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EXPLORATION OF THE NEUTRON-RICH MASS SURFACE FROM ^{11}Li TO ^{66}Fe

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INTRODUCTION

A small revolution in our ability to perform mass measurements of light-mass, neutron-rich nuclei has occurred during the last five years with the extension of the direct, total mass measurement method to fast recoiling nuclei. To date the work of two groups, one using the SPEG spectrometer at GANIL and the other using the TOFI spectrometer at LAMPF, has yielded over 85 mass measurements of which 62 had not been reported previously. Extending from the neutron-halo nucleus ^{11}Li up to ^{66}Fe, ' region relevant to the astrophysical r-process, these measurements have provided a valua irst glimpse into the interesting nuclear structure present in many of these exotic nuclei.

Herein we highlight the nuclear structure insight which has been gained from these measurements, especially that learned from a comparison to recent shell model calculations. Attention is given to: (1) the binding of loosely-bound neutron halo nuclei; (2) the N=14-16 region in the neutron-rich isotopes of O, F, and Ne where the strong two-body interaction plays an important role; (3) the deformed intruder state region around ^{31}Na of long standing interest; (4) the neutron-rich isotopes of sulfur and chlorine; and (5) the question of the isospin dependence (or independence) of neutron and proton pairing energies in the fp shell. Only the briefes. account of this work can be given here; emphasis is place on the most recent results.

DIRECT MASS MEASUREMENTS OF FAST RECOILS

As mentioned above two separate groups have pioneered slightly different approaches for determining the total mass of fast recoiling nuclei. In the mass measurements using the Energy-Loss Spectrometer SPEG[1-3], a combined two-parameter determination of velocity and magnetic rigidity is carried out, while at TOFI[4-7] a single-parameter measurement of the ion's time-of-flight through the Time-Of-Flight Isochronous spectrometer serves to determine the mass-to-charge ratio of the ion. Z and Q identifications were obtained in both approaches from additional measurements of stopping power, velocity, total kinetic energy, and/or range. The SPEG experiments rely on the concentration of projectile fragmentation products at forward angles using 30-100 MeV/u heavy ion beams, while the TOFI measurements utilize fast (1-4 MeV/u) recoils produced in 800-MeV proton-induced target fragmentation and fission reactions. Given that a large variety of recoils are produced in these reactions and that both methods have reasonably large acceptances and are fast (with flight times typically of 1 μs or less), both groups have been able to make a wide range of systematic measurements which extend far from the valley of β-stability. Typical mass resolutions for both approaches are on the order of 3×10^{-4} with mass measurement accuracies ranging from 70 keV to 1.6 MeV depending on counting statistics. For the most part, good agreement between these two fast recoil methods has been found (see Fig. 1 caption for noteworthy exceptions).

A convenient way of displaying the nuclear mass surface without the complication of the odd-even staggering due to neutron pairing is to plot the masses in terms of two-neutron separation energies (S_{2n}) versus neutron number. Several interesting nuclear structure features can be gleamed from such a plot (see Fig. 1 and the discussion that follows).

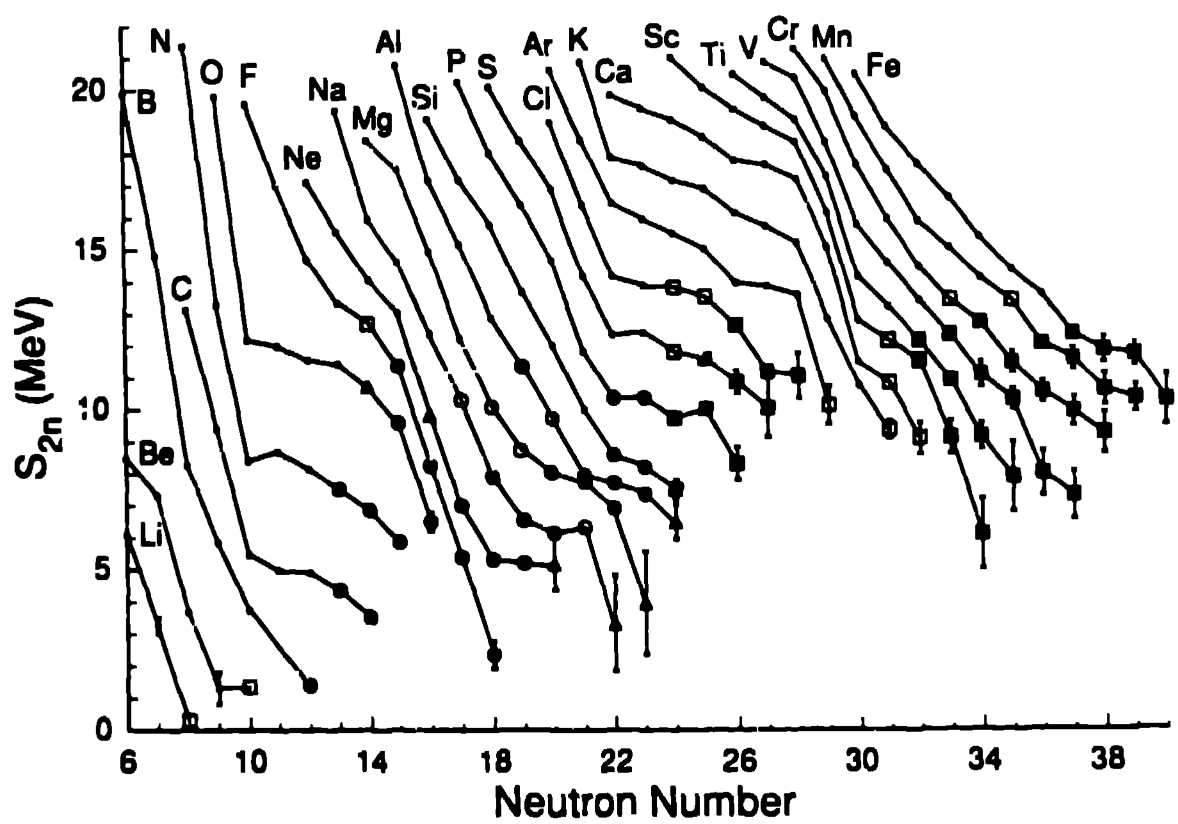

Fig. 1. Two-neutron separation energy versus neutron number for the neutron-rich isotopes of lithium to iron. Small data points (•) represent isotones with well known masses[8]. Open symbols indicate those isotopes for which masses have been remeasured and the solid symbols are given for those nuclei where the first mass determination was reported by either the SPEG or TOFI groups[1-7]. ● = SPEG + TOFI overlapping measurements; ▲ = SPEG measurements and; ■ = TOFI measurements. A weighted average of all reported masses is plotted with the exclusion of ^{27}Ne and ^{30}Na from Ref.[7], ^{38}P from Ref.[2], $^{31-34}$Na from Ref.[9,10], and ^{31}Mg from Ref.[11]. Error bars are given where they exceed the symbol size.

Z=3-15 NEUTRON RICH NUCLEI

Of current excitement are those nuclei which are very loosely two neutron (or single neutron) bound, such as ^{11}Li, (^{11}Be), ^{14}Be, ^{17}B, where enhanced interaction (both total and electromagnetic dissociation) cross sections have been observed. These results are being interpreted in terms of an increased neutron radius, i.e., "a neutron halo", the extension of which is directly related to how weakly bound the last neutrons are. In the case of ^{11}Li, for example, the rms radius of the last two neutrons is calculated[12,13] to be anywhere from 5 to 12 fm (i.e., roughly 2 to 5 times the size of the proton rms radius) depending on which model is used. To date three mass measurements[9,6,14] have been performed for ^{11}Li yielding S_{2n} values of 190 (110), 320 (120) and 340 (50) keV, respectively. The resulting weighted average is 315 (43) keV. Given that the size of the neutron halo is extremely sensitive to the S_{2n} value, additional higher precision measurements are needed to further constrain and test the validity of these models.

Other neutron-halo candidates worthy of attention are those of ^{19}B and ^{22}C which have been observed to be particle stable, but for which no mass determinations have been possible as yet due to their small production cross sections (roughly two orders of magnitude smaller than ^{17}B and ^{20}C). Using the latest SPEG and TOFI masses, the transverse Garvey-Kelson mass relationship[15] predicts S_{2n} values for ^{19}B and ^{22}C to be 360 and 110 keV, respectively. As such these nuclei should have neutron halos which are similar, if not larger, than that of ^{11}Li. Intensity and acceptance upgrades now being planned or built at several research facilities are likely to make the first measurement of such rare species possible.

Returning to Fig. 1, one prominent feature evident in this plot is the rapid S_{2n} falloff that occurs after N=8 which is then followed by a much slower decrease in S_{2n} values after N=10. This behavior is characteristic of a shell closure, in this case the completion of the p shell. Similar features, although less dramatic and not fully delineated here due to limitations in the vertical axis (i.e., several neutron-deficient isotopes have been excluded), are observed for the sd shell closure at N=20 and the completion of the $0f_{7/2}$ subshell at N=28. Analogous to the latter case, one might expect to see a sudden transition in the S_{2n} trend occurring at N=14 due to the completion of the $0d_{5/2}$ subshell. However, as is evident in the neutron-rich isotopes of O, F, and Ne, this transition occurs at N=15, not N=14. The explanation[6] of this effect came out of a detailed comparison to the shell model calculations of Wildenthal et al.[16] whose predictions, in contrast to most other mass models, were found to reproduce the observed S_{2n} trend in this region extremely well. In these calculations the single-particle energy spacing between the $0d_{5/2}$ and $1s_{1/2}$ levels is fairly small ($\sim$0.9 MeV), so the strong S_{2n} decrease observed in going from N=15 and N=16 results primarily from the interplay of two-body interactions, in this case the strongly attractive $[0d_{5/2} \cdot 0d_{5/2}]_{J=0}$ ($\sim$-3 MeV) interaction is dominant. At N=14 and N=15 the contribution made by this $0d_{5/2}$ $0d_{5/2}$ interaction to the calculated S_{2n} value is sizable, while at N=16 its effect is minimal. In a strong sense this work has provided a challenging test of the shell model and verified the two body interaction energies relevant to this region.

Moving up to the N=20 region one comes to the ^{31}Na region where enhanced binding energies relative to systematics and the predictions of most models has been noted for some time[9]. The SPEG and TOFI groups have now remeasured the masses of several Na isotopes and provided a number of new mass measurements for the adjoining Ne, Mg, and Al isotopes (see Fig. 1). The picture is now clear, given the good agreement between the SPEG and TOFI results, that the original[9] and subsequent[10] measurements of the Orsay group yielded masses which where consistently too bound with increasing deviations observed with increasing mass number, i.e., ^{31}Na (2.0 and 0.8 MeV, respectively), ^{32}Na (2.0 and 1.9 MeV), and ^{33}Na (and 4.0 MeV). Although the reported Orsay error bars are large (0.6 to 1.1 MeV), most of these deviations fall between 2 and 3 standard deviations.

After discussions[17] with the Orsay group, it appears that there where many possible sources of error in this early work, such as interference due to hydrocarbons, a bad divider network, and sagging high voltage during the accelerator beam pulses. Determining the true source of these errors now appears difficult and for the most part academic. However, the suggestion[4] that these errors may have arisen from boot strapping errors, analogous to those found[18] in the neutron deficient Cs isotopes, is unfounded given that the different isotopic combinations used in the Na triplet (or double doublet) measurements never involved more than one unknown.

As can be seen in Fig. 1, an up-to-date view of the $^{31-32}$Na region no longer shows a dramatic S_{2n} upturn only a small increase, while the adjacent isotopes of Ne and Mg exhibit a slowly decreasing S_{2n} trend. However, evidence of enhanced binding in these nuclei is still indicated. These enhancements can be seen better in Fig. 2 where we contrast the experimental masses to recent shell model calculations. Concentrating on the solid line, i.e., the comparison to the normal $0\hbar\omega$ calculations of Wildenthal et al.[16] and Warburton et al.[19], a large deficiency in binding (2-3 MeV) is predicted in the N=20-21 isotones of Ne, Na, and Mg. By including two particle–two hole neutron excitations from the sd shell to the fp shell, so-called $2\hbar\omega$ excitations, Warburton et al.[19] has shown in the limit of weak coupling that increased binding in these nuclei occurs. In particular, a deformed intruder state which is dominated by neutron $(fp)^2$-$(sd)^{-2}$ configurations is found to be more bound (by 0.4 to 1.1 MeV) than the lowest $0\hbar\omega$ state in the localized Z=10-12, N=20-22 region. Moreover, Warburton et al. go on to show that the lowest $1\hbar\omega$ state in the odd neutron N=21,23 isotones competes with the lowest $2\hbar\omega$ state as being the most bound state.

Other shell model calculations have been performed by Poves and Retamosa[20] in the limit of $(0+2)\hbar\omega$ mixing. Even better agreement is noted in Fig. 2, however, there is considerable debate as to the validity of these calculations. For example, this calculation could suffer from the exclusion of $4\hbar\omega$ and higher order excitations which are known[21] to strongly mix with $0+2\hbar\omega$ configurations causing a binding energy shift in the ground state. None the less, both approaches result in the same basic finding – that a deformed intruder state is more bound than the lowest $0\hbar\omega$ state giving rise to enhanced binding of Z=10–12, N=20–22 nuclei. Given the very localized nature of this strongly prolate deformed region and the rich nuclear spectroscopy that these nuclei promise, additional investigations are clearly needed.

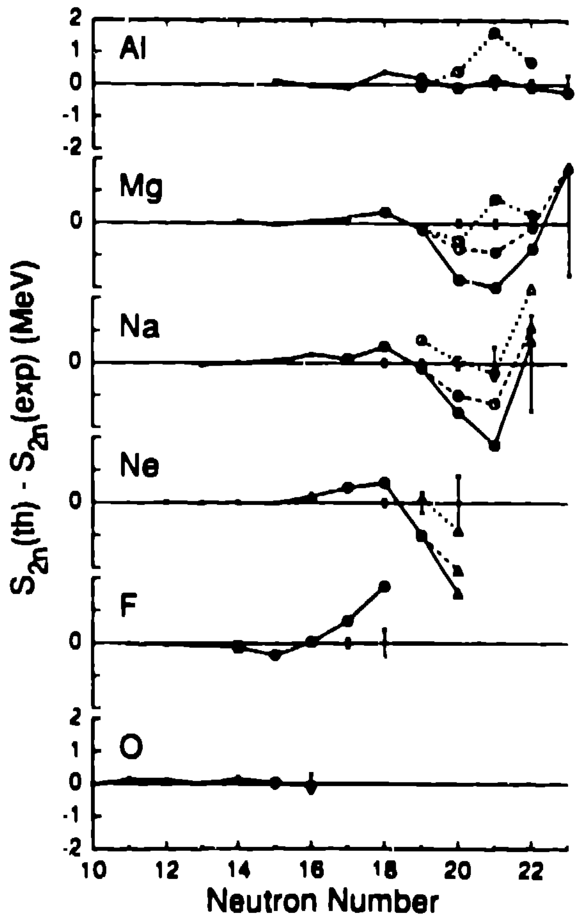

Fig. 2. A difference between the calculated two neutron separation energies and the experimental S_{2n} values is plotted versus neutron number for the neutron rich isotopes of Z=8–13. The symbols are as defined in Fig. 1. The solid line indicates the $0\hbar\omega$ shell model calculations of Wildenthal et al.[16] for N<18 or Warburton et al.[19] for N≥18. The dashed lines are for the $2\hbar\omega$ weak coupling calculations of Warburton et al.[19] and the dotted lines indicate the mixed $(0+2)\hbar\omega$ shell model calculations of Poves and Retamosa[20].

As is noted in Fig. 1 several new mass measurements have recently been reported in the heavier nuclei by the TOFI group[1,5]. Two major features are worth mentioning here one is a shell model comparison to several neutron-rich S and Cl isotopes and the second is the neutron and proton pairing energies for several Z=21-26 isotopes. Concerning the first topic, remarkably good agreement (rms deviation=280 keV) between the experimental mass of $^{40-43}$S and $^{41-45}$Cl and those predicted by the relatively restrictive $\pi 0d_{3/2}$ $\nu 0f_{7/2}$ shell model calculations of Hsieh et al.[21] was found. This agreement confirms the general observation that in the middle of both proton and neutron shells the shell model works quite well even within a limited basis space, while near shell closures problems often develop if the basis space is not large enough to include important cross-shell contributions.

Finally, we would like to turn your attention to pairing energies and the question of their isospin dependence. An evaluation[22,23] of pairing energy systematics has revealed an apparent neutron excess ((N-Z)/A) dependence in both neutron (Δ_n) and proton (Δ_p) pairing energies. However, we suspect that the observed dependence could arise from the natural correlation of pairing energy with mass number rather than with neutron-excess since the masses used in the evaluation covered a large mass range and that their fits where dominated by those nuclei lying along the valley of β-stability (i.e., the average neutron-excess and mass number are strongly correlated along stability). Moreover, the recent pairing energy study by Möller and Nix[24] finds that no inherent neutron excess dependence in the pairing interaction itself is required. To experimentally answers this question a localized test of pairing energies in a limited A region which covers a wide range of neutron-excess is needed. Given the strong increase in binding energy per nucleon and the individual character of light nuclei, the first region where such a test could be made is in the fp shell. Thus we have applied our latest mass measurements of neutron-rich $0f_{7/2}$ subshell nuclei[5] to examining the neutron excess dependence of pairing energies (see Fig. 3).

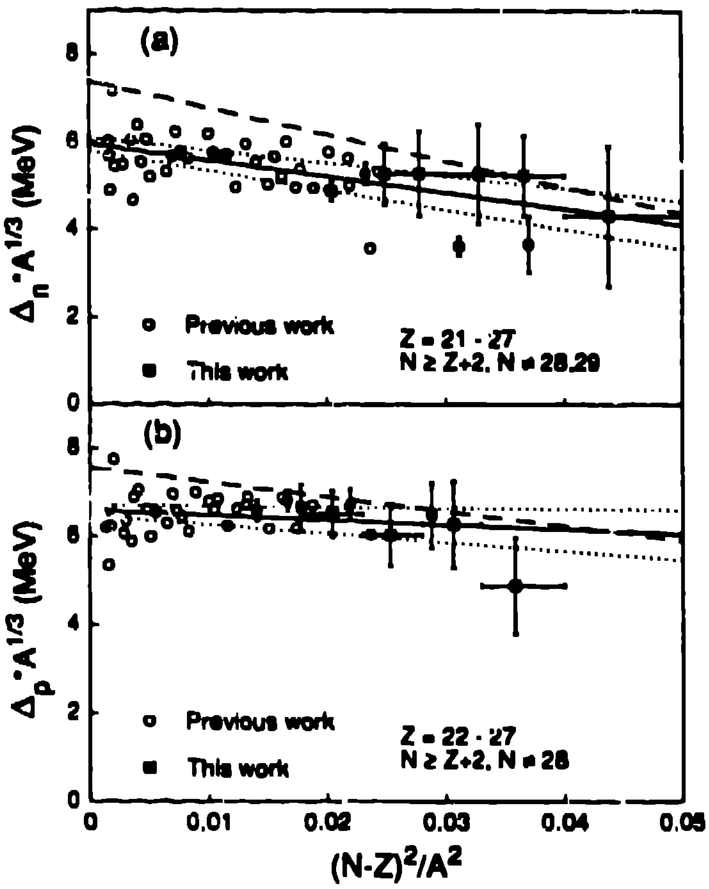

Fig. 3. A plot of (a) $\Delta_n A^{1/3}$ and (b) $\Delta_p A^{1/3}$ versus $(N-Z)^2/A^2$. The solid squares indicate the weighted average value of data points reported by Tu et al.[5] and the open circles indicate those data that were previously known[8]. The dashed lines are the global fits of Jensen et al.[23] while the solid lines are a fit to the data shown. The dotted lines indicate $\pm 1\sigma$ limits of the latter fit.

Although there is a considerable amount of scatter in the data and the latest measurements have larger error bars than are desired, the data show considerably less neutron excess dependence than that obtained by Jensen et al.[23]. (Note that we are not so concerned with the offset difference, but rather the slopes of these fits.) In particular, for the neutron pairing energies the neutron-excess dependence is roughly half as large as that of Jensen et al. while the proton pairing energies are one quarter as large. More to the point, in the case of proton pairing energies no neutron-excess dependence at all is indicated at the 1σ level. Clearly additional measurements of this type and further theoretical efforts are needed to elicit the underlying nature of nuclear pairing interactions and to show to which degree they are isospin dependent.

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