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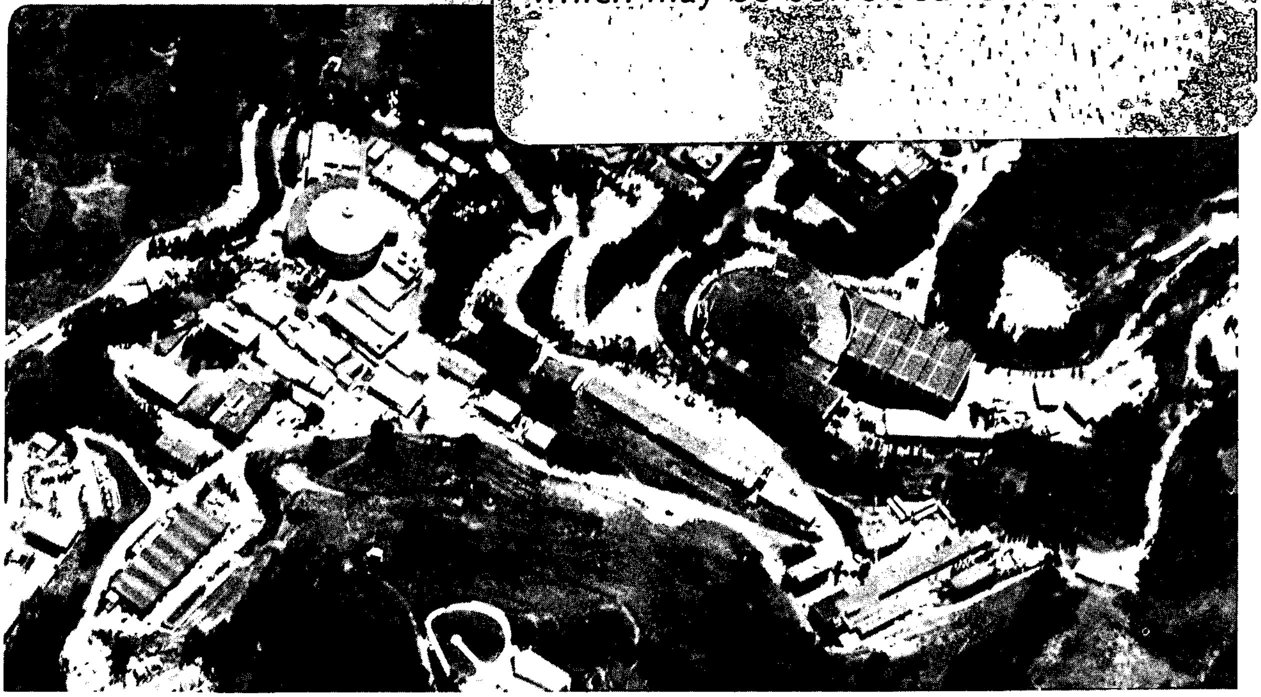

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Trends in the Study of Light Proton Rich Nuclei

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Abstract

Recent work on light proton-rich nuclei is reviewed. Evidence for the first $T_z = -5/2$ nuclide, ^{35}Ca, is presented. Future directions in this field are discussed.

Introduction

Advances in the study of the limits of known nuclei have made possible investigations of nuclear structure in nuclei with unusual neutron to proton ratios. Questions, such as the limits of nuclear stability, the role of charge-dependent effects in nuclear systems and the existence of new radioactive decay modes, have guided the recent research on the most proton-rich light nuclides. Results from these studies have also made possible tests of advanced shell model analyses [WIL 83] far from the valley of beta-stability. Figure 1 shows a portion of the chart of nuclides through the titanium isotopes. It summarizes our present experimental knowledge of light nuclei. The most important advances in the studies of proton-rich nuclei since the last reviews [CER 77, AYS 80] have been the discoveries of the β-delayed proton decays of ^{27}P [AYS 85b], ^{31}Cl [AYS 82], and ^{36}Ca [AYS 81], the mass measurements of the $T_Z = -2$ nuclides ^{24}Si [TRI 80], ^{28}S, ^{32}Ar and ^{40}Ti [BUR 80] and the discoveries of the new $T_Z = -2$ nuclides ^{22}Al [CAB 82] and ^{26}P [CAB 83b]. The latter two were found to decay via β-delayed two-proton emission [CAB 83a, HON 83], a new mode of radioactivity predicted by Goldanskii [GOL 80]. Also, the first $T_Z = -5/2$ nuclide, ^{35}Ca, has been discovered via its β-delayed 2p-decay [AYS 85a]. Most recently a complete β-decay study of the $T_Z = -2$ nucleus ^{32}Ar by the ISOLDE-group [BJO 85]has been reported.

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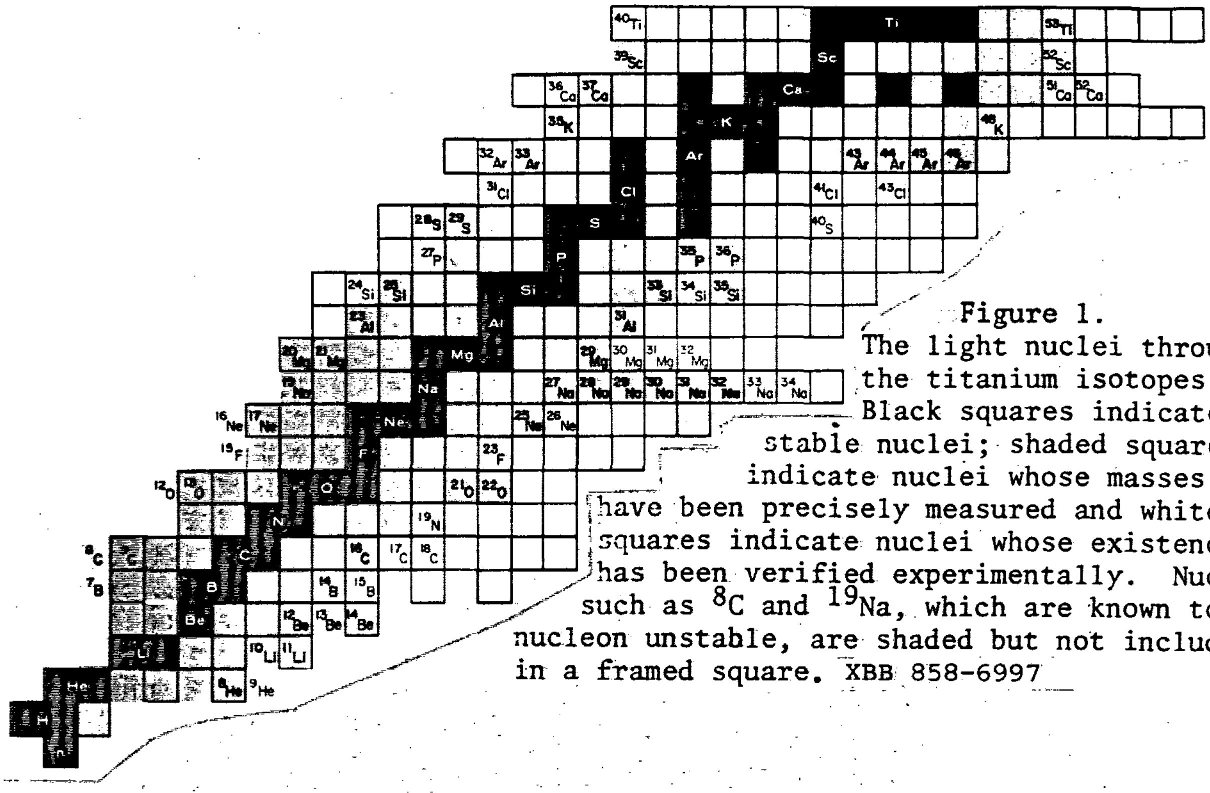

Figure 1.
The light nuclei through the titanium isotopes. Black squares indicate stable nuclei; shaded squares indicate nuclei whose masses have been precisely measured and white squares indicate nuclei whose existence has been verified experimentally. Nuclei such as ^{8}C and ^{19}Na, which are known to be nucleon unstable, are shaded but not included in a framed square. XBB 858-6997

Mechanism of two-proton emission following beta decay

Two-proton emission could in principle proceed via sequential emission, ^{2}He emission or simultaneous uncoupled emission. A decomposition of the observed two-proton spectra should indicate which mechanism dominates. Monte Carlo simulations of the first two mechanisms have been performed for ^{22}Al [CAB 84b] and have shown that ^{2}He emission would yield a proton energy continuum, with an angular correlation peaked at 40°, whereas sequential emission would be essentially isotropic and would exhibit two distinct peaks - one constant in energy corresponding to the first proton and a second one with appropriate kinematical shift.

The distinct peak structure of the individual proton spectra in the decay of ^{22}Al suggested that the major part of the decay occurred sequentially [CAB 84b]. Since this experiment could not completely exclude the possibility of ^{2}He emission, an experiment was performed utilizing position sensitive detectors to measure the relative angular correlation of the two emitted protons [JAH 85]. The essentially isotropic angular correlation shown in Figure 2 confirms that the two-proton decay of the 4^{+}, T = 2 isobaric analog state in ^{22}Mg to the first excited state in ^{20}Ne is predominantly a sequential process. The observed minor

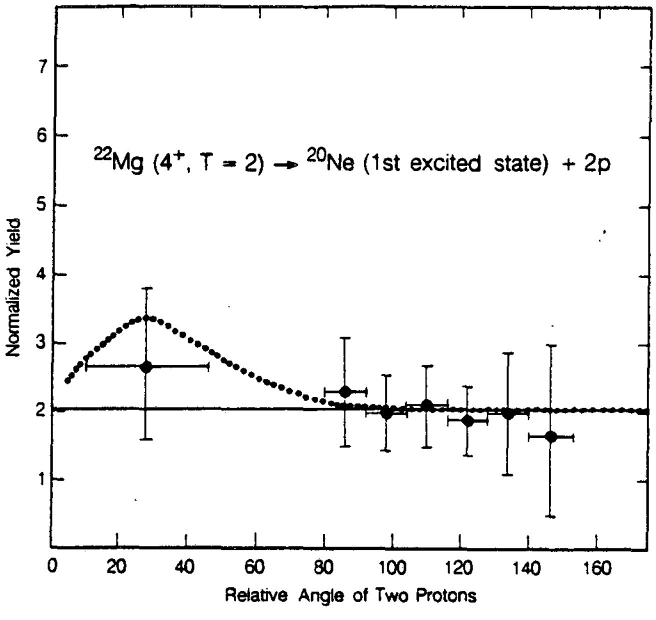

Figure 2. Normalized angular correlation of the two protons following ^{22}Al beta deacy. The dotted line corresponds to a 15% admixture of ^{2}He emission to an otherwise isotropic distribution. See text.

enhancement at small relative angles cannot be interpreted as positive evidence for correlated diproton (^{2}He) emission due to the poor statistics in this low yield reaction. However, a 15% admixture of this process cannot be excluded. The dotted line in Figure 2 has been calculated assuming the break-up properties of ^{2}He observed in reaction studies.

Observation of the $T_Z = -5/2$ nucleus, ^{35}Ca

By exploiting the relatively unusual decay mode of beta-delayed two-proton emission, we have discovered the first $T_Z = -5/2$ nucleus, ^{35}Ca [AYS 85a]. Figure 3 shows the two-proton sum spectrum of ^{35}Ca collected after bombarding a natural Ca target with a 135 MeV ^{3}He beam from the Lawrence Berkeley Laboratory 88-Inch Cyclotron for an integrated beam of 2.1 C and using helium-jet techniques. The distribution of individual proton energies suggests a sequential decay process via intermediate states in ^{34}Ar. Since both of the individual proton spectra comprising G and X have a peak at the same energy, 2.21 MeV, this indicates that the decays proceed via the same state in ^{34}Ar. The ^{35}Ca decay scheme is shown in Figure 4.

The assignment of the observed 2p-activity to ^{35}Ca is primarily based (i) on the agreement with the known energy difference for decays to the ground and the first excited state in ^{33}Cl, (ii) on the agreement with predicted 2p-energies, (iii) on various reaction energetics and (iv) on the expected absence or non-existence of nearby $T_z = -2$ and $-5/2$ nuclides with similar predicted decay modes. Also see [AYS 85a].

Since three members of the A = 35, T = 5/2 isospin sextet (^{35}K*, ^{35}S*, ^{35}P) are now known, the ground state mass of ^{35}Ca can be predicted with the Isobaric Multiplet Mass Equation, IMME. The resulting value 4453 ± 60 keV is more than 300 keV better bound than predicted by the Kelson-Garvey relations with the most recent input masses [KEL 66].

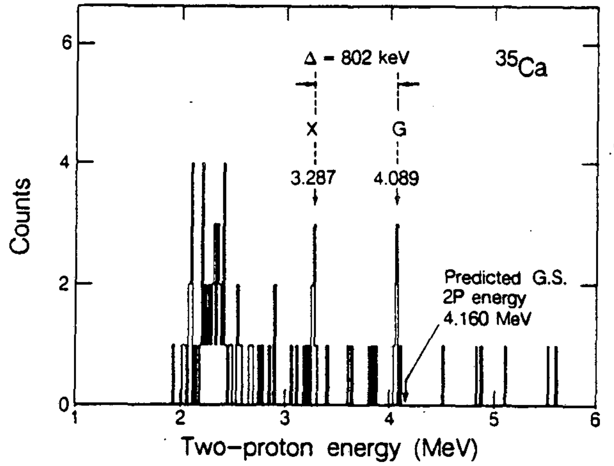

Figure 3. Beta-delayed two-proton spectrum of ^{35}Ca. G and X refer to the transitions to the ground and first excited states in the ^{33}Cl daughter, respectively.

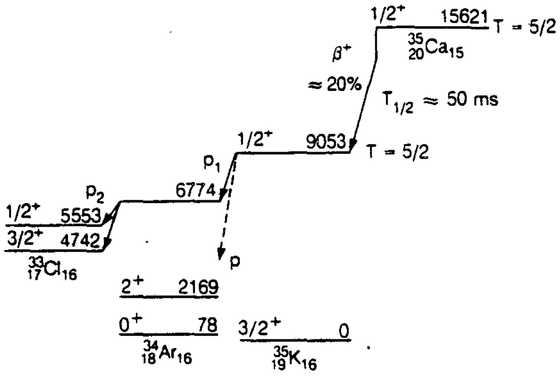

Figure 4. Proposed partial decay scheme for the beta-delayed two-proton emission of ^{35}Ca.

Future studies

Additional examples of β-delayed two-proton emitters may be sought among the A = 4n+2, T_Z = -2 nuclei such as ^{46}Mn and ^{50}Co [CAB 84a]. However, our preliminary searches for β2p emitters among the products of ^{14}N + ^{40}Ca reactions at 130 and 180 MeV have proven inconclusive.

The β-delayed two-proton decay of ^{35}Ca yields a value for the mass for the T = 5/2 state in ^{35}K; however, this only partially completes the isospin sextet, leaving three members (^{35}Ca, ^{35}Ar* and ^{35}Cl*) unmeasured. Use of the isospin-conserving (p,t) reaction to locate the T = 5/2 state in ^{35}Cl would therefore provide the first test of the IMME for an isospin sextet.

Further isospin sextets in the sd shell, with A = 23, 27 and perhaps 31, might be investigated via the β-delayed particle emission of the T_Z = -5/2 nuclei ^{23}Si, ^{27}S and ^{31}Ar. In this context the recent discovery of the lowest T = 5/2 state in ^{23}Na [EVE 85] will contribute towards the A = 23 sextet. The Kelson-Garvey mass formula [KEL 66] predicts the T_Z = -3 nuclide ^{22}Si to be effectively particle stable. Studies of this nucleus and its decay would provide data for possibly the only sd-shell example of an isospin septet, of which one member is already known (the mass of ^{22}O).

Also of great interest is the possibility of ground state two-proton radioactivity. Kelson-Garvey mass predictions suggest that two (three?) T_Z = - 5/2 nuclei are potential candidates for this new mode of radioactivity. These are ^{19}Mg, (^{31}Ar) and ^{39}Ti, with predicted 2p separation energies of -1170, -190 and -790 keV, respectively. However, any such observations would require specialized techniques due to their very short predicted half-lives (< 10 ms).

Techniques for the study of exotic nuclei

Traditionally, light-ion induced reactions have been used to produce light proton-rich nuclei, both for decay studies via (light-ion, xn) reactions and for mass measurements from reaction Q-values such as (α, ^{8}He). Although the helium-jet technique has proven effective for the former, fast on-line mass separation will be useful in the future. Recent developments in the area [ARJ 85] may have an important impact on such studies. With the observation of ^{35}Ca from the ^{40}Ca(^{3}He, α4n)^{35}Ca reaction at extremely low levels, it is possible that this kind of reaction has reached its limits. While the (^{3}He,^{8}He) reaction could be used to measure the masses of the A = 4n, $T_Z = -5/2$ series, the cross-sections are likely to be forbiddingly small.

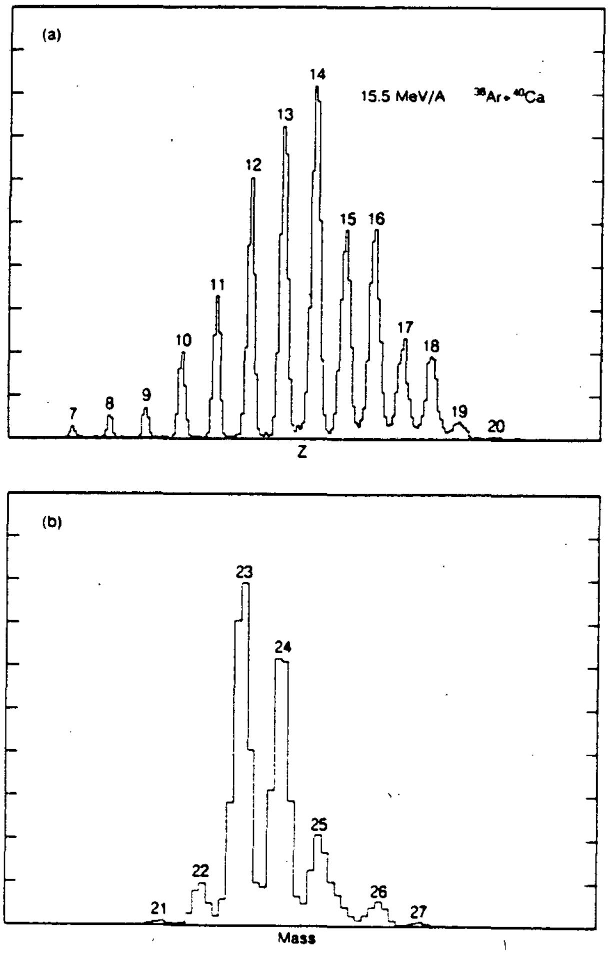

Figure 5. a) Charge distribution for the reaction 15.5 MeV/A ^{36}Ar + ^{40}Ca and b) the corresponding mass distribution for Z = 12 (Mg isotopes).

Highly neutron-rich nuclei have been produced in heavy-ion deep inelastic and fragmentation reactions (for example, [GUI 85]). We are investigating the possibility of using this technique to produce new proton-rich nuclei. A 15.5 MeV/A ^{36}Ar beam from the 88-Inch Cyclotron injected by the ECR ion source has been used to bombard a thick calcium target. Reaction products emitted at 5° were detected in the focal plane of a magnetic spectrometer. Measurements of magnetic rigidity, time-of-flight and differential energy loss allowed identification of the wide range of nuclei so produced. Figure 5 shows a preliminary analysis of a small portion of the data. These initial results are encouraging. The collection for decay studies of new proton-rich nuclides from such reactions presents a further experimental challenge. Multinucleon transfer reactions with heavy ions might be used to measure the masses of very proton-rich nuclei. Recent results for neutron-rich nuclei [FIF 82] indicate that similar reactions for proton-rich nuclei may have substantially greater cross-sections than the light ion reactions used in the past. One might envisage, for example, using the ^{40}Ca(^{28}Si,^{28}S)^{40}Ar and ^{40}Ca(^{28}Si,^{27}S)^{41}Ar reactions to remeasure the mass of ^{28}S and then to investigate ^{27}S.

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