observed [8]. A very big ^{11}Li halo radius (of about 12 fm) was inferred from this experiment. In the following it became clear [11], that the narrow component in the neutron angular distribution appears due to decay of ^{10}Li nucleus which is formed after the knock-out of one of the halo neutrons from ^{11}Li, and that the width of this distribution is linked not with the internal neutron halo momentum distribution, but with the energy of the intermediate excited state of this decaying ^{10}Li nucleus. The observed fragment

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momentum distributions may be significantly distorted also by the interaction of the target with the nuclear constituents, and by the final-state interaction of the knocked-out nucleon (or fragment) with the rest of the system. For this reason, the information on the halo sizes, obtained from the performed fragmentation experiments is rather qualitative than quantitative.

In our previous paper [12] we have proposed an experiment that would allow to obtain accurate information on the neutron halo momentum distribution. The momentum distribution of halo neutrons measured in such an experiment is expected to be distorted by the reaction mechanism less as compared to experiments performed before. Then, the width of this distribution may be used for evaluation of the halo size.

Here we discuss another approach for determination of the halo size based on measurement of transverse momentum distributions of fragments appearing from "elastic" nuclear break-up of a beam of exotic nuclei interacting with a fragmentation target. The method we propose [13] is essentially different from that which was ordinary used in studies of exotic nuclei by fragmentation reactions.

In the following we shall consider the "elastic" break-up at intermediate energy when one may use the Glauber theory for description of the scattering process. By "elastic" break-up we mean a process of fragmentation in which the target is left in the ground state and new particles (primarily pions) are not produced. Note that at small momentum transfers to the target, the "elastic" break-up is the dominant mechanism of exotic nucleus fragmentation. We suppose that the exotic nucleus consists of a compact nuclear core, the internal structure of which is described by a wave function ψ_c, and of one or two halo nucleons, the relative motion of which around the core is described by a wave function $\varphi(\mathbf{r})$. We start the consideration from the case of one-nucleon halo nucleus. The wave function for such a nucleus may be written as:

$$\Psi_{f,i} = \varphi_{f,i}(\mathbf{r})\psi_c. \tag{1}$$

Here $\mathbf{r} = \mathbf{r}_n - \mathbf{r}_c$; $\mathbf{r}_n = (A_c/A)\mathbf{r}$ and $\mathbf{r}_c = -(1/A)\mathbf{r}$ are the halo nucleon and the core radius-vectors in the nuclear CM-system; $\mathbf{r}$ is their relative radius-vector.

We describe the scattering of the target nucleus on the exotic one as a process of consecutive independent interactions of the target nucleus with the exotic nucleus subsystems: its core and the halo nucleon. It is more convenient to perform the consideration in the center-of-mass system of the halo nucleus. Then, in agreement with [9,14], for the amplitude of elastic break-up of the exotic nucleus to the core fragment and the halo nucleon we can write the following formula:

$$F_{fi}(\mathbf{q}) = (ik/2\pi)\int \exp(i\mathbf{q}\mathbf{b}) < \varphi_f|\Gamma(\mathbf{b})|\varphi_i > d^2b, \tag{2}$$

$$\Gamma(\mathbf{b}) = \Gamma_{tn}(\mathbf{b}-\mathbf{s}_n) + \Gamma_{tc}(\mathbf{b}-\mathbf{s}_c) - \Gamma_{tn}(\mathbf{b}-\mathbf{s}_n)\Gamma_{tc}(\mathbf{b}-\mathbf{s}_c). \tag{3}$$

Here $\mathbf{q}$ is the momentum transfer from the target to the halo nucleus (we consider relatively small momentum transfers when $\mathbf{q}$ is practically perpendicular to the direction of the beam), k is the magnitude of the wave vector $\mathbf{k}$ of the projectile, $\mathbf{b}$ is the impact vector ($\mathbf{b} \perp \mathbf{k}$), brackets $< | | >$ mean integration over the radius vector $\mathbf{r}$, $\mathbf{s}_n$ and $\mathbf{s}_c$ are the transverse coordinates of the halo neutron and of the core, $\Gamma(\mathbf{b})$ is the profile function for interaction between the target and the exotic nucleus (for fixed relative positions of the halo nucleon and the core), $\Gamma_{tn}(\mathbf{b}-\mathbf{s}_n)$ and $\Gamma_{tc}(\mathbf{b}-\mathbf{s}_c)$ are the profile functions for the interaction of the target with the halo nucleon and with the core. These profile functions are connected with the corresponding amplitudes for the elastic scattering of the target on the halo nucleon and on the core by the following relations:

$$\Gamma_{tn}(\mathbf{b}) = (1/2\pi ik) \int \exp(-i\mathbf{q}\mathbf{b}) f_{tn}(\mathbf{q}) d^2q, \tag{4}$$

$$\Gamma_{tc}(\mathbf{b}) = (1/2\pi ik) \int \exp(-i\mathbf{q}\mathbf{b}) f_{tc}(\mathbf{q}) d^2q. \tag{5}$$

The amplitudes $f_{tn}(\mathbf{q})$ and $f_{tc}(\mathbf{q})$ may be calculated by the standard way using the Glauber multiple scattering theory, the ground state density distributions of the target and of the core-fragment, and free-scattering nucleon-nucleon amplitudes. The formula for $F_{fi}(\mathbf{q})$ may be rewritten as

$$F_{fi}(\mathbf{q}) = F_{tn}(\mathbf{q}) + F_{tc}(\mathbf{q}) + F_{tnc}(\mathbf{q}), \tag{6}$$

$$F_{tn}(\mathbf{q}) = f_{tn}(\mathbf{q}) S_{fi}((A_c/A)\mathbf{q}), \tag{7}$$

$$F_{tc}(\mathbf{q}) = f_{tc}(\mathbf{q}) S_{fi}((-1/A)\mathbf{q}), \tag{8}$$

$$F_{tnc}(\mathbf{q}) = -(2\pi ik)^{-1} \int S_{fi}(\mathbf{q}') f_{tn}(\mathbf{q}/A + \mathbf{q}') f_{tc}((A_c/A)\mathbf{q} - \mathbf{q}') d^2q', \tag{9}$$

where A and A_c are the mass numbers of the exotic nucleus and of its core ($A = A_c + 1$), and the inelastic form-factor $S_{fi}(\mathbf{q})$ is defined by

$$S_{fi}(\mathbf{q}) = < \varphi_f(\mathbf{r}) | \exp(i\mathbf{q}\mathbf{r}) | \varphi_i(\mathbf{r}) > = \int \varphi_f^*(\mathbf{r}) \exp(i\mathbf{q}\mathbf{r}) \varphi_i(\mathbf{r}) d^3r. \tag{10}$$

The calculation of the cross section for elastic break-up becomes very simple if one neglects the final state interaction between the knocked-out nucleon and the core-fragment, and uses plane waves for the wave functions $\varphi_f(\mathbf{r})$. Here we shall take into account only the amplitude $F_{tn}(\mathbf{q})$ that gives, as it will be discussed later, the main contribution to the total amplitude $F_{fi}(\mathbf{q})$ (except very small and very big values of $\mathbf{q}$). Then, integrating over the relative momentum between the knocked-out nucleon and the core fragment, for the differential cross section $d\sigma/d^2q$ one obtains:

$$d\sigma/d^2q = k^{-2} |f_{tn}(\mathbf{q})|^2. \tag{11}$$

It is seen that in the approximation used the differential cross section $d\sigma/d^2q$ does not depend on the halo nucleus structure, and that at $\mathbf{q} = 0$ it has the maximum value. However, as follows from a more accurate consideration, the dependence of $d\sigma/d^2q$ over $\mathbf{q}$ at small values of $\mathbf{q}$ occurs basically different from that presented by Eq.(11), since $\varphi_f(\mathbf{r})$ is not a plane wave. We do not know the exact behaviour of the wave functions $\varphi_f(\mathbf{r})$. Nevertheless, making use of completeness of the system of the wave functions $\varphi_f(\mathbf{r})$, it is easy to obtain the differential cross section summed up over all final states. Supposing that the halo nucleus has no bound excited states, we obtain:

$$d\sigma/d^2q = k^{-2} \sum_{f \neq i} |F_{fi}(\mathbf{q})|^2 = k^{-2} |f_{tn}(\mathbf{q})|^2 [1 - (S_n(\mathbf{q}))^2] \tag{12}$$

with $S_n(\mathbf{q}) = S((A_c/A)\mathbf{q})$, where $S_n(\mathbf{q})$ is the halo nucleon form-factor, and $S(\mathbf{q})$ is the form-factor, corresponding to the wave function $\varphi_i(\mathbf{r})$:

$$S(\mathbf{q}) = \int \exp(i\mathbf{q}\mathbf{r})|\varphi_i(\mathbf{r})|^2 d^3r. \tag{13}$$

It is seen that the cross section $d\sigma/d^2q$, following from amplitude (7), does not depend on the details of the final-state interaction between the knocked-out nucleon and the core-fragment, but depends only on the amplitude $f_{tn}(\mathbf{q})$, which may be calculated rather accurately, and on the form-factor $S_n(\mathbf{q})$, characterizing the halo nucleon space distribution under study. Note that $S_n(\mathbf{q}) = 1$ at $\mathbf{q} = 0$, and $|S_n(\mathbf{q})| << 1$ at $q >> R_h^{-1}$. At small values of q

$$S_n(\mathbf{q}) \approx (1 - q^2 R_h^2/6), \tag{14}$$

where $R_h =< \mathbf{r}^2 >_h^{1/2}$ is the root-mean-square radius of the halo space distribution. Therefore, $d\sigma/d^2q$ at small values of $\mathbf{q}$, according to (12), is proportional to q^2 : $d\sigma/d^2q \sim$ $\sim q^2$ (at $qR_h << 1$). At $q = 0$, as a consequence of orthogonality of the wave functions $\varphi_f(\mathbf{r})$ to the ground-state wave function $\varphi_i(\mathbf{r})$, $d\sigma/d^2q = 0$. Though obtained here for the wave function of the type (1), this result holds true for any wave functions provided only a single-nucleon scattering term is considered. Thus, in the distribution over the transverse momentum $\mathbf{q}$, there should exist a dip at $\mathbf{q} = 0$ with the width proportional to R_h^{-1}. Analysing the shape of this distribution, one can determine the value of R_h.

Now, let us consider other terms in Eq.(6). If we take into account only term (8), then from a similar consideration we shall obtain that

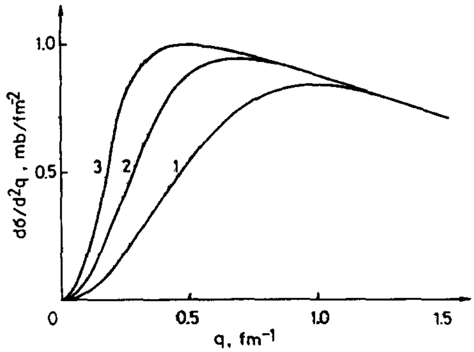
$$d\sigma/d^2q = k^{-2}|f_{tc}(\mathbf{q})|^2[1 - (S_n(\mathbf{q}/A_c))^2]. \tag{15}$$

(Note that $S_c(\mathbf{q}) = S(-\mathbf{q}/A) = S_n(\mathbf{q}/A_c)$; for simplicity we limit the consideration for an s-state spherical wave function $\varphi_i(\mathbf{r})$.) Thus, here again $d\sigma/d^2q = 0$ at $q = 0$. At the same time, the shape of this distribution is different from that given by Eq.(12), the sensitivity of the shape to the halo size at small values of $\mathbf{q}$ being relatively low. The magnitude of the amplitude $f_{tc}(\mathbf{q})$ at small values of $\mathbf{q}$ exceeds that of the amplitude $f_{tn}(\mathbf{q})$, however the contribution to the fragmentation cross section of the scattering of the target on the core is suppressed by the factor $[1 - (S_n(\mathbf{q}/A_c))^2]$. For this reason, the contribution of this term to the total cross section for fragmentation is relatively small. The contribution to the cross section of term (9) is also small. Note that this term is not zero at $q = 0$. Of course, all the three terms contribute to the cross section coherently, so that the amplitudes should be added up, and then the cross section corresponding to the total amplitude can be calculated.

An important channel of fragmentation of exotic nuclei at small momentum transfers for targets with high charge number Z is the Coulomb dissociation. To a first approximation the contribution from the Coulomb dissociation may be taken into account by adding to amplitude (6) the relevant Coulomb term:

$$F_{Coul}(\mathbf{q}) = f_{Coul}(\mathbf{q})S_{fi}((-1/A)\mathbf{q}), \tag{16}$$

where $f_{Coul}(\mathbf{q})$ is the Coulomb amplitude for the scattering of the target on the core. The contribution from the Coulomb dissociation is essentially big at very small momentum transfers, and added up to the strong-interaction fragmentation, it may result in filling



The expected shape of the fragmentation cross section distribution over the transverse momentum **q**, calculated from Eq.(12) for three values of the halo radius: 3 fm, 5 fm, and 8 fm (correspondingly, curves *1*, *2*, and *3*)

of the q-distribution dip discussed above. Thus, it is evident that to use the method proposed for determination of the halo size, one has to work with low Z targets.

The analysis of the data is especially simple and much less ambiguous if hydrogen is taken as a target. The shape of $d\sigma/d^2q$, calculated in this case using only amplitude (7) at the energy around 800 MeV/u for three halo density distributions parametrized by a Gaussian function with the root-mean-square radii of 3 fm, 5 fm, and 8 fm, is demonstrated in the figure. It is seen that the size of the halo may be determined easily from the shape of this distribution. The contribution to the cross section of amplitudes (8) and (9), as was mentioned before, should be small. Due to contribution of amplitude (9), the minimum in $d\sigma/d^2q$ at $q = 0$ will be partly filled. However, the general character of the dependence of $d\sigma/d^2q$ over $\mathbf{q}$, with a dip at $q = 0$, will remain the same, so that the width of this dip may be used for determination of the halo size. The method discussed may be applied to determine the sizes of neutron as well as proton halos. A similar picture for the distribution of the fragmentation cross section over the transverse momentum $\mathbf{q}$ is expected also for two-neutron halo nuclei. The value of the momentum $\mathbf{q}$ may be determined experimentally in this case from the sum of transverse momenta of the registered core fragment and the halo neutrons.

The method of the halo size determination discussed here is similar in a certain sense to the method of small-angle elastic scattering of intermediate energy protons we proposed and used before [15,5]. In both cases the information about the halo size is obtained from scattering with small momentum transfers, and in both cases the shape of the halo form-factor is studied. However, in case of proton elastic scattering, there are significant contributions to the cross section at small scattering angles (at small momentum transfers) both from the halo nucleons and from the core, so that a problem of separation of these contributions arises. As for the nuclear fragmentation, the shape of the $\mathbf{q}$-distribution at small values of q is determined mainly by the $\mathbf{q}$-dependence of the halo form-factor, the contribution from the core scattering, as discussed before, being suppressed. We note also that to disentangle the contributions of scattering from the halo and from the core in case of nuclear fragmentation, a correlation between the momentum transfer $\mathbf{q}$ and the measured fragment momenta could be helpful.

In conclusion, we have shown that in the distribution of the sum of transverse momenta of fragments there should be observed a dip. The width of this dip depends on the halo size. It would be interesting to check experimentally this theoretical prediction. Note that for incoreherent scattering from stable nuclei there was also predicted a minimum at $q = 0$ [16], however there were no investigations carried out that could confirm existence of this minimum. Provided this minimum exists, the method discussed above may be used for measuring sizes of halos in exotic nuclei. In any case, measurement of the distribution of the sum of the observed transverse momenta $\mathbf{q}$ of the core-fragment and the halo nucleons at small values of q is important for understanding of the mechanism of fragmentation of exotic nuclei.

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