Final Remarks

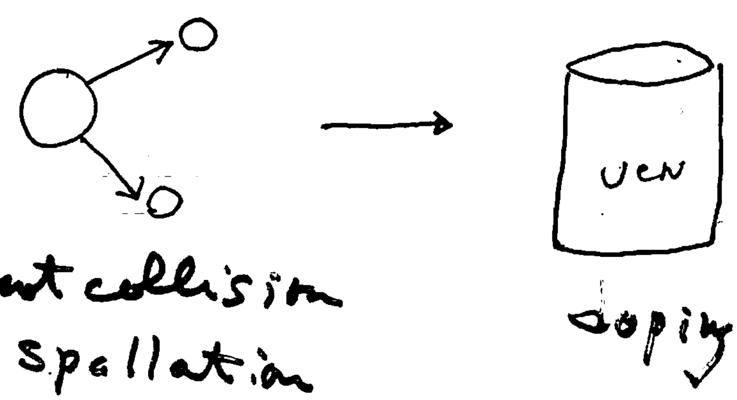
UCN will provide a new way of probing nuclear force

and

will give further insights to nuclear synthesis, formation of neutron stars, and others.

For halo-physics

fragmentation ⟶ dopping in UCN



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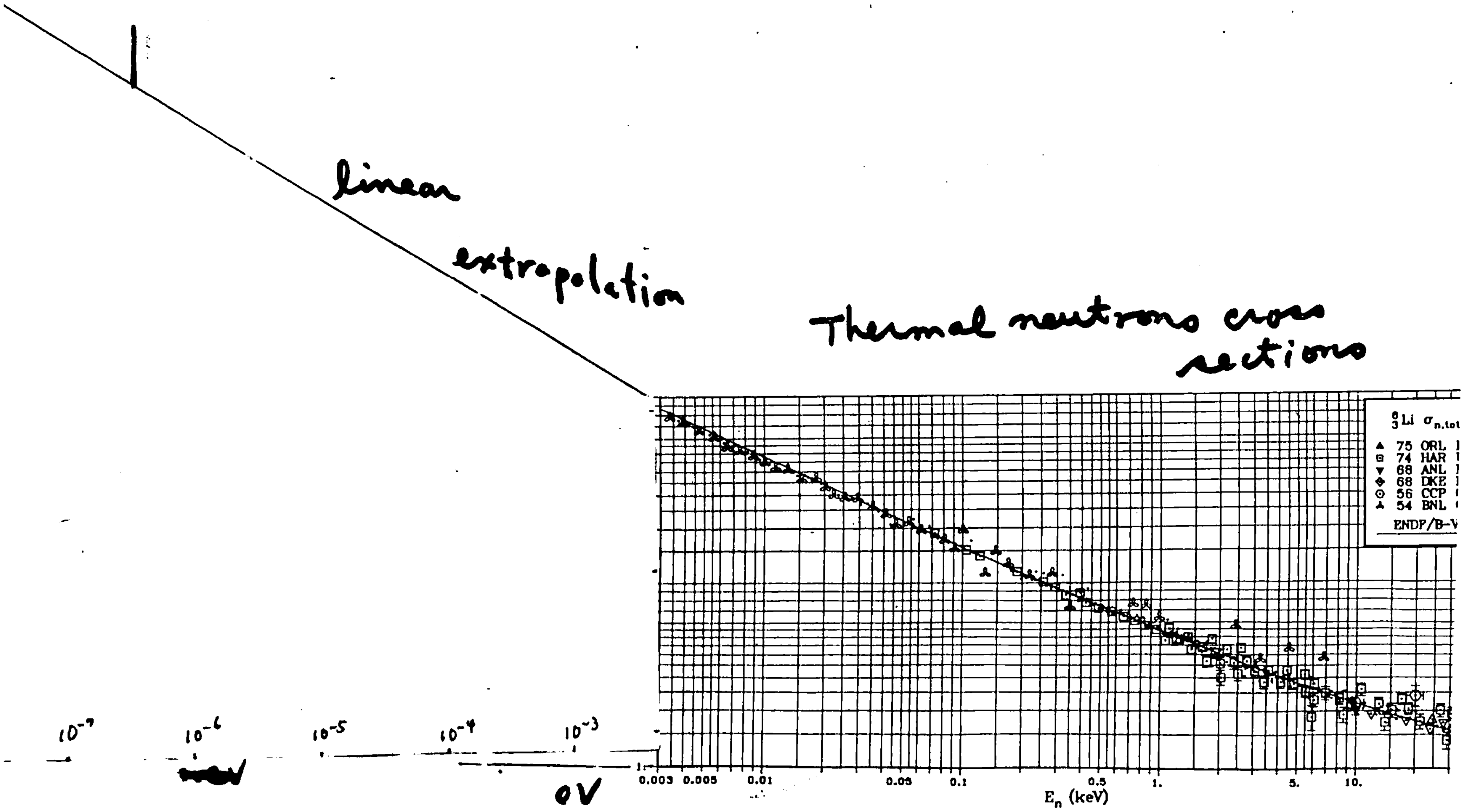
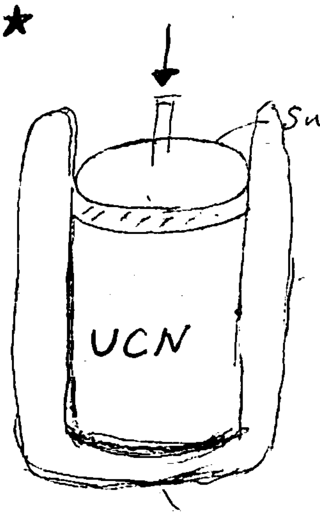


linear
extrapolation
Thermal neutrons cross sections
$^6_3$Li $\sigma_{n,tot}$
▲ 75 ORL
▫ 74 HAR
▼ 68 ANL
◆ 68 DKE
⊙ 56 CCP
⅄ 54 BNL
ENDF/B-V
0.003 0.005 0.01 0.05 0.1 0.5 1. 5. 10.
E_n (keV)
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3}
eV

(III) How can we make nuclei of extremely neutron rich nuclei using UCN facilities ?

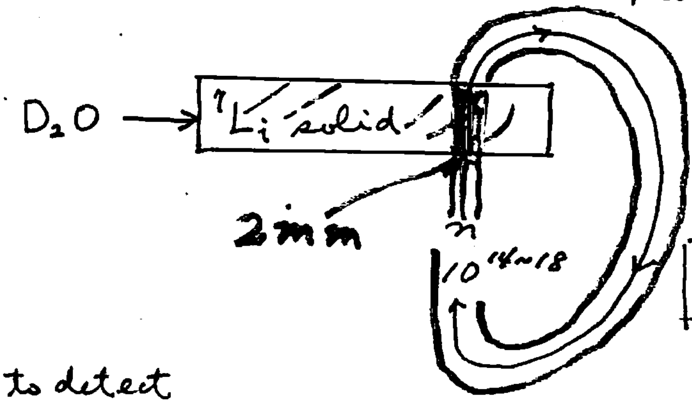
- High UCN density
- Make CN absorbed by nuclei
- Cross section increases as $E \to$ small : $E \to 10^{-2} \longrightarrow \sigma \to 10^{1.2}$
- Spin x Spin interaction
  2 neutron Singlet state
  under "weakened" nuclear force

★



vapor settled nucleus on the surface at the bottom

★ Using the fact not many UCN's are produced (meaning the most of incoming neutrons are absorbed or deflected in the cooling process)



$^{14}L_i$ is produced

★ How to detect

^6L_i (stable), ^7L_i (stable), ^8L_i (863 ms), ^9L_i (178 ms)

$^{11}L_i$ (8.7 ms)

(II) Has it been produced ? ΔE, 2n removal is smalle

An example : ^{11}Li ? $\left(\begin{matrix} Z=3 \\ N=8 \end{matrix} \right)$ $\left\{ \begin{matrix} ^{9}Li + 2n \\ ^{11}Li + n \end{matrix} \right.$

$t_{life} \sim 10\ ms$

Two components in momentum distribution ?
"not decisine"

fragmentation $^{11}Li + A \rightarrow {}^{9}Li + X$

small δ, large radius.

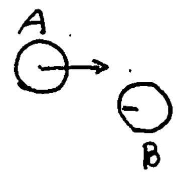
momentum distribution of ^{9}Li produced.

(·) Heavy Ion experiment showed momentum distribution, the width is the avarage of Fermie motions of constituents, of stable nuclei such as C^{12}, ^{16}O, ^{14}N etc

Kobayashi et. al (1988)

History

<u>Peripheral Interaction</u> of nuclei collision



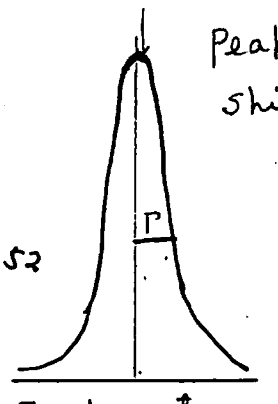
A fragments

(Small energy exchange)

momentum distributions of fragments are Gaussian

$A = {}^{12}C, {}^{16}O, {}^{14}N$

$1 \sim 3$ GeV/c per nucleons



D. Greiner. Physical Review Letters 35 (1975), 152

N. A. Orr Physical Review C51 (1995) 3116

for a halo nucleus is the sum of two differential cross sections having two different diffraction minimums due to the two nucleon distributions which behave incoherently with respect to each other; more generally, incoherence of halo neutron wave functions with respect to ordinary nucleon wave functions implies that the probability for any process is the sum of two probabilities,the probability for the process to occur with halo neutrons and the probability for the process to occur with the other nucleons. Namely in the case of a nucleus with a halo, neutrons in the halo act as independent entities distinguishable from nucleons in the core, while in the case of neutrons in the skin, there are no independent and no incoherent behavior with respect to any other nucleons in the nucleus.

To express the above idea mathematically, we express the wave functions for a nucleus with halo and a nucleus with skin using one particle wave functions. We denote the numbers of nucleons, protons, neutrons, and neutrons in halo by A, Z, N, and k, where A=Z+N, and k neutrons out of N are forming a halo around a core made out of Z protons and (N-k) neutrons.

The neutron distribution function for a nucleus having a neutron skin is expressed by the square of the totally antisymmetrized wave function of N neutrons. If we express the wave function in terms of single particle wave functions, $\phi(\vec{r})$ for an example, the antisymmetrized wave function for a nucleus without halo can be written as a Slater determinant,

$$\Psi_{neutron}(\vec{r}_1, \vec{r}_2, \ldots \vec{r}_N) = \frac{1}{\sqrt{N!}} \begin{vmatrix} \phi_1(\vec{r}_1) & \phi_2(\vec{r}_2) & \ldots & \phi_N(\vec{r}_N) \\ \phi_1(\vec{r}_N) & \phi_2(\vec{r}_1) & \ldots & \phi_N(\vec{r}_{N-1}) \\ \multicolumn{4}{c}{\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots} \\ \multicolumn{4}{c}{\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots} \\ \phi_1(\vec{r}_2) & \phi_2(\vec{r}_3) & \ldots & \phi_N(\vec{r}_1) \end{vmatrix}$$

The so called neutron skin will come from the neutrons which are occupying the states in the larger quantum numbers. On the other hands, the wave function of the halo nucleus

as halos even though there exist new effective field theoretical attempts[8] that connects to QCD. For this reason, we rely on qualitative analysis.

2 Neutron Skin or Neutron Halo

The difference between neutron skins and neutron halos has never been analyzed explicitly[9] and the two terminologies are often used interchangeably[5]. The loosely bound neutrons in the neutron distributions of nuclei near drip line form a neutron skin. In the skin, the proton distribution is small compared with that of neutron. The same is true for neutron halos and therefore the distinction between neutron skins and neutron halos is difficult to make from neutron distributions alone. Because neutron distributions can have long tails, large mean radii can come out for both cases. Should we call large neutron skins neutron halos? If that is the case, what is the limit of the size of neutron skins to be called neutron halos? If the distinction is purely quantitative, should we just use a modifier, such as "large" or "giant"., to describe the neutron skin instead of using an entirely different term, "neutron halo"?.

The neutrons in halo or skin are bound loosely regardless. Therefore the binding energy is not a good signature to distinguish the two. We propose to distinguish halo neutrons from skin neutrons by the difference of their behavior upon interaction with the other target/beam nuclei or particles: The neutrons in a halo (which is a part of a nucleus) behave incoherently with respect to the nucleons in the core(the major part of the nucleus) while all nucleons in ordinary nuclei without halos behave coherently as one unit in high energy interactions with strongly interacting elementary particles. In other words, in a halo nucleus, there are two groups of nucleons which are incoherently behaving with respect to each other. For example, the shapes in differential cross section data of elementary particles scattered from nuclei targets of ordinary kinds have the first diffraction minimums at around the radii of the target nuclei in a certain energy region. On the other hand the differential cross sections

These characteristics are in some literatures claimed to be the signatures of halo in nuclei ; they are necessary but not sufficient signatures for halo nuclei because of aforementioned reasons. The question is then; what are the qualitative differences between nuclei with halos and nuclei with large skins?

It has been suggested[4] that for halo nuclei, neutrons in the halo are incoherent with respect to nucleons in the core, in agreement with one's intuitive image of a halo. There are many theoretical analysis of halo nuclei based on various models as well as many experimental measurements for neutron and proton rich nuclei. We refer to all these works [5] in the publications of proceedings of conferences and in the reference in review articles for the related subjects in the reference except those directly concerned with the question and relevant to my present work. In recent years, further investigation [6] of longitudinal momentum distribution of ^{9}Li produced from ^{11}Li by peripheral interactions with various targets confirmed the existence of such narrow momentum distribution of ^{9}Li and precision experiments that select the ground state of fragments from neutron rich nuclei, ^{15}C and ^{11}Be have been performed[7].

In this letter, I wish to clarify the differences between a neutron halo and a neutron skin in model independent way. I look for qualitative differences in momentum distributions due to the difference described in detail below, namely the incoherent character of halo-neutrons. As the result of incoherent nature of halo-neutrons, an asymmetry in the momentum distributions, where there is a broadening of the momentum distribution which is more exaggerated in the negative direction in the center of mass system of halo-nuclei arises. This asymmetry is more easily observed than the two distinctive Gaussian distributions arising from interactions with halo neutrons and core neutrons. There are many successful models such as the Glauber model, the Skyrme method ,eikonal approximations, potential models, etc [5] which are useful for relating data. In my view, there is still no reliable low energy nuclear theory that can predict nuclear force saturation phenomena such

1 What is Neutron Halo?

D. Wilkinson[1] in 1967 suggested that in neutron rich nuclei, a few neutron might be loosely bound forming "halos." In general, Halo nuclei consist of two parts, the core and neutron halo surrounding the core. The core part is made of protons and neutrons with usual binding energy range, and the halo is made of only neutrons being bound to the core loosely. As name indicates, they behaves like two independent parts. Namely the nucleons in the two parts though they are made of identical neutrons behaves incoherently to incoming strongly interacting particles.

Is a halo nucleus found?: The narrow width(70 MeV/c) of transverse momentum distribution [2] in ^{9}Li fragments from neutron rich ^{11}Li ignited interest for the possibility of ^{11}Li having a halo. Because, in high energy ($\geq 1Gev/c$)heavy ion experiments, at that time, it was found that momentum distributions of fragments produced from ordinary natural nuclei such as ^{16}O in peripheral interactions were Gaussian whose widths were statistical averages of Fermi motions of the nucleons in the nuclei[3] (200-350 MeV/c). In addition, the unexpectedly large radius [2] indicated the possibility for ^{11}Li being an unusual nucleus (the number of neutrons in ^{11}Li is a magic number, 8). Taking notice of the small binding energy of two neutrons in ^{11}Li, the narrowness of one of the widths was considered as the revelation of such structure as halo[4] due to incoherent neutrons..

Is then, ^{11}Li indeed a halo nucleus? Are small binding energy, and large radius sufficient signatures for a nucleus to be described as a new type of nucleus, a halo nucleus? The answer is "No". Because many neutron rich ($(\frac{N}{Z}) \geq 1$ where N and Z are the neutron and charge numbers of a nucleus) nuclei have neutron skins due to the fact that the last few neutrons occupy the large principal quantum number states . Therefore these last few neutrons make the radius larger and can also have small binding energies comparing to that of the rest of nucleons in the core, which have a binding energies of order of a few MeV.

Contents of Discussion

(I) What is neutron halo?

(II) Has it been produced?

(III) How can we make nuclei of extremely neutron rich nuclei using UCN facilities?

On the possibility of forming neutron halos in using facilities of UCN

Fumiyo Uchiyama

Prepared for the International Conference on Physics with UCN

March 18, 2005

Abstract

We discuss about the possibility of forming neutron halos of nuclei using facilities of UCN. Neutron halos are nuclei possessing extremely large neutron and proton ratios which are characterized by the halo neutrons behaving incoherently with the rest of nucleons, that is the core-nucleons. The binding energies of these halo neutrons will be many orders of magnitudes smaller than the usual nuclear binding energies and the core-nucleons and the neutrons in halo are independently behaving in the interacting with other strongly interacting particles. Difference between halos and skin is described along with an possible example. Feasibilities of producing such halos utilizing UCN-facilities is discussed.