Pis'ma v ZhETF, vol.66, iss.2, pp.75 - 80 © 1997 July 25

HOW CAN WE STUDY THE HALO MOMENTUM DISTRIBUTION IN EXOTIC NUCLEI?

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Submitted 30 May 1997

Conditions for applicability of the "sudden" approximation to description of fragmentation of exotic nuclei are discussed. An experiment that may allow to obtain rather accurate information on the halo internal momentum distribution is proposed.

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

Since the discovery of exotic nuclei [1], which have an unusual spatial structure with a normal-sized nuclear core and an extended nucleon halo, their properties have been studied extensively by different methods. Much valuable information on the nuclear structure of exotic nuclei was obtained from the data on nuclear fragmentation. Nevertheless, the situation with the nucleon momentum distributions in these nuclei remains still uncertain. It occurred that the reaction mechanism of nuclear fragmentation may significantly affect the momentum distributions obtained. So, up to now it is not quite clear to what extent the measured distributions reflect the true internal ones [2,3].

The idea of the nuclear fragmentation experiments is as follows. A beam of exotic nuclei intersects a fragmentation target. Due to interaction with the target, the nuclear break-up (or the Coulomb dissociation) takes place. In the beginning of these studies it was supposed with a reference to the "sudden" approximation that the observed fragment momentum distributions were the true internal ones. The sudden approximation implies that the participants of the interaction are removed from the nucleus under study quickly enough, so that the rest of the nuclear system may be supposed intact, its momentum being the same as it was before the interaction. The conditions for applicability of the sudden approximation in fragmentation reactions, however, are usually not fulfilled. Indeed, even when the experiment is performed at relatively high energy, so that the target crosses the nucleus rather fast (in the nucleus center-of-mass system of reference), the rescattering of the target on the nuclear components violates the applicability of this approximation. Moreover, the nuclear participants of the interaction with the target may be removed from the nucleus not fast enough. For this reason the sudden approximation does not work either.

Let us consider main mechanisms of one-neutron-halo exotic nucleus fragmentation at intermediate energy to a core and a neutron. We assume that the exotic nucleus consists of two well separated by-systems, a halo neutron and a core, so that its wave function may be represented as $\Psi_{f,i} = \varphi_{f,i}(\mathrm{r})\psi_c$, where $\varphi_{f,i}(\mathrm{r})$ describes the relative motion of the neutron and the core, while ψ_c describes the internal motion of the core nucleons. Let q be the momentum transfer from the target to the exotic nucleus. Since the binding energy of the halo neutron

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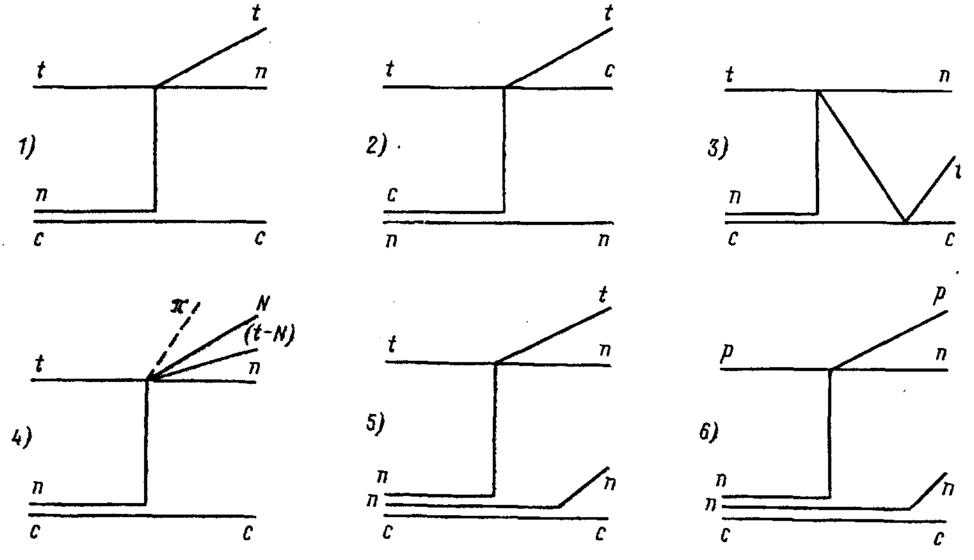
is low, even small momentum transfers may induce fragmentation of the exotic nucleus, the target nucleus being left in the ground state. Thus, it is evident that the "elastic" break-up (the target nucleus being left in the ground state) is an important channel of exotic nucleus fragmentation. Describing the target interaction with the exotic nucleus as consecutive independent interactions of the target with the halo neutron and with the core, and using the Glauber–Sitenko theory, for the amplitude of elastic break-up we obtain the well-known formula [4,5]:

$$F_{fi}(\mathrm{q}) = (ik/2\pi) \int \exp(i\mathrm{qb}) < \varphi_f|\Gamma(\mathrm{b})|\varphi_i > d^2b, \tag{1}$$

$$\Gamma(\mathrm{b}) = \Gamma_{tn}(\mathrm{b}-\mathrm{s}_n) + \Gamma_{tc}(\mathrm{b}-\mathrm{s}_c) - \Gamma_{tn}(\mathrm{b}-\mathrm{s}_n)\Gamma_{tc}(\mathrm{b}-\mathrm{s}_c). \tag{2}$$

Here $\Gamma(\mathrm{b})$ is the profile function for the interaction between the target and the exotic nucleus; b is the relevant impact vector; k is the value of the wave vector of the projectile; $\Gamma_{tn}(\mathrm{b}-\mathrm{s}_n)$ and $\Gamma_{tc}(\mathrm{b}-\mathrm{s}_c)$ are the profile functions for the interactions between the target and the halo neutron, and between the target and the core of the exotic nucleus, correspondingly; s_n and s_c are the transverse coordinates of the neutron and the core.



Main diagrams for fragmentation of exotic nuclei (t – target; c – core; n – halo nucleon; N – target nucleon; p – proton; π – pion)

Three terms in Eq.(2) are presented in the figure by the corresponding diagrams 1, 2, and 3. Let us consider the first diagram, which corresponds to fragmentation due to "elastic" scattering of the halo neutron on the target. Due to low binding energy, the halo neutron spends a significant part of its time beyond the range of nuclear forces of the core. This allows to suppose that in the break-up process the effect of the final-state interaction between the knocked off neutron and the core is not essential, so that the wave function $\varphi_f(\mathrm{r})$ may be taken as a plane wave. Then from Eq.(1) and from the first term of Eq.(2), it follows immediately that

$$d\sigma/d^3k_c = \sigma_{tn}\rho(\mathrm{k}_c), \qquad d\sigma/d^3k_n = \int (d\sigma_{tn}(\mathrm{q})/d^2q)\rho(\mathrm{k}_n - \mathrm{q})d^2q. \tag{3}$$

Here $d\sigma/d^3k_n$ and $d\sigma/d^3k_c$ are the break-up cross section distributions over experimentally observed neutron and core-fragment momenta (in the projectile CM-system), $d\sigma_{tn}(\mathrm{q})/d^2q$ and σ_{tn} are the differential and the integral elastic cross sections for neutron scattering on the target, and $\rho(\mathrm{k}_c)$ and $\rho(\mathrm{k}_n)$ are the core and halo neutron internal momentum distributions.

It is seen that the observed core momentum distribution is equal to the internal one, while the observed neutron transverse momentum distribution is distorted by the interaction with the target, the longitudinal one being not distorted. (Note that the momentum transfer q for not too big values is practically perpendicular to the direction of the incoming beam). Now, if we consider diagram 2, we shall come to similar conclusions with the roles of the neutron and the core interchanged. We see that momentum distributions of the "participants" of interaction with the target are distorted, while the distributions of the "spectators" are not. Diagram 3 corresponds to the break-up process when the target interacts with the neutron halo as well as with the core. In this case both momentum distributions of the neutron and of the core are distorted.

Expressions (3) are obtained under assumption that $\varphi_f(\mathrm{r})$ is a plane wave. However, as a matter of fact, it is distorted by the final-state interaction. Amplitude $F_{fi}(\mathrm{q})$ for the "elastic" fragmentation, corresponding to the 1st diagram, may be written in the form

$$F_{fi}(\mathrm{q}) = f_{tn}(\mathrm{q})S_{fi}(\mathrm{q}), \qquad S_{fi}(\mathrm{q}) = <\varphi_f|\exp(i\mathrm{q}\mathrm{s}_n)|\varphi_i>, \tag{4}$$

where $f_{tn}(\mathrm{q})$ is the amplitude for elastic scattering of the neutron on the target. The wave function φ_f should be orthogonal to the ground-state wave function φ_i. As a consequence of this, the inelastic formfactor $S_{fi}(\mathrm{q})$ is zero at $\mathrm{q} = 0$, which is significantly different from the case when φ_f is a plane wave. Now, with a realistic φ_f, there is no direct connection between the measured momentum distributions and the internal ones.

For targets with high charge number Z, the nuclear break-up may proceed as the Coulomb dissociation. The amplitude for this process at intermediate energy may be written in the form (4) with $F_{tcCoul}(\mathrm{q})$ instead of $F_{tn}(\mathrm{q})$, where $F_{tcCoul}(\mathrm{q})$ is the amplitude for the Coulomb scattering of the target on the exotic nucleus core. So, it is evident that the momentum distributions of fragments appearing due to the Coulomb dissociation are subject to final-state interaction distortions as well. In addition, they are distorted also by the strong interaction of the target with the exotic nucleus.

Another important channel of the exotic nucleus fragmentation, that is dominant in fact at sufficiently high energy, is the "inelastic" break-up, when the target is broken too, and new particles (primarily pions) are produced (diagram 4). This process is often referred to as a "stripping" reaction [6]. The neutron, knocked out from the exotic nucleus, receives usually a big momentum transfer in this reaction, and it is "absorbed" from the elastic channel. Therefore, effects of final-state interaction are small here, and the measured momentum of the core-fragment, which is a "spectator", is supposed to reflect the internal momentum of interest. However, due to interaction of the target with the nuclear core, the stripping reaction is mainly peripheral, so that the sensitivity to the momentum distribution in the nuclear interior is low, the measured momentum distributions of the core-fragments of exotic nuclei being narrower than the true internal ones [7,8].

To summarize the previous discussion, we can make the following conclusions. The observed momentum distributions of fragments may be distorted substantially by the interaction with the target, by the final-state interaction, and by rescattering effects. It is not possible to take the final-state interaction into account exactly since we do not know it well enough. It is not easy to take the effects of rescattering into account accurately due to complexity of nucleus-nucleus interaction. Information on the neutron momentum distribution in the central part of the exotic nucleus is lost because of strong absorption.

As for investigation of two-neutron halo nuclei, the situation is more complicated here. The break-up of such a nucleus may go as a suquential process. For example, in case of fragmentation of ^{11}Li nuclei, one of the halo neutrons may be knocked out, the rest of the system being left as an intermediate excited state of the nucleus ^{10}Li which decays to ^{9}Li and another neutron [9] (see diagram 5). The latter is observed in the experiment in the forward direction, however the narrow transverse momentum distribution of this neutron has little to do with the internal neutron momentum distribution in ^{11}Li nuclei.

In what experiment can one obtain information on the halo neutron momentum distribution that is not distorted significantly by the reaction mechanism? Let us enumerate the requirements which to our opinion are demanded for such an experiment.

1. The experiment should be performed at intermediate energy. This allows to select a direct process, to reduce distortion effects, and to have a reliable scattering theory.

2. Since momentum distributions of "participants" are disturbed by interaction with the target, the "participants" have to be separated out, and information on the internal momentum distributions should be extracted from the "spectators" only. Note that in this case the transverse and longitudinal observed momentum distributions are expected to be identical.

3. To minimize effects of final-state interaction, "participants" have to receive a sufficiently high momentum transfer.

4. For the same reason "participants" should be light enough.

5. To minimize effects of distortions of momentum distributions, the target should have a small cross section for interaction with the nuclear components.

6. To minimize the contribution from the Coulomb dissociation, the target should have low Z-value.

7. To get rid of problems of description of nucleus-nucleus interaction, it is desirable to have for the target an elementary particle.

Here below we describe an experiment that satisfies all these requirements. We propose to perform fragmentation of an exotic nucleus on a liquid hydrogen target. The appropriate energy of the beam may be around 300 MeV/u or somewhat higher. To be more concrete, let us consider the case of ^{11}Li. Due to interaction with a target proton, one of the halo neutrons may be knocked out from the nucleus (diagram 6). To suppress the influence of the final-state interaction of the knocked out neutron with the rest of the nucleus, we demand that the momentum transfer to this neutron, which is a "participant", should be sufficiently high. This may be reached by measuring energy of the scattered target proton and by selecting the events when this energy is above some value, say above 50 MeV. Note that the energy resolution of the proton detector may be rather low since the value of the proton energy will be used only for event selection. The information on the neutron internal momentum distribution in ^{11}Li may be obtained by measuring the transverse momenta of another halo neutron and of the core-fragment ^{9}Li. From the relative transverse velocities of the detected neutron and ^{9}Li nucleus, one can obtain information on the energy of the possible intermediate resonant state of ^{10}Li. The sum of the measured tranverse momenta of the neutron and of the ^{9}Li nucleus is expected to be equal to the internal momentum of the knocked out neutron.

The proposed experiment differs from the previous experiments on fragmentation of exotic nuclei mainly in three respects. Firstly, the fragmentation target is an elementary particle. Secondly, "participants" of the reaction and "spectators" are separated out, and only spectators whose motion is little affected by the interaction with the target are used to deduce information on the internal momentum distributions. And thirdly, the halo neutron, which is a "participant", is removed from the nucleus very quickly so that effects of final-state interaction between this neutron and the rest of the system are small. Note also, that in distinction from previous works, the information on the halo neutron motion is proposed to obtain here for two-neutron-halo nuclei not from the observed core-fragment momentum or from the forward neutron momentum alone, but from the sum of these momenta. The conditions for applicability of the "sudden" approximation are fulfilled (it is more correct to speak here about the "impulse" approximation), and the influence of rescattering effects is minimized. We believe that from this experiment one can obtain rather accurate information on the halo neutron momentum distribution. Of course, similar approach may be used for studying a halo proton momentum distribution in proton-rich nuclei, as well.

The experiment discussed may be considered as a version of the classical experiment for (p, pn) or $(p, 2p)$ quasi-elastic scattering in inverse kinematics. The shell from which a nucleon is knocked off is determined in traditional (p, pn) and $(p, 2p)$ experiments from the energy balance of the incident, scattered and knocked off nucleons. As for the present experiment, the fact that a nucleon is knocked out from the halo (but not from the core) is determined from observation of the core-fragment. Strictly speaking, if we observe a core-fragment, say ^{9}Li when we consider ^{11}Li fragmentation, this does not mean that the break-up of ^{11}Li nucleus proceeds obligatory due to a halo neutron knock off. In principle, the break-up of the ^{11}Li nucleus may occur due to "elastic" scattering of the core on a target proton. However, the probability of such a process with a high momentum transfer to the core is very low. Note that the observed momentum of the ^{9}Li-fragment in this case will be outside the range of interest.

An estimate of the counting rate of the events of interest for a liquid hydrogen target of 10 cm length shows that a rather high statistics (more than 10^5 events) may be accumulated during a reasonable time of the experiment with the intensity of the beam of exotic nuclei even lower than 10^3 1/s.

The proposed experiment is discussed in more detail in Ref.[10].

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