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institut de physique nucléaire CNRS - IN2P3 UNIVERSITÉ PARIS - SUD

IPNO DRE 92-37

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Received (Submitted to Physics Letters B 3 December 1992)

ABSTRACT

Reactions of a radioactive ^{11}Be beam at 41 MeV/u have been investigated. The absolute magnitude of the differential cross-sections of the forward neutrons in the exclusive (^{10}Be+n) channel can be accounted for quantitatively in a simple model. The narrow distribution from high-Z targets turns out to arise from Coulomb dissociation whereas the broad distribution from the beryllium target is due to diffraction dissociation.

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[a] Supported by Bundesministerium für Forschung und Technologie under contract number 06DA 184A.

1. Introduction

Halo nuclei, see [1], are mainly situated at the neutron drip line and owe their extended neutron cloud or "halo" to the low separation energy for one or two neutrons. The interest has concentrated around the two-neutron halo, which seems to present interesting three-body or molecular aspects. Since the halo nuclei have one or, at most, a few bound states their spectroscopy necessarily involves excitations leading to the continuum, so that structure and reaction information become intermingled.

We attempt here to clarify this problem through a study of a projectile with a single-neutron halo, the radioactive ^{11}Be. Its ground state is known to be a $1/2^+$ intruder state [2] with a neutron separation energy S_n of 504±6 keV, corresponding to an external (Yukawa) decay length $\rho = \hbar/(2\mu S_n)^{1/2} = 6.75$ fm, where μ is the reduced mass. The existence of the long tail in the ^{11}Be matter distribution has been verified experimentally [3] in a comparison of total reaction cross-sections at 33 MeV/u and 790 MeV/u. The unknowns are therefore all in the reaction sector of the problem.

2. Aperçu of the two-neutron halo

The strategy of the present and also of our previous work [4, 5] has been to focus on dissociation reactions. These highlight the halo because core-core collisions contribute little to this channel at the high beam energies involved. For the two-neutron halo nucleus ^{11}Li, experiments with high-Z targets demonstrate [4-7] the predicted [8] large cross-sections for Coulomb dissociation. For a low-Z target the (quasi-free) halo neutron interacts via two nuclear channels, one inelastic and one elastic, which in a black-disc picture correspond to absorption and diffraction dissociation. The Coulomb processes [9, 10] and also the total cross-sections [11] seem well in hand theoretically, but the global picture of the momentum distributions of the fragments presents problems.

The transverse momenta of the neutrons [4, 5] and the longitudinal momenta of the ^{9}Li recoils [12] are strikingly narrow, very similar in magnitude (if the two neutrons are assumed to be uncorrelated) and essentially identical in shape for light and heavy targets. Surprisingly, the transverse momentum distribution of the recoils is very much broader, even for a target as light as deuterium [13]. Qualitatively the narrow distributions agree well with the picture of the neutron halo, since large spatial distribution corresponds to a narrow distribution in momentum, provided that it is assumed [4,12] that the momentum distribution is that of the initial state. For the Coulomb mechanism this is only a partial truth and it is not at all the case for the diffraction mechanism, which for a light target is expected to entail [4] a broad diffraction pattern. This was not observed in the ^{11}Li experiment, most likely because it was masked by the narrow component, but a hint of this effect came from a broad neutron distribution (in coincidence with core recoils) which unexpectedly [14] had emerged in a

^{11}Be experiment at high energy. On this background we decided to carry out a learning experiment with ^{11}Be, less interesting from the point of view of nuclear structure but better suited for clarifying the reaction mechanisms quantitatively.

3. Experimental techniques and results

The experiment was very similar to the previous one [4, 5] but the techniques had been improved in two important ways. The new LISE3 spectrometer [15] at GANIL incorporates a Wien filter after the doubly achromatic spectrometer and gives more intense as well as much cleaner radioactive beams. The second improvement was a more powerful array of neutron detectors with higher granularity near zero degrees and more detection efficiency at large angles. A primary beam of 55 MeV/u ^{18}O was used to produce a ^{11}Be beam with an energy of 41 MeV/u (mid-target value). As in the previuos experiment the targets (Be, Ti and Au) were sandwiched in a detector telescope operated in coincidence with the neutrons with a flight path of 3 m. The efficiencies of the neutron detectors and the (negligible) contributions from cross-talk were obtained from Monte-Carlo calculations and checked against measurements performed with 14 MeV neutrons [16]. A more detailed description of the experiment will be published later.

For each target $(2\text{-}3)\cdot 10^7$ incoming ions were recorded and a background run with approximately the same number of ions was performed without the reaction target and with appropriately reduced beam energy to correct for reactions that take place in the thick Si detector after the target. In the analysis, the energy gate on the neutrons was set around beam velocity (from 26 MeV up to 80 MeV) in order to eliminate neutrons from deep inelastic and evaporation processes following core-target collisions, which have a large neutron multiplicity and become important for large angles, even if most of them are eliminated by the ^{10}Be gate in the exclusive channel. The resulting differential cross-sections for the single-neutron inclusive (^{11}Be, n) and exclusive (^{11}Be, ^{10}Be+n) cross-sections are shown in Figs. 1-3. The errors are statistical errors and in addition there is an estimated over-all scale error of ±20% on the absolute cross sections.

The exclusive cross-sections clearly demonstrate the expected effects. For the two high-Z targets (Z=79 and 22, Figs. 1 and 2) the angular distribution is narrow reflecting the large spatial extent of the ^{11}Be halo. The low-Z target (Z=4, Fig. 3) shows a broad angular distribution characteristic of the diffraction mechanism. In Section 4 we come back to a more quantitative appreciation of these results.

The inclusive cross-section is for the gold target essentially identical to the exclusive cross-section and demonstrates the pre-eminence of the Coulomb mechanism as the nuclear contribution to the exclusive cross-section can be estimated to be a few tenths of a barn. For titanium and

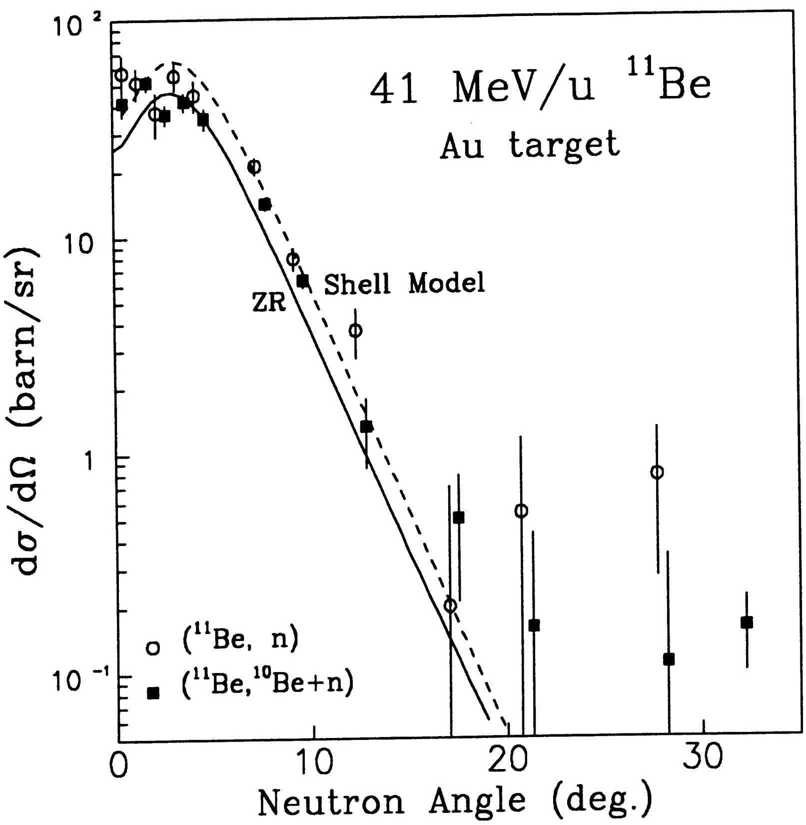

Fig. 1
The exclusive and inclusive neutron angular distributions of neutrons ($26<E_n<80$ MeV) from reactions with the gold target. The two Coulomb-excitation calculations, which have no free parameters, are described in the text. The integrated experimental cross-section to 20^0 is 2.2 b.

beryllium the inclusive cross section is very much larger than the exclusive one. Our interpretation is that this reflects two dominant contributions, both linked to core-target collisions[a], namely: (i) a broad distribution from core fragmentation and pre-equilibrium neutrons, and (ii) a narrow distribution coming from the halo neutron, which has a large probability of escaping the core-target collision.

4. Theoretical analysis

4.1 Coulomb dissociation. Fig. 1 shows the results of two calculations based on the theory of Coulomb excitation with fast heavy ions [17, 18]. In the first the transition strength was obtained from a single-particle shell model based on the Woods-Saxon potential applied previously [9] to ^{11}Li, and with the strength adjusted to reproduce the experimental binding energy. The

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[a] In retrospect it is clear that this aspect would have been illuminated by a run with ^{10}Be on a beryllium target. With a gold target the inclusive yield of forward neutrons was one fifth of that for a ^{11}Be projectile, confirming that forward neutrons provide a very clear "halo signal". We have previously demonstrated [4] a similar effect for the pair ^{9,11}Li.

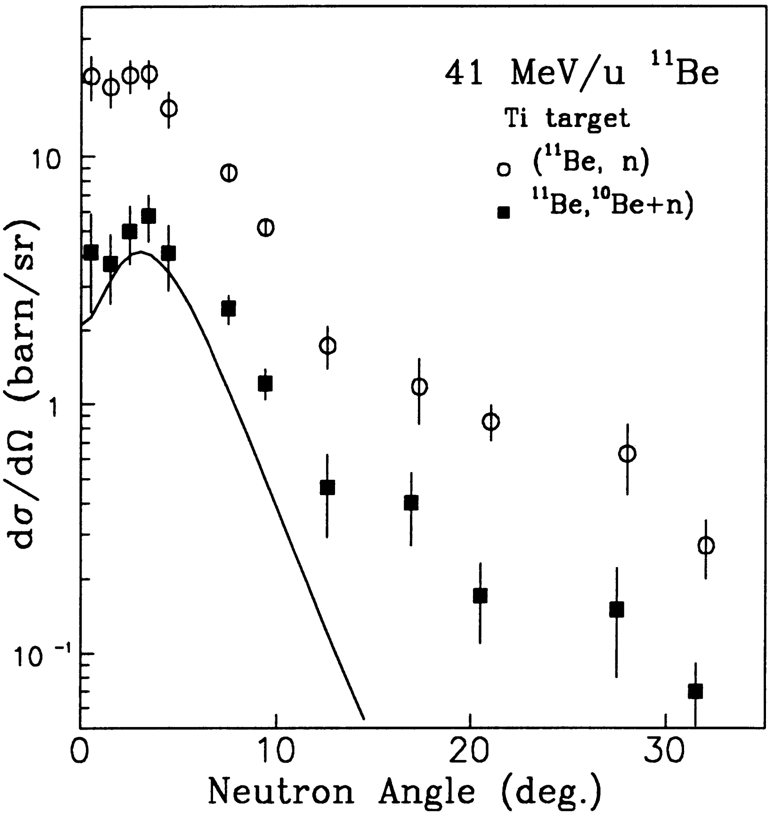

Fig. 2
Exclusive and inclusive neutron angular distributions from reactions with the titanium target compared with a Coulomb-excitation calculation based on the zero-range approximation.

rms radius is 7.18 fm for the halo neutron. The relevant states are the $1s_{1/2}$ valence state and the associated continuum states, and the resulting angular distribution is in excellent agreement with the experiment except at larger angles where nuclear contributions presumably begin to play a role. Even this comparison, however, does not do full justice to the accuracy of the estimate. It is known [2] from (d,p) experiments that the $s_{1/2}$ spectroscopic factor for the ^{11}Be ground state is 0.77; the remaining part due to complex-structure states (mainly $d_{5/2}$ components) will contribute little here. When the calculation shown in Fig. 1 is multiplied by 0.77 this theory without free parameters is in exact agreement with experiment.

The second model is simpler and also without free parameters. In this the ^{11}Be ground state is approximated by a Yukawa wave function, usually referred to as the zero-range approximation (ZR),

$$\psi_0(r) = (2\pi\rho)^{-1/2}\exp(-r/\rho) \qquad (1)$$

giving the correct shape at large distances, but underestimating the absolute value by a factor that can be approximated as

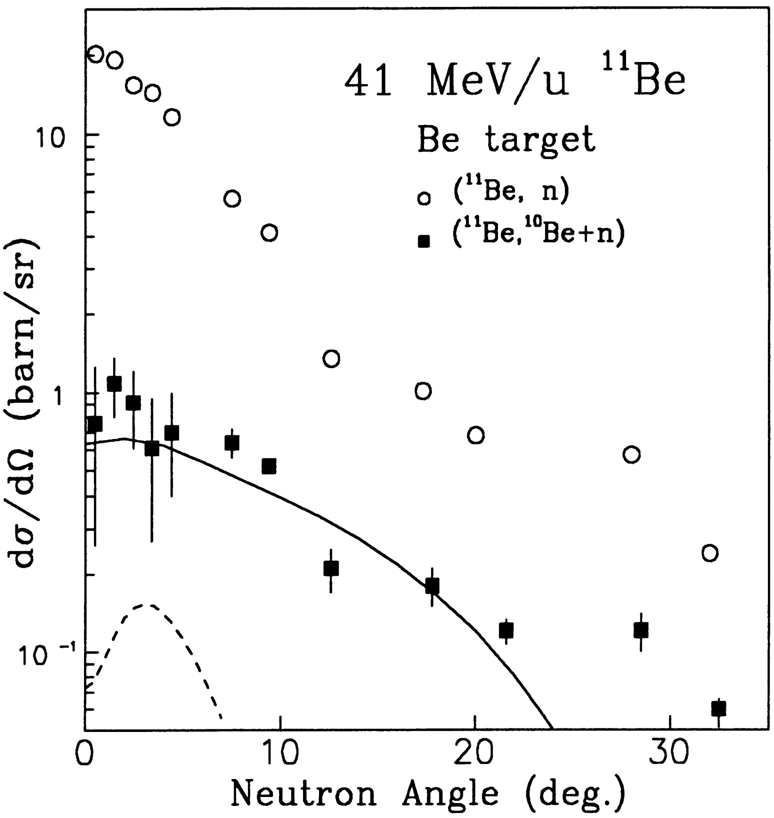

Fig. 3
Exclusive and inclusive neutron angular distributions from reactions with the beryllium target compared with diffraction-dissociation (full drawn) and Coulomb-excitation calculations based on the zero-range approximation.

$$F=\exp(a/\rho)/(1+a/\rho)^{1/2} \qquad (2)$$

where a of the order of 2.3 fm is the radius of the corresponding square-well potential. For processes that are dominated by the neutron wave function at large distances one must therefore augment the final reaction probability by a factor F^2, the finite-size correction [8]. In this δ-potential model the final p-states are plane waves. The differential cross-section calculated in this way is shown in Figs. 1-3.

4.2 Diffraction dissociation. The *E1* Coulomb contribution is much too small to explain the results with the beryllium target (Fig. 3). Similar to our interpretation [4] of the nuclear dissociation of the two-neutron halo of ^{11}Li, we assume that the dissociation of ^{11}Be on beryllium is due to elastic and inelastic interactions of the halo neutrons with the target. These can be calculated in a simple geometrical model developed by Glauber [19]. The validity of a black-disc model finds support in a more elaborate calculation [11] of the dissociation of ^{11}Li on a carbon target, and in which optical potentials were used for describing the neutron-core and neutron-target interactions. The cross-sections agree with the black-disc estimates [4] when scaled to a Be target, and the elastic and inelastic contributions are approximately identical up to about 100 MeV/u, just as for a black-disc model.

In the present work the black-disc model has been extended to give momentum distributions. For simplicity the Coulomb interaction is left out so that the calculation is valid only for the Be target. The effective radius of the black disc was chosen to reproduce the experimental [20] 0^0 cross-section of 14 MeV neutrons. The ground-state wave function was removed from that of the collision complex in a Schmidt orthogonalization procedure; the result is the wave function of the decaying state in the sudden approximation. The square of the Fourier transform of this approximates the momentum distribution. In Fig. 3 the full-drawn curve, to which the small Coulomb part has been added for completeness, shows the final result. The agreement is satisfactory, in fact almost quantitative, below 20°.

5. Concluding remarks

The Coulomb excitation calculation successfully accounts for the Au experiment. It is, however, also significant that a simplified nuclear model gives essentially the same result. This is a reminder that the halo manifests itself mainly through an asymptotic property: The tail of its wave function.

It should also not be forgotten that the theoretical calculations are based on assumptions that differ radically from the conventional wisdom. The E1 transitions have the full single-particle strength and are not quenched by collective mechanisms[a], and the low-energy final states are well approximated by a structureless continuum. This is a memento to those, who in the low-lying excitations of the halo see "soft giant-dipole resonances" and such similar; we note that Ieki et al. [21] also rule against a resonance picture and favour a direct break-up process.

What then remains of the notion that the narrow momentum distributions reflect the initial distribution in the halo nucleus? Superficially seen not much; note e.g. the dip near 0^0 in Figs. 1 and 2, which is the signature of a (final) p state. However, the opening half angle for the neutron of about 5^0 corresponds to the experimental momentum width parameter [1] $\Gamma \approx 63$ MeV/c and is in agreement with the theoretical value for the s ground state $\Gamma = 2\hbar/\rho = (8\mu S_n)^{1/2} = 58.4$ MeV/c. The agreement is not accidental and would occur also for other (small) values of the neutron separation energy S_n. This is a confirmation of the observation by Esbensen and Bertsch [10] that "the dipole operator does not change the momentum content much". It is interesting that the corresponding transverse momentum width [22], as in the case of the lithium isotopes, is much larger, $\Gamma =$ 108 MeV/c.

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[a] In fact, in the two-neutron halo of ^{11}Li [10] the nn interaction in the final state leads to an enhancement of the E1 strength at low energy.

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