# Possibility of determining the radius of the neutron halo in light exotic nuclei

G. D. Alkhazov and A. A. Lobodenko
*B. P. Konstantinov St. Petersburg Institute of Nuclear Physics, 188350, Gatchina*

(Submitted 5 Feburary 1992)
Pis'ma Zh. Eksp. Teor. Fiz. **55**, No. 7, 377–379 (10 April 1992)

A unique opportunity for determining the mean square radius of the neutron halo, by a nearly model-independent method, arises in the elastic scattering of intermediate-energy protons by nuclei with an extreme neutron excess in the inverse kinematics.

One of the most significant events in nuclear physics in recent years was the discovery of nuclei which have a neutron halo.[1] These nuclei have a very unusual shape. In contrast with all previously known nuclei, which have a fairly thin surface layer of nuclear matter, these newly discovered nuclei have a neutron halo, whose size is several times the size of the core of the nucleus. These neutron-excess nuclei, which fall right at the boundary of nuclear stability, have been the subject of a large number of studies, both experimental and theoretical. The nucleus $^{11}$Li has attracted the greatest interest. Although the existence of a neutron halo in the nucleus $^{11}$Li and in certain other exotic nuclei is now a solidly established fact, the methods which have been used to study these nuclei have been incapable of providing accurate information on the size of the neutron halo.

The most reliable information on the distribution of nuclear matter has been found from elastic scattering of intermediate-energy protons.[2] The use of protons with energies of 800–1000 MeV as probes to study nuclei has proved successful because at this energy the scattering can be described by the theory of diffractive multiple scattering, which relates the measured cross sections to the nuclear densities of interest in a completely unambiguous way. This method can also be used in an inverse kinematics to study unstable nuclei. We recently proposed experiments of this sort in fast beams of light exotic nuclei with the help of the IKAR recoil-nucleus detector,[3,4] which is a hydrogen-filled ionization chamber.

The error in the nucleon densities found from the elastic scattering of fast protons stems for the most part from the uncertainty in the selection of a nuclear model, i.e., in the specific parametrization of the density distribution. In the case of exotic nuclei with a neutron halo, in contrast, it turns out that the mean square radius of the neutron halo can be determined by an essentially model-independent method, as we show below.

In accordance with the Glauber–Sitenko theory,[2] we write the amplitude for elastic proton–nucleus scattering in eikonal form:

$$F(\vec{q}) = \frac{ik}{2\pi}\int d^2\vec{b}\, e^{i\vec{q}\vec{b}}\{1 - e^{i\chi(\vec{b})}\}, \tag{1}$$

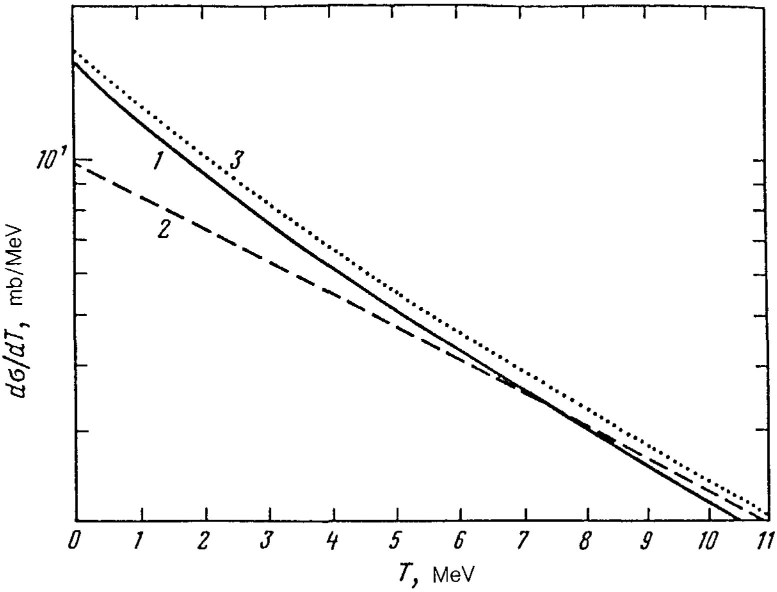

FIG. 1. Differential cross sections for elastic $p\ ^{11}$Li scattering at an energy of 1 GeV/nucleon versus the energy of the recoil protons. These calculations were carried out in an orbital-cluster model of the $^{11}$Li nucleus with Gaussian densities with $\langle r^2\rangle^{1/2}_{\text{core}} = 2.5$ fm and $\langle r^2\rangle^{1/2}_{\text{halo}} = 6.77$ fm. *1*—Calculation from the Glauber–Sitenko formula with all the multipole-scattering terms (the Coulomb interaction, ignored here, makes a substantial contribution to the cross section at $T < 1$ MeV); *2*—component from scattering by the core alone; *3*—sum of the components representing scattering by the core and by the halo [the amplitude $F(\vec{q})$ was calculated from (2) without the term $\Delta F(\vec{q})$].

where $k$ is the wave number, $\vec{b}$ is the impact vector, and $\chi(\vec{b})$ is the eikonal phase shift of the proton–nucleus interaction. Ignoring the small nucleon-correlation effect, we replace the phase shift $\chi(\vec{b})$ by the sum of phase shifts $\chi_{\text{core}}(\vec{b})$ and $\chi_{\text{halo}}(\vec{b})$, which describe the scattering by the nuclear core and by the neutron halo. Since the halo is much larger than the core, and since the density of neutrons in the halo is extremely low, we can then write amplitude (1) in the form

$$F(\vec{q}) = F_{\text{core}}(\vec{q}) + F_{\text{halo}}(\vec{q}) + \Delta F(\vec{q}) \ . \tag{2}$$

Here $F_{\text{core}}(\vec{q})$ is the ordinary amplitude for elastic multiple scattering of protons by nucleons of the nuclear core in the form in (1) with $\chi(\vec{b}) = \chi_{\text{core}}(\vec{b})$, and $F_{\text{halo}}(\vec{q})$ is the amplitude for scattering by the neutrons of the halo. This amplitude is given by

$$F_{\text{halo}}(\vec{q}) \approx -\frac{ik}{2\pi}\int d^2\vec{b}e^{i\vec{q}\vec{b}}i\chi_{\text{halo}}(\vec{b}) \approx Nf_{pn}(\vec{q})S_{\text{halo}}(\vec{q}) \ , \tag{3}$$

where $N$ is the number of neutrons in the halo, $f_{pn}(\vec{q})$ is the elementary amplitude for proton-neutron scattering, and $S_{\text{halo}}(\vec{q})$ is the form factor of the neutron halo. The term $\Delta F(\vec{q})$ is a part of the amplitude which makes a relatively small contribution to the total amplitude. Its $q$ dependence is nearly the same as that of the amplitude $F_{\text{core}}(\vec{q})$:

$$\Delta F(\vec{q}) = \frac{ik}{2\pi} \int d^2\vec{b} e^{i\vec{q}\vec{b}} i\chi_{\text{halo}}(\vec{b})\{1 - e^{i\chi_{\text{core}}(\vec{b})}\} \approx i\chi_{\text{halo}}(0) F_{\text{core}}(\vec{q}) . \tag{4}$$

The scattering by the halo neutrons makes a substantial contribution to the total amplitude only at a small momentum transfer. The form factor $S_{\text{halo}}(\vec{q})$ can thus be expanded in a series in $q^2$, in which we need retain only the first term: $S_{\text{halo}}(\vec{q}) \approx 1 - \vec{q}^2\langle \vec{r}^{\,2}\rangle_{\text{halo}}/6$, where $\langle \vec{r}^{\,2}\rangle_{\text{halo}}^{1/2}$ is the mean square radius of the neutron halo. We finally find

$$F(\vec{q}) \approx [1 + i\chi_{\text{halo}}(0)] F_{\text{core}}(\vec{q}) + N f_{pn}(\vec{q}) \left[1 - \frac{\vec{q}^2\langle \vec{r}^{\,2}\rangle_{\text{halo}}}{6}\right] . \tag{5}$$

We recall that expression (5) has been derived for the case in which the halo is considerably larger than the core.

That component of the slope of the differential cross section which stems from scattering by halo neutrons at a small momentum transfer (at a small scattering angle) depends on only a single parameter (if the number of neutrons in the halo is known). This one parameter is the mean square radius, which can thus be determined from the measured slope of the cross section. Scattering by the core of course also contributes to this slope at small angles. This contribution, however, can be dealt with easily, since the size of the core can be determined from the behavior of the cross sections at large angles, where the contribution from scattering by the halo is relatively small.

The conclusions reached in this qualitative analysis have found support in accurate calculations of the amplitude for elastic $p\ ^{11}\text{Li}$ scattering at an energy of 1 GeV directly from the expression of the Glauber–Sitenko theory (Fig. 1). Several calculations were carried out, with quite different shapes of the halo density distribution, at a fixed mean square radius of the halo. The differences between the calculated cross sections turned out to be minor (the corresponding curves are not drawn in Fig. 1, since they nearly merge). The mean square radii found for the neutron halo from the calculated slope of the differential cross section at small angles differ only slightly (by 1%–4%) from the halo radius incorporated in the model for the $^{11}\text{Li}$ nucleus. It has thus been shown that the mean square radius found for the neutron halo by this approach is indeed only a weak function of the particular model used for the distribution of the halo neutrons.

[1] I. Tanihata, Nucl. Phys. A **522**, 275 (1991).

[2] G. D. Alkhazov, S. L. Belostotsky, and A. A. Vorobyov, Phys. Rep. **42**, 89 (1978).

[3] G. D. Alkhazov *et al.*, in *Abstracts of Planned Experiments in Elementary Particle Physics and Nuclear Physics. Proceedings of the Winter School of the Leningrad Institute of Nuclear Physics,* Leningrad, 1991, p. 28.

[4] G. D. Alkhazov *et al.*, in *Abstracts of International Conference on Nuclear Shapes and Nuclear Structure at Low Excitation Energies,* Cargese, 1991, p. 2.

Translated by D. Parsons