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Novel Structures of Exotic Nuclei

Vandana Arora[1]
[1](Department of Physics, Keshav Mahavidyalaya , University of Delhi ,India)

Abstract: *Due to structures and decay modes of nuclei in the vicinity of the neutron driplines a good amount of focus and research is required in this area. The hidden properties of these exotic nuclei are yet to be discovered completely. Nuclei near the neutron driplines are weakly bound and exhibit unique physical properties, which are of considerable interest for testing theories describing exotic nuclei.The present article is devoted to the study of these exotic nuclei .*
Background:
Key Word: *EXOTIC NUCLEI, HALO NUCLEI,TWO-NEUTRON SEPARATION ENERGIES*

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I. Introduction

Despite more than a century of intense study, the nucleus remains a fascinating quantum laboratory, still full of surprises. The most recent spectacular phenomenon in nuclear structure physics has been the advent of radioactive beams [1] allowing new nuclear phenomenon to be uncovered. With the help of radioactive beams we have explored the nuclear landscape far from stability. The significant advancement in experimental techniques has led to the discovery of exotic nuclear structures, such as Halo nuclei [1]. Halo is a threshold phenomenon resulting from weak binding of core and valence nucleon(s). There is quantum mechanical tunneling of nucleon(s) from core forming a diffused cloud around the core resulting in very large matter radius. The halo structure is comparable to the luminous rings found in our planetary system e.g. moon or the Sun , which is the source of the term halo for these exotic nuclei[2]. It has become the label for a few light exotic. The necessary condition for a nucleus to form a halo state is a small nuclear binding energy of valence neutron(s).

II. Discovery of Halo nuclei and Probing its structure

1) In 1985 Tanihata and his coworkers[1] made a startling discovery by measuring the interaction cross section of the radioactive ^{11}Li beam on the carbon target and found that the matter radius of ^{11}Li to be abnormally large (3.2 fm).We know for stable nuclei R shows a normal $A^{1/3}$ dependence ($R=R_0 A^{1/3}$, R_0=1.2 fm). However, the radii of ^{11}Li changes drastically. The r.m.s radius of ^{11}Li is 3.16 fm, as large as that of ^{48}Ca.
2) A large r.m.s value of radius is also found in nuclei being deformed which would provide a more natural solution to this anomaly. To clarify this, the crucial measurement of the quadrupole moment of ^{11}Li were made using β-NMR spectroscopy at ISOLDE[3], CERN. The value relative to the quadrupole moment of ^{9}Li was measured and gave the result
   $|Q(^{11}Li)/Q(^{9}Li)| = 1.14(16)$

Excluding a strong deformation of ^{11}Li and supporting the picture of a ^{9}Li core, unchanged by the additional neutrons.

3) A very convincing experiment illustrating the halo picture was performed by Blank and co workers[4]. They measured the charge changing and total reaction cross section of the isotopes ^{8}Li, ^{9}Li and ^{11}Li. The data was taken with taken with 80 MeV/u beam energy on a carbon target. The total interaction cross section rises drastically by adding two neutrons to ^{9}Li. In contrast, the charge changing cross section remained practically constant strongly supporting the idea that the core ^{9}Li is hardly influenced by the valence neutrons located far away from it.
4) To know the structural properties of halo nuclei the most promising method used is the measurement of momentum distributions of the reaction products after the fragmentation of the halo nucleus following the interaction with a target. With the help of shape and width of the momentum distribution one can estimate extent of halo. The narrow momentum distributions are typically associated with a large spatial extent showing halo nucleons situated far from the core. This is indeed in accordance to the Uncertainty Principle.

In fact, a very fruitful experiment was first performed by Kobayashi et al [5] and halo structure of light nuclei was established.

Experiments provided the compelling evidences of halo formation of matter into an ordinary core nucleus and weakly bound neutron(s) orbiting the core. Nuclear halo states have been found in number of light, nuclei close to the nucleon dripline. These shows a threshold phenomenon where a low separation energy allows the weakly bound nucleon to tunnel into the space surrounding the nuclear core to give a large nuclear radius.

There are mainly two types of halo state: the two-body halos with one nucleon surrounding the core, for example: ^{11}Be,^{19}C etc. and three body halos with two valence nucleons around the core, the key examples being ^{6}He ^{11}Li,^{14}Be,^{20}C,^{22}C etc.

Striking features of halo nuclei are:

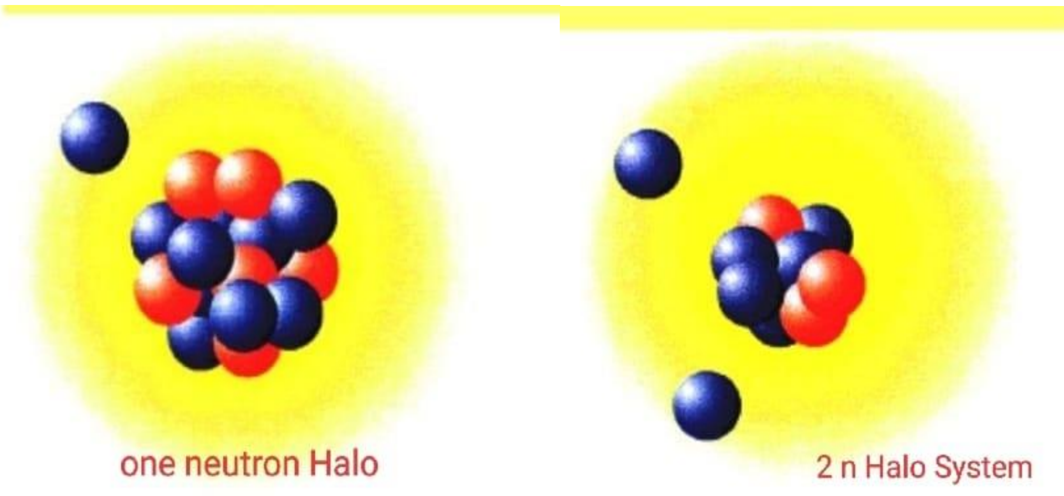
1) The separation energy S_n or S_{2n} of a valence nucleon(s) is extremely small (< 1 MeV) compared to the separation energy of a valence nucleon in a stable nucleus which is about 6-8 MeV. For example the two neutron separation energy for ^{11}Li is 0.3 MeV. Consequently, the wave function for these weakly bound neutrons extends far beyond the wave function of a neutron in a stable nucleus of similar mass. The low binding energy is an indication of a threshold phenomenon.

S no.	Candidate Name	Number of valence Nucleons	Separation Energy (MeV)
1.	^{6}He	2n	0.972
2.	^{11}Li	2n	0.300
3.	^{11}Be	1n	0.504
4.	^{14}Be	2n	1.260
5.	^{19}B	2n	0.550
6.	^{19}C	1n	0.580
7.	^{22}C	2n	0.420

Table 1: one and two neutron S_{2n} separation energies of halo nuclei candidates. This table is from Ref. [6]

2). Halo nuclei have abnormally large matter radius, a well-established relation (liquid drop model) $R=R_0 A^{1/3}$ is violated in halo nuclei. For instance ^{11}Li has radius of 3.2 fm as large as that of ^{48}Ca

3). Narrow momentum distribution of fragmentation products indicating that spatial spread is quite large in accordance to Heisenberg uncertainty principle.



To understand the novel structure of halo nuclei various models have been proposed. To study one halo system one can use simple two body cluster model of core nucleus plus valence neutron which are bound by a short range potential [7]. For 2n halo nuclei like ^{11}Li which is actually three body system having core plus valence neutrons weakly coupled a few body approach is required to understand its features [8]. The effective field theory seems to be useful in understanding low energy properties of halo nuclei [9].

III. Conclusion

Tremendous progress has been made over the last four decades in extending our knowledge into hitherto unknown regions of the nuclear chart. Today we know that there are 254 stable nuclei. However, a total of about 7000 different unstable nuclei are thought to exist, and almost 4000 of these have been created and studied in the laboratory. The discovery of neutron and proton halos have opened up new avenues of theoretical and experimental research. The halo nuclei are novel quantum systems having fragile binding of valence nucleon(s) with core resulting in astonishing large radius .The well-established one neutron halo are ^{11}Be and ^{15}C. The most studied two neutrons halos are ^{6}He, ^{11}Li and ^{22}C. As exotic nuclei have an open structure, the usual mean field theories and shell model breaks down. The new theories are required to understand the general properties of halo nuclei. Since in halo structure there is core and weakly bound nucleon(s) resulting in the either two-body system or three body system therefore a few body model is best suited to study such systems [8].

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