Simple model of neutron ''halo nuclei''

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Analysis of experiments with radioactive beams from ^{6}He to ^{20}C have yielded rms matter radii of neutron-rich nuclides. These radii increase more rapidly than $A^{1/3}$, suggesting the existence of neutron halos. We have used a single-particle potential model to compute these radii by adding the radius of a valence neutron in quadrature with that of the core. This radius is then taken to be the core radius of the next isotope, etc. The resulting radii are in reasonable agreement with reported values obtained with various models of reaction mechanism and nuclear structure. [S0556-2813(96)04009-5]

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INTRODUCTION

In the last ten years there have been many experiments with beams of light radioactive nuclei. Measurements of interaction cross sections by Tanihata *et al.* [1] for neutron-rich nuclei such as ^{8}He and ^{11}Li yielded nuclear cross sections that were considerably larger than expected for an $A^{1/3}$ dependence. Since then, experiments have been carried out with many neutron-rich radioactive beams. There have been many papers interpreting these cross sections in terms of the rms radii of the nuclides and different models of the nuclear structure of the projectiles and models for the interaction process ranging from pure mean-field approach [2] to ones with empirically adjustable parameters [3]. There is general agreement that single- or double-neutron binding energies play a dominant role. However, the resulting radii for many nuclides vary appreciably from paper to paper. For comparison, we present a simple boot-strap model in which the rms radius r_v of the valence neutron (obtained with a Woods-Saxon well) and a core radius r_c are combined in quadrature to yield a matter radius r_m. This approach allows configuration admixtures of the valence neutron to be simply examined.

Recent fragmentation experiments which determine the momentum distribution of the neutron support our method for r_v. In the experiment of Kelly *et al.* [4] with ^{11}Be($\frac{1}{2}^+$), the momentum distribution of the valence neutron corresponds to that of a $2s$ neutron bound in a Woods-Saxon well; the valence radius is 6.5 fm, much larger than the 2.3 fm radius of the ^{10}Be core.

The description of these light neutron-rich nucleii as having a ''halo'' or ''skin'' implies that the charge radius in a isotopic sequence remains essentially constant as neutrons are added. Our model explicitly assumes this. Hartree-Fock calculations indicate that this is a fair approximation. Bertsch *et al.* [2] find, for example, that the charge radii for ^{7}Be to ^{14}Be changes by at most only 0.14 fm, while r_m varies by 1.52 fm. Liatard *et al.* [5] find a change of charge radius between ^{9}Be and ^{14}Be of only 0.07 fm, while Tanihata *et al.* [6] find that the change for ^{4}He to ^{8}He is 0.13 fm, while r_m changes by 0.83 fm.

BOOT-STRAP MODEL

We start with a $T=0$ (or $T=\frac{1}{2}$) core such as ^{4}He, ^{6}Li, ^{7}Be, etc., whose rms matter radius (r_m) is ''known'' (i.e., previously reported in the literature). Then we proceed to determine the valence rms radius (r_v) using the Woods-Saxon well to correctly bind the valence neutron of ^{7}Li. Using the r_m of ^{6}Li as the core radius (r_c) in ^{7}Li, we compute the matter radius of ^{7}Li via the equation [7]

$$r_m^2(A)=\frac{A-1}{A}\left\{r_c^2+\frac{1}{A}\,r_v^2\right\}. \tag{1}$$

We then find r_m for ^{8}Li by coupling its valence neutron radius to the just-computed r_m for ^{7}Li, etc. In cases where the orbital of valence neutron is uncertain, we present possible choices as for example for ^{12}Be (0^+) where it could be $2s$, $1p$, or $1d$ coupling to ^{11}Be $\frac{1}{2}^+$, $\frac{1}{2}^-$, or $\frac{5}{2}^+$ cores.

This procedure fails when the core nuclide (such as ^{5}He, ^{10}Li, etc.) is unbound. Therefore to compute r_m for ^{11}Li, e.g., we use a ^{9}Li core and assume that the $2n$ binding is equally shared by the two neutrons [2,8,9]. Then, using $B(2n)/2$ for each, we find r_v and then use $(A-2)/A$ and $2/A$ in Eq. (1).

Our results are presented in Table I. After the mass number A and the spin of the nuclide are the core and its spin, followed by B_v, the valence binding. The angular momentum l_v of the valence neutron is then used to determine the radius r_v in a Woods-Saxon well. The well parameters used throughout were $r_0=1.25$ fm, $a=0.65$ fm, and $V_{ls}=0$. (The predicted radii are insensitive to moderate changes of these parameters.) The eighth column lists the core radius r_c (r_m of the preceding isotope). The next column gives the ratio of r_v to r_c for later reference. Our computed matter radius is in the tenth column. The remaining columns A–F list values of r_m which have been reported in the literature. Our results are also presented in Fig. 1, viz, r_m vs A for each element, displaying our values and the reported values.

COMMENTS ON TABLE I AND FIG. 1

(a) He isotopes. For ^{4}He, we assume the average of Columns A and B. The reported values for ^{6}He range from 2.46 to 2.75 fm; our result coincides with their average. For ^{8}He, ours is about 0.4 fm above the three reported values. The qualitative agreement is quite satisfactory.

(b) Li isotopes. For ^{6}Li we took 2.30 fm, a simple average of the reported values. The comparison for ^{7,8,9}Li is fair except for the calculations of Bertsch *et al.* [2] (column E). Our

TABLE I. Computations of rms matter radii of neutron-rich nuclides.

Nucleus	J_A^π	Core	J_c	l_v	B_v	r_v	r_c	$\left(\frac{r_v}{r_c}\right)$	r_m	*A* [3]	*B* [1,6]	*C* [5]	*D* [16]	*E* [23]	*F* [15]
^{4}He	0^+								1.58	1.57	1.59				
^{6}He	0^+	^{4}He	0^+	1	$\frac{0.98}{2}$	4.74	1.58[a]	2.96	2.58	2.46	2.52		2.75		
^{8}He	0^+	^{6}He	0^+	1	$\frac{2.14}{2}$	4.18	2.58	1.61	2.88	2.46	2.55		2.55		
^{6}Li	1^+									2.20	2.35	2.46	2.50	2.03	
^{7}Li	$\frac{3}{2}^-$	^{6}Li	1^+	1	7.25	2.81	2.30[a]	1.22	2.34	2.25	2.35	2.38	2.51	2.07	
^{8}Li	2^+	^{7}Li	$\frac{3}{2}^-$	1	2.03	3.66	2.34	1.56	2.50	2.47	2.38	2.58	2.60	2.18	
^{9}Li	$\frac{3}{2}^-$	^{8}Li	2^+	1	4.06	3.22	2.50	1.29	2.57	2.59	2.32	2.53	2.50	2.22	2.45
				0	$\frac{0.30}{2}$	10.3	2.57	4.01	4.61						
^{11}Li	$\frac{3}{2}^-$	^{9}Li	$\frac{3}{2}^-$	1	$\frac{0.30}{2}$	6.38	2.57	2.48	3.38	3.15	3.10	2.78	3.05	2.85	3.26
				2	$\frac{0.30}{2}$	4.17	2.57	1.62	2.83						
^{7}Be	$\frac{3}{2}^-$									2.34	2.33		2.45	2.09	
^{9}Be	$\frac{3}{2}^-$	^{7}Be	$\frac{3}{2}^-$	1	$\frac{20.56}{2}$	2.72	2.30[a]	1.18	2.32	2.32	2.38	2.53	2.59	2.18	
^{10}Be	0^+	^{9}Be	$\frac{3}{2}^-$	1	6.81	2.96	2.32	1.28	2.37	2.40	2.28	2.48	2.43	2.25	
^{11}Be	$\frac{1}{2}^+$	^{10}Be	0^+	0	0.50	7.06	2.37	2.98	3.02	2.92	2.71	3.04		2.77	2.90
^{11}Be*	$\frac{1}{2}^-$	^{10}Be	0^+	1	0.18	6.18	2.37	2.60	2.85					2.72	
^{12}Be	0^+	^{11}Be	$\frac{1}{2}^+$	0	3.17	4.25	3.02	1.41	3.12	2.54	2.57	2.62		2.57	
		^{11}Be*	$\frac{1}{2}^-$	1	3.49	3.44	2.85	1.21	2.91						
^{14}Be	0^+	^{12}Be		0	$\frac{1.12}{2}$	6.94	2.91	2.40	3.67	3.01	3.11	3.36		3.61	
				2	$\frac{1.12}{2}$	4.05	2.91	1.40	3.05						
^{10}B	3^+									2.42		2.56			
^{11}B	$\frac{3}{2}^-$	^{10}B	3^+	1	11.45	2.72	2.49[a]	1.09	2.50	2.41		2.61			
^{12}B	1^+	^{11}B	$\frac{3}{2}^-$	1	3.37	3.46	2.50	1.38	2.58	2.53	2.35	2.72			
^{13}B	$\frac{3}{2}^-$	^{12}B	1^+	1	4.88	3.27	2.58	1.27	2.64	2.63	2.46	2.75			
^{14}B	2^-	^{13}B	$\frac{3}{2}^-$	0	0.97	5.86	2.64	2.22	2.97	2.73	2.40	3.00			
				2	0.97	3.89	2.64	1.47	2.74						
^{15}B	$\frac{3}{2}^-$	^{14}B	2^-	0	2.77	4.66	2.97	1.57	3.08	2.69	2.40	2.61			2.70
				2	2.77	3.53	2.74	1.29	2.80						
				0	$\frac{1.35}{2}$	6.58	2.80	2.35	3.40						
^{17}B	$\frac{3}{2}^-$	^{15}B	$\frac{3}{2}^-$	2	$\frac{1.35}{2}$	4.11	2.80	1.45	2.95	3.00		4.10			
				2	$\frac{1.35}{2}$	4.11	3.08	1.33	3.19						
^{12}C	0^+									2.36	2.32	2.48		2.47	
^{13}C	$\frac{1}{2}^-$	^{12}C	0^+	1	4.95	3.25	2.42[a]	1.34	2.48	2.45		2.42			
^{14}C	0^+	^{13}C	$\frac{1}{2}^-$	1	8.18	3.00	2.48	1.21	2.51	2.46		2.50			
^{15}C	$\frac{1}{2}^+$	^{14}C	0^+	0	1.22	5.53	2.51	2.21	2.79	2.74		2.78			
(^{15}C*)	$\frac{5}{2}^+$	^{14}C	0^+	2	0.48	4.15	2.51	1.65	2.64						
^{16}C$_1$	0^+	^{15}C	$\frac{1}{2}^+$	0	4.25	4.05	2.79	1.43	2.87	2.60		2.76			
^{16}C$_2$	0^+	^{15}C*	$\frac{5}{2}^+$	2	4.99	3.36	2.64	1.27	2.67						
^{17}C$_1$	$\frac{5}{2}^+$	^{16}C$_1$	0^+	2	0.73	4.11	2.87	1.43	2.95	3.02		3.04			
^{17}C$_2$	$\frac{5}{2}^+$	^{16}C$_2$	0^+	2	0.73	4.11	2.67	1.54	2.77						
^{18}C$_1$	0^+	^{17}C$_1$	$\frac{5}{2}^+$	2	4.19	3.51	2.95	1.19	2.98	2.82		2.90			
^{18}C$_2$	0^+	^{17}C$_2$	$\frac{5}{2}^+$	2	4.19	3.51	2.77	1.29	2.81						
^{19}C	$\frac{1}{2}^+$	^{18}C$_2$	0^+	0	0.16(11)[b]	10^{+3}_{-1}	2.81	3.6	$3.53^{+0.45}_{-0.14}$	3.75					
^{20}C	0^+	^{19}C	$\frac{1}{2}^+$	0	~3.34[b]	~4.37	~3.53	~1.24	~3.56	3.05					
^{22}C	0^+	^{20}C	0^+	2	$\frac{1.12(0.92^b}{2)}$	~4.40	~3.56	~1.23	~3.62						

[a]Average of reported radii (A–F) of core nuclides.
[b]Audi and Wapstra, Nucl. Phys. **A565**, 1 (1993).

values are about 0.3 fm larger than Ref. [2] for ^{6,7,8,9}Li and about 0.5 fm larger for ^{11}Li. The difference originates mainly from the radius for ^{6}Li, which we take from experiment, but which is calculated in Ref. [2].

In Fig. 1 we plot the $\ell=1$ results for the individual nucleons of the neutron pair in ^{11}Li. However, recent papers by Benenson [10] and by Zinser *et al.* [11] suggest that the two neutrons could be an equal mixture of $(1p)^2$ and $(2s)^2$. Calculation assuming $(2s)^2$ leads to $r_m=4.61$ fm, completely off scale in Fig. 1, arguing against an appreciable admixture of $(2s)^2$. However, recent calculations by Brown [12] lead to an admixture of 61% $(1p)^2$, 26% $(1d)^2$, and 13% $(2s)^2$. These yield a weighted r_m of 3.40 fm, the $1d$ and $2s$ components offsetting each other. Recent measurements [13] of

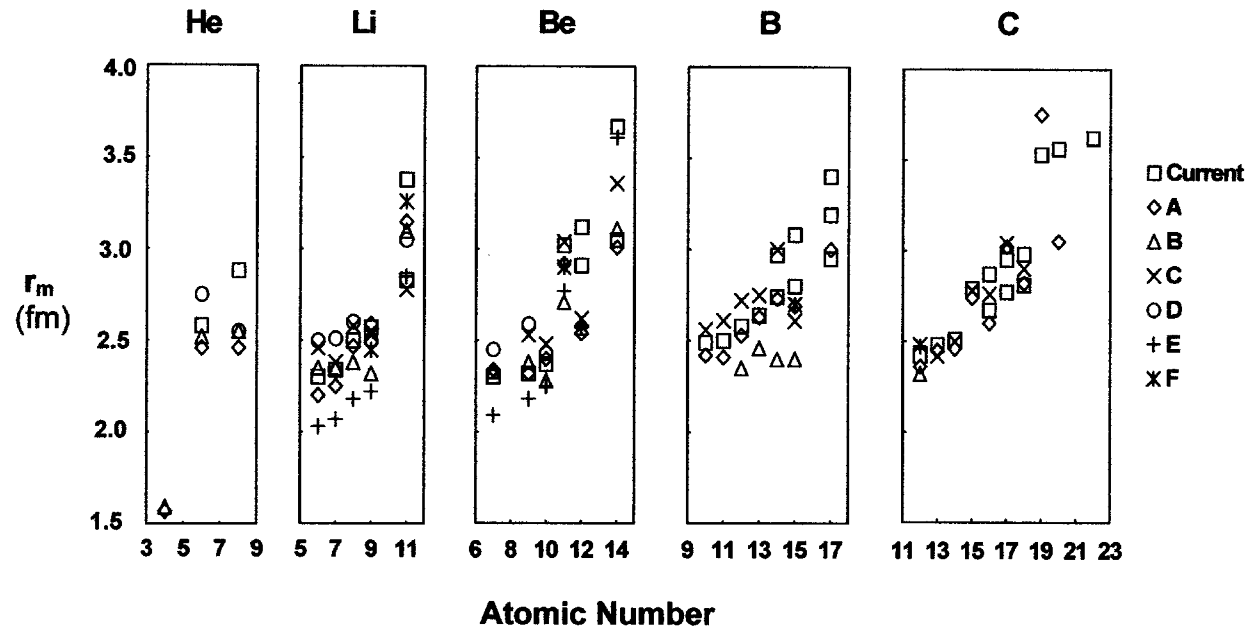

FIG. 1. Plot of r_m vs A for He, Li, Be, B, and C isotopes. (see Table I).

the momentum distributions of ^{9}Li arising from the breakup of a ^{11}Li beam (similar to the ^{11}Be breakup of Ref. [4]) lead to the conclusion that there was an extended neutron distribution with an rms halo radius of about 5 fm, which is not inconsistent with an r_v of 6.31 obtained with Brown's configuration.

(c) Be isotopes. Our starting point is the average of reported values, 2.30 fm, for ^{7}Be. The tight $2n$ binding in ^{9}Be leads to a barely larger r_m of 2.32 fm. The weak binding of the $2s$ neutron of the ^{11}Be ground state yields an r_v of 7.1 fm, consistent with the findings of Ref. [4]. As in the Li isotopes, our results parallel those of Bertsch *et al.* [2] for ^{9,10,11}Be, but are 0.14–0.25 fm larger (as a result of the core radius for Be).

For ^{12}Be, if we assume the $1p_{1/2}$ shell is filled, our values of r_m are about 0.35 fm greater than the reported values. Fortune, Liu, and Alburger [9] recently reported on the ^{10}Be(t,p) ^{12}Be reaction and concluded that ^{12}Be has comparable $(sd)^2$ and (p^2) components. The r_m values for $(1p)^2$ and $(2s)^2$ are tabulated. ^{11}Be$(\frac{5}{2}^+)$ is unbound, but using $(\frac{5}{2}^+)^2$ bound to ^{10}Be, we estimate 2.84 fm for r_m. Thus a mixture of all three components would still be too high. Considering ^{12}Be as $(1p)^2$ coupled to ^{10}Be yields a more compatible radius of 2.61 fm. In Ref. [2], an admixture of 71% $(2s)^2$ and 29% $(1d)^2$ was used. This admixture yields $r_m=3.47$ fm, in fair agreement with columns C and E. Our overall qualitative fit to the reported values for the Be isotopes is good, showing the large changes at ^{11}Be and ^{14}Be.

(d) Boron isotopes. The agreement for $A=10$–13 is good. For ^{14}B where we expect either a $2s$ or $1d$ neutron, values are computed for each ℓ. Unfortunately the reported values cover the range for both. However, for ^{15}B, the reported values suggest a d^2 configuration. For ^{17}B three configurations are computed. Of the reported values, one agrees with d^4, while the second goes off scale in Fig. 1. If we assume $1p$ and $1d$ filling, there is no suggestion of overly large neutron radii. If, however, there is appreciable $2s$ admixture in ^{14}B or ^{17}B, these might be halo nuclei. Shell model predictions would be interesting.

(e) Carbon isotopes. Beyond ^{14}C, the $2s$ and $1d$ orbitals are available. The odd-A nuclei can have $J^\pi=\frac{1}{2}^+$ or $\frac{5}{2}^+$, while for even A there can be a mixture of $(2s)^2$ and $(1d)^2$. Consequently, we designate the nuclei where $(2s)^2$ components may occur by the subscript 1, e.g., ^{18}C, and subscript 2 for pure $(1d)^{2n}$. One can see that the change in r_m is small and both are in good agreement with published results. Recent fragmentation measurements [14] for ^{17,18,19}C show momentum distributions for ^{19}C consistent with $\frac{1}{2}^+$ and suggest $\frac{5}{2}^+$ for ^{17}C. We adopt these assignments, but note than for $\frac{1}{2}^+$, for ^{17}C$_2$, $r_m=3.00$, in excellent agreement with columns A and C, but is disagreement with the measurements Ref. [14]. However, $\frac{5}{2}^+$ for ^{19}C yields a small $r_m\approx3.0$ fm. Our valence radius for ^{19}C$(\frac{1}{2})$ is about 10 fm, larger than 6.0 ± 6.9 fm of Ref. [14], probably a difference arising because our B_v is 0.16(11) MeV, while they use 0.242(93) MeV. For ^{17}C$(\frac{5}{2}^+)$, our r_v is 4.1 fm, while they report 3.0(6) fm. For ^{20}C we find $r_m=3.56$ fm for an $(2s)^2$ configuration and about 3.1 fm for $(1d)^2$; the reported value is 3.05 fm, suggesting a major $(1d)^2$ amplitude. Detailed shell model calculations would be interesting to compare with our computations.

In view of the appreciable variation of reported values, it is evident that there is no unambiguous way to deduce r_m from the experimental data. Therefore an overall comparison with our model is limited to generally qualitative agreement.

The basic experimental data which lead to calculations of r_m have been the experimental cross sections obtained from transmission measurements (or equivalent techniques). These cross sections, for complex nuclei, are generally assumed to be

$$\sigma_1=\pi(R_p+R_t)^2,$$

where R_p and R_t are the "interaction radii" of projectile and target [1,2]. The various values of r_m inferred from R_p and

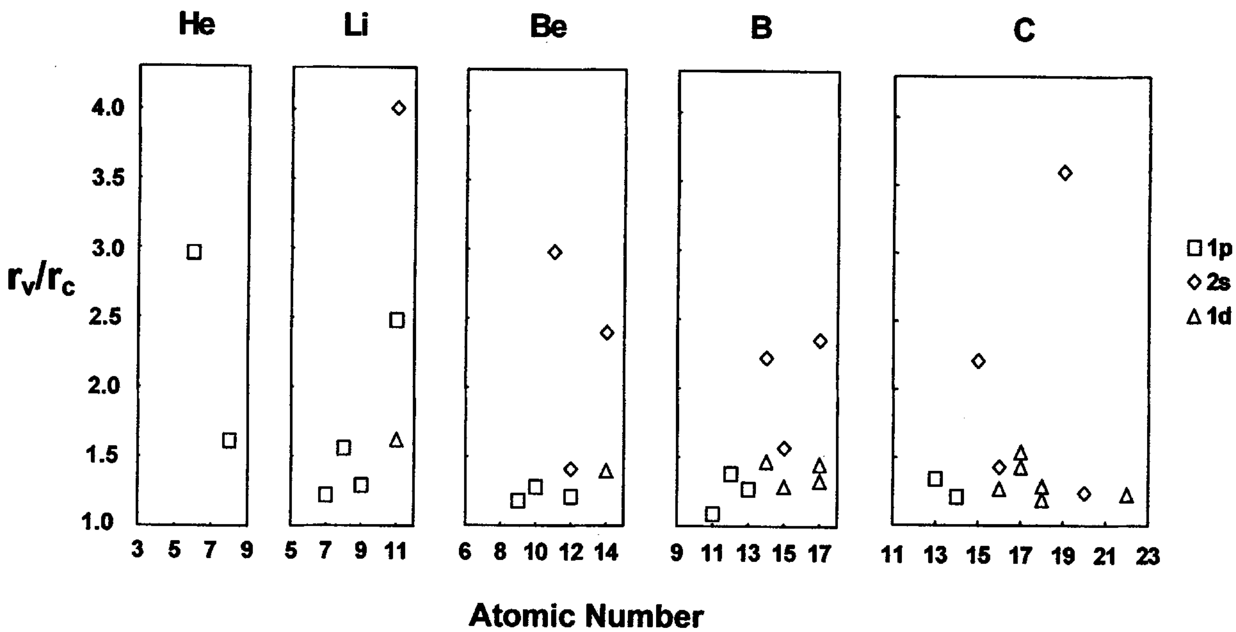

FIG. 2. Plot of (r_v/r_c) vs A for various isotopes. Isotopes for which this ratio is greater than ~2 are considered halo nuclei.

listed here were based on models for nuclear densities which were then usually used in Glauber-type interaction models to either deduce or fit the experimental interaction cross sections or R_p.

Tanihata *et al.* [1,6] used Gaussian or harmonic-oscillator densities and free *N-N* cross sections for point nucleons. Effects due to binding were not included. Bertsch *et al.* [2] used Hartree-Fock (HF) theory modified to account for binding energies. Their matter radii were also calculated with point density operators. As the actual nuclear radii require folding of nucleon sizes larger values would result than those listed in columns *B* and *E*. Sagawa [15] also used the Hartree-Fock model including spherical shell model occupation probabilities; the valence neutron was treated separately to account for its binding energy. Bang *et al.* [16] use a Woods-Saxon well for the last neutron, incorporating this with HF theory for the core particles.

Two of the listed papers use models with parameters adjusted to fit observed cross sections. Liatard *et al.* [5] use a simple model in which MS proton and neutron radii are added (weighted by *Z* and *N*) to yield the MS matter radius. The former is obtained from HF calculations while the latter is adjusted to reproduce the measured cross sections. Lassaut and Lombard [3] decompose the nucleus into a core and a weakly bound cluster, arriving at a two-parameter expression involving each cluster, and its binding energy. The two constants are adjusted separately for each isotopic series to maximize the fit to experimental cross sections. We note that as some measure of comparison between models, about 70% of our radii agree within 0.10 fm (roughly 3–5%) with each of the above two empirical models [3,5].

COMMENTS

Our model is perforce a ''halo'' model in the trivial sense that only r_n the rms neutron radii grows with neutron excess. A more unique meaning to ''halo'' is suggested by Riisager [17], namely, when there is a loose coupling between a core and valence particle or particles. In these cases, one observes large collision cross sections and narrow neutron momentum distributions [4,13,14]. Tanihata *et al.* [6] reported on rms-calculations for ^{4}He, ^{6}He, and ^{8}He and conclude that ^{6}He consists of an inert α core plus two neutrons, whereas ^{8}He does not have an ''inert'' ^{6}He core; they suggest that not all neutron excesses (skins) are to be classed as ''halos.'' Csoto [18] finds agreement with them for ^{6}He.

In our model it is simple to identify Riisager halo nuclides. Figure 2 is a plot of r_v/r_c. For most nuclides this ratio lies between 1.1 and 1.6. Then after a large gap we find ^{6}He(2.96), ^{11}Li(2.48), and ^{11}Be(2.98). Figure 2 suggests that ^{14}Be(2.40), ^{14}B(2.22), ^{17}B(2.35), ^{15}C(2.21), and ^{19}C(3.36) are Riisager nuclei.

Our model can easily be used to look for Riisager nuclides in other isotopic series. A preliminary look at nitrogen and oxygen (pending shell model predictions of configurations) yielded values of r_m in good agreement with Liatard *et al.* [5].

For ^{15}N to ^{22}N, the assumption of either $2s$ or $1d$ yielded about the same r_m. This varied smoothly with *A* and is well fitted with an r_0 (of the uniform model) of 1.38(2) fm. The highest ratio r_v/r_c is 1.65 for a $2s$ component of ^{18}N, while for the others the ratio is about 1.3.

For ^{16}O to ^{22}O, r_m was again insensitive to orbitals $2s$ or $1d$ and an r_0=1.33(1) fm yields a satisfactory *A* dependence. The largest r_v/r_c is 1.53 for ^{21}O if its spin is $\frac{1}{2}^+$, the remainder having a ratio below 1.3. For ^{23}O, however, the low neutron binding leads to $r_v \approx 9$ fm and r_v/r_c of 3.2 for a $2s$ orbital. If ^{24}O also involves the $2s$ orbital, the high binding yields a low r_v/r_c=1.29. Thus fragmentation of ^{23}O (and perhaps ^{18}N and ^{21}O) would be interesting to investigate.

CONCLUSION

Some puzzling problems may result from the weak binding of the Riisager nuclides, such as the structure of ^{11}Li, which is barely stable against two-neutron decay. However, only conventional shell model techniques [17,19] have been used here, but the final answer is not at hand. Furthermore, only conventional reaction theory has been used to interpret nuclear reactions such as stripping or pickup involving these neutron rich nuclei, e.g., ^{4}He(t,p) ^{6}He [20], ^{10}Be$(d,p)^{11}$Be [21], or the astrophysically interesting reaction (^{8}Li, ^{7}Li) [22]. Fragmentation experiments, such as ^{11}Be$\rightarrow^{10}$Be$+n$ [4], afford exceptionally convincing support for the single-particle model. While our extreme model is a far cry from the conventional mean-field approach, it illuminates the basic properties of halo nuclei.

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