Very Neutron Rich Light Nuclei

How many neutrons can a specified number of protons bind? This simple well-defined query is proving difficult to answer experimentally for any save the lightest nuclei ($Z \leqq 5$). The basic reason for the difficulty is that the answer to the question forces us far from the valley of beta stability to study pieces of nuclear matter with larger N/Z ratios ($N/Z \sim 2.5$–3) than are customarily studied.

The question is clearly of great interest to nuclear structure physics. One will attempt to see if the nuclear models (e.g., the shell model) applied in the valley of stability yield comparably good results for these more exotic species. In particular, regarding their ground state masses, it is crucial to understand whether the nuclear density alters slightly. If the density were to decrease for large values of N/Z there would be a dramatic change in the total binding energy of the nucleus.

Liquid drop theories of the nucleus are inappropriate for light nuclei and, at least in their simplest forms, are extremely unreliable away from beta stable nuclei. One is forced to some other kind of theory to give guidance as to what masses should be expected for these neutron rich nuclei on the basis of our present knowledge. The most useful strategy we have at hand employs equations relating mass differences.[1-3] These allow one to use existing data to predict masses of yet unobserved nuclei. In some special cases more conventional and better understood theories, based on the nuclear shell model, may be employed.

In addition to the basic interest these nuclei hold for the nuclear physicist the resulting information bearing on their neutron binding energies is of prime importance to the nuclear astrophysicist investigating the "*r*" process[4] of nuclear synthesis. The "*r*" process occurs in a star when the neutron flux is so large that the time for neutron capture (n, γ) is very much shorter than the time required for β decay. Thus nuclei capture as many neutrons as they can and remain in that saturated state till the neutron flux abates. The nuclei then β decay back to the valley of stability. To satisfactorily describe the "*r*" process, one has to know neutron binding energies for very neutron rich nuclei. Estimates of these are plagued by the doubts that surround the mass relationships which have been tested only near the valley of stability. It certainly would be useful to do a few spot checks on some nuclear masses far from stability to see how reliable our theories are. In the following paragraphs I will try to sum up the present experimental status of the problem in light nuclei ($Z < 10$) and point out what I think are the directions to be pursued.

It is experimentally evident that a single proton binds at most two neutrons. In a very lovely experiment[5] A. Poskanzer at the Brookhaven Cosmotron showed He^8 to be bound and measured its half life ($t_{1/2} = 122$ ms). Subsequently the mass of He^8 was measured[6] and as a result we know that He^8 is stable against decay into $He^6 + 2n$ by 2.0 MeV. It certainly seems in any reasonable picture that He^{10} is unstable to multiple neutron decay. The mass relation procedure mentioned above predicts it unstable by several MeV and further, our knowledge of $1p$ shell interactions predicts the same thing. As the lowest configuration expected for ^{10}He would be $[(1S)_p{}^2(1S)_n{}^2(1P)_n{}^6]$, in obvious notation, the wave function is completely determined and the associated binding energy is readily obtained using experimentally determined values for $1P_{3/2}$ and $1P_{1/2}$ single particle energies and the $T = 1$ two-body matrix elements. If we use the very successful results of Cohen and Kurath[7] we obtain a total binding energy for He^{10} the order of 25.2 MeV. This predicts He^{10} unstable against decay into $He^8 + 2n$ by some 6 MeV, and incidentally predicts He^{10} unstable into $He^4 + 6N$. However, a Russian group[8] still felt the matter of He^{10} to be in some reasonable doubt and have shown rather convincingly that He^{10} does not exist as a nucleus stable against heavy particle decay. Thus two protons seem able to bind 6 neutrons.

At the Berkeley bevatron, Poskanzer, Casper, Hyde, and Cerny showed[9] that the bombardment, with 7 BeV protons, of neutron rich heavy targets such as U^{238} could provide a sufficient number of neutron rich light fragments via spallation reactions that they could be unambiguously identified by measuring their rate of energy loss in solid state detectors. In this initial report they identified Li^{11}, Be^{12}, B^{14} and B^{15}, each of which represents the current limit of our knowledge of the most neutron rich isotope in each species. Li^{11} and Be^{12} are most certainly the heaviest particle stable isotopes for their respective Z values. A word should be said about the observed stability of Li^{11}. Using the recently measured[10] mass for the Be^{12} ground state, the mass relations technique[2] would predict that Li^{11} is unstable to decay into $Li^9 + 2n$ by 0.6 ± 0.2 MeV. As the lowest Li^{11} configuration is $[(1S)_p{}^2(1S)_n{}^2(1P)_p(1P)_n{}^6]$ the wavefunction is completely determined and again we use the results of Ref. 7 to obtain the total binding energy of Li^{11}; however, in this case as distinguished from He^{10}, some $T = 0$ two-body matrix elements must be used. This procedure would predict Li^{11} unstable by 0.8 MeV. Neither of the above procedures can be considered as being in serious disagreement with the fact that Li^{11} is shown to be stable as long as Li^{11} is not found to be bound by more than 1 MeV, say, against decay into Li^9+2n. At any rate it is interesting and exciting to see a nucleus far off the stability line more stable than predicted by current reasonable theories. Clearly more work needs to be done and in particular mass measurements are needed not just tests of particle stability. The mass of Li^{11} is an especially important number to obtain. All the possible experiments are nontrivial as the expected cross sections are likely to be considerably below 1μb. Examples of possible reactions are (i)Mg^{26} (Li^7, Li^{11})Mg^{22}, (ii) $B^{11}(\pi^-, \pi^+)Li^{11}$, (iii) C^{14}(Li^6, C^9)Li^{11}. A technique of directly measuring the mass of Li^{11} to ± 0.5 MeV by its orbit in a magnetic field seems feasible[11] and is proposed by the Orsay group at C.E.R.N. This group has previously measured[12] the half-life of Li^{11}.

In the case of Be it appears certain that Be^{12} is the last particle stable isotope. Thus while 2 protons can bind 6 neutrons, 4 protons can bind only 8. The limit at 8 is surely the result of shell closure so that those neutrons added beyond 8 must go into the 2s–1d shell with the attendant decrease in their overall binding energy.

The situation in the boron isotopes is most interesting. B^{14} and B^{15} are both heavy particle stable.[9] However there has been a recent speculation[13] that B^{17} may be stable. Using mass relations techniques[3] with recently determined values for the masses of N^{18}, F^{22} and Na^{26}, Thibault–Philippe has shown that B^{17} should be stable against neutron decays. The earlier prediction,[1] claiming it unbound, needs to be reconsidered in the light of the new experimental mass values for the above odd-odd isotopes.

Above boron ($Z > 5$) we are not yet at the line delineating neutron instability, C^{19} has been reported,[14] but further verification of its existence is in order. If C^{19} is shown stable, then C^{20} certainly will also be stable leaving attention to be focused on C^{21}, C^{22}, and C^{24}.

The real progress in the subject of neutron rich light nuclei in the past 18 months, apart from the work[13] of the above mentioned French group on Na, lies with the heavy ion program at the Dubna cyclotron. The results[15,16] achieved using moderate energy (174 MeV Ne^{22}, 290 MeV Ar^{40}) neutron rich heavy ion projectiles on Th^{232} can only be described as spectacular. In a recent publication concerning the results following from the bombardment of Th^{232} with 290 MeV A^{40}, they report[16] *17 new isotopes*. Isotope identification is performed using a large solid angle magnetic spectrograph in conjunction with a $\Delta E - E$ solid state detector telescope. Thanks to their splendid effort, the heaviest isotopes of N–F that we now know are N^{21}, O^{24}, F^{25}.

The benefits achieved with the use of neutron rich heavy ion beams over high energy protons likely arise from 2 sources. The heavy ion reactions are far more selective in atomic number; thus one is able to produce light isotopes with atomic number within 10 units of the incident projectile with rather large cross sections.[16] Further each particular reaction product has a relatively limited spread in velocity. Properly chosen range selective devices are able to separate all particles of a particular type; this is different from the case with high energy proton spallation reactions where the energy spectra spread out much more. There have been studies of the cross section systematics for these heavy ion reactions[17] and while the ground state Q value seems a decisive factor in accounting for the variation in cross section observed within each isotope, the variation in cross section with Z seems more related to a compound nucleus model for the reaction. More effort towards understanding these mechanisms would be useful so that one can make optimal choices of energies and targets for the production of particular species.

One thing I think however is evident; that is a high current heavy ion facility ($E/A \sim$ 5–10 MeV/amu) with an on-line isotope separator could really do some excellent and interesting nuclear physics studying the decays and hence the masses of these neutron rich light nuclei.

In the way of spot checks on extremely neutron rich nuclear masses experi ments exploiting multiproton pickup reactions such as $Ca^{48}(O^{18}, Mg^{22})$ S^{44} (Q value ~ -33.0 MeV[3]) would really be a help to see if the mass relations technique is on the right path.

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