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Joseph Cerny

March 1968

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HIGH ISOSPIN NUCLEI AND MULTIPLETS IN THE LIGHT ELEMENTS

Joseph Cerny

March 1968

High Isospin Nuclei and Multiplets in the Light Elements^{a,b}

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March 1968

INTRODUCTION

This review has two complimentary purposes: to indicate the progress made in establishing the limits of nucleon stability in the light elements; and to assay the rapidly growing data on high isospin states ($T \geq 3/2$) and the resulting isobaric multiplets in this region. In general, the nuclei to be considered have masses of $5 \leq A \leq 40$. A complete discussion of isobaric spin in nuclear physics has recently been given by Robson (1) (also see Burcham (2) and MacDonald (3)).

One naturally expects that the limits of nucleon stability will be delineated first in the light elements and most probably among the rarer neutron-deficient isotopes. Many authors have considered various aspects of this problem (see, for example, Jänecke (4); Baz, Goldanskii & Zeldovich (5)) and have described the phenomena to be expected—beta-delayed proton and

^aThe survey of literature for this review was concluded in February 1968.

^bThis review was written under the auspices of the United States Atomic Energy Commission.

neutron emission, and proton and two-proton radioactivity. We choose to use the present data on the masses of high isospin nuclei along with some mass predictions arising from partially complete isobaric multiplets to evaluate the recent nuclidic mass relationship of Garvey and Kelson (6,7). Their relation, based on an independent-particle model of the nucleus, permits explicit mass predictions of nuclei far from stability and has had considerable success in fitting the available mass data.

The observation of high isospin states, such as $T = 3/2$ states in $T_z = \pm 1/2$ nuclei ($T_z = \frac{N-Z}{2}$) and $T = 2$ states in $T_z = 0, 1$ nuclei, has aroused much experimental interest. Studies of the locations and properties of these states have several purposes. First, they enable one to investigate the isobaric multiplet mass equation (IMME)

$$M(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2.$$

This relation among the masses of the $(2T+1)$ members of an isobaric multiplet has been discussed by Wigner (8), Weinberg & Treiman (9), and by Wilkinson (10). It results from the assumption that the wave functions of members of an isospin multiplet can be regarded as identical (and are eigenstates of the isospin) and that any charge-dependent forces (Coulomb plus nuclear) are of a two-body character that can be treated

as perturbations. Since the equation is a quadratic, it obviously requires a measurement of the mass of each member of at least isospin quartets to test its applicability. An example of such a quartet among the mass 9 nuclei would be the ${}^9\text{Li}$ ground state ($J^\pi = 3/2^-, T = 3/2, T_z = 3/2$); the lowest $T = 3/2$ state in ${}^9\text{Be}$ (14.39 MeV excitation, $J^\pi = 3/2^-, T = 3/2, T_z = 1/2$); the lowest $T = 3/2$ state in ${}^9\text{B}$ (14.66 MeV excitation, $J^\pi = 3/2^-, T = 3/2, T_z = -1/2$); and the ${}^9\text{C}$ ground state ($J^\pi = 3/2^-, T = 3/2, T_z = -3/2$).

Further, the observation of the gamma-ray decay of $T = 2$ states in $T_z = 0$ nuclei would permit the first study of the fundamental electromagnetic selection rule $\Delta T = 0, \pm 1$, violations of which should be a sensitive probe for admixtures of states of differing isospin in these highly excited states. Finally, since the energetically allowed particle decay of these $T = 3/2$ or 2 states is usually isospin forbidden (some exceptions exist, particularly below mass twelve), observation of these decay modes is a further sensitive measure of the isospin impurity admixed into these states by charge dependent forces.

HIGH ISOSPIN NUCLEI

Although the main concern of this review will be with nuclear masses, information on both the decay scheme and the mass determination of the selected high isospin nuclei are given in Table I (11-33). This table presents the known nucleon-stable nuclei with $5 \leq A \leq 40$ which are at least three neutrons lighter than (or three neutrons heavier than) the lightest (heaviest) stable isotope of each element. This, in general, restricts the nuclei to be discussed to those which cannot be reached in simple two-neutron or two-proton transfer reactions such as (t,p) or ($^3\text{He},n$) or their inverses. Primary sources are listed except for references to decay data of nuclei of $Z \geq 11$ compiled in the review by Endt & Van der Leun (31) and mass data compiled in the 1964 Mass Tables by Mattauch, Thiele, & Wapstra (21).

Noting first the decay scheme data, two classes of nuclei are readily apparent. One is the recently discovered group of beta-delayed proton emitters (the A equals $4n + 1$ mass series from ^9C to ^{37}Ca) reached via ($^3\text{He},2n$) reactions on $4n, T_z = 0$ targets, for example, and already reviewed by Goldanskii (34). The other comprises those negatron emitters (^{18}N through ^{40}Cl) generally obtained

from (n,p) reactions on stable nuclei; most recently, ^{18}N and ^{22}F were discovered by the Lockheed group (22, 26). The decay properties (and mass) of ^{16}C were established by Hinds et al. (20) using the (t,p) reaction on ^{14}C ; this nuclide, like all the neutron-excess nuclei in the table below this mass, is a beta-delayed neutron emitter. Both ^{12}Be (16) and, in an ingenious experiment, ^8He (11) were characterized by Poskanzer and his collaborators in experiments at the Brookhaven Cosmotron.

The remaining tabulated nuclei were established using two of the new general procedures capable of studying nuclei far from beta stability—semiconductor telescopes coupled to particle identifier systems and/or computers, and isotope separators on line (ISOL). Figure 1 shows the particle identifier spectrum resulting from the 5.3 GeV proton bombardment of uranium obtained by Poskanzer et al. (15) which established the nucleon stability of ^{11}Li , ^{14}B and ^{15}B . The experimental equipment was developed by Goulding and his associates at Berkeley (35). It employs a four-counter semiconductor telescope, consisting of two ΔE detectors, an E detector and a rejection detector, feeding a power-law particle identifier system capable of performing two identifications of each

particle traversing the telescope and rejecting those events whose identifications do not agree within preset limits. Fast coincidence and pile-up rejection techniques are additionally used to reduce background. Given a flight time plus stopping time of greater than one nanosecond for such particles, the observation of these new nuclides in the spectrum of Figure 1 is sufficient to guarantee their stability against nucleon emission (note that the known "nucleon"-unstable nuclei ^8Be and ^9B are absent from the spectrum).

An ISOL system was employed by Klapisch et al. (32) in an experiment at CERN which established the nucleon-stability of ^{27}Na and, most probably, ^{28}Na . Their technique is described in reference (36) while a comprehensive review of ISOL plans and progress is given in reference (37). These isotopes were observed in an on-line mass spectrometer as reaction products from the 10.5 GeV proton bombardment of ^{100}Mo , Ta, Ir and U. As presently employed, both the above techniques establish the stability of certain isotopes without gaining any further information on their decay scheme or mass; as such, the upper limit to their mass-excess is given in Table I and their probable decay mode is indicated.

One of the above general techniques and several other specific ones, in addition to the measurement of negatron end-point energies, have led to the mass-excesses (based on $^{12}\text{C} = 0$) given in Table I. Two four-counter semiconductor-telescope, particle-identifier systems similar to the one discussed above were employed in conjunction with an on-line computer by Cerny and his associates in a general program of mass measurements of neutron-deficient nuclei. In particular, they utilized the low-yield three neutron transfer ($^3\text{He}, ^6\text{He}$) reaction to measure the masses of ^9C (18), ^{13}O (25), ^{21}Mg (33) and ^{37}Ca (33). (See (33) for a detailed discussion of the procedure.) As an example of these results, Figure 2 presents two independent energy spectra of the ^6He ions arising from the $^{40}\text{Ca}(^3\text{He}, ^6\text{He})^{37}\text{Ca}$ reaction (33). Transitions to both the ground state and to an excited state at 1.62 MeV were observed; the laboratory cross section to the ground state was only 175 nb/sr. This technique was also employed by Cerny et al. (13) in measuring the mass of ^8He via the $^{26}\text{Mg}(^4\text{He}, ^8\text{He})^{22}\text{Mg}$ reaction; investigations by Batusov et al. (14, 38) utilizing reactions induced by stopped pions in the carbon and oxygen nuclei of photoemulsions have also measured the ^8He mass. Finally, a very accurate

measurement of the ^9C mass was reported by Barnes and associates (19) through a threshold determination of the $^7\text{Be}(^3\text{He},n)^9\text{C}$ reaction, and Esterlund et al. (29, 30) reported a ^{17}Ne mass derived from the threshold of the $^{16}\text{O}(^3\text{He},2n)^{17}\text{Ne}$ reaction.

Table II (39-48) presents the available data on nucleon-unstable nuclei, subject to the same restrictions as governed inclusion in Table I. Only two of these nuclides have been characterized: ^7He was investigated by Stokes & Young (43) via the $^7\text{Li}(t,^3\text{He})^7\text{He}$ reaction and ^7B was studied by McGrath, Cerny, & Norbeck (47) via the $^{10}\text{B}(^3\text{He},^6\text{He})^7\text{B}$ reaction. The remaining nuclei in the table were not observed in various experimental searches with differing degrees of reliability, and the original references should be consulted for any details.

Tables I and II also tabulate all the available mass predictions by Garvey & Kelson (6, 7, 23) which should be compared to the experimental data. Except for the very light neutron-excess nuclei ^8He and ^{11}Li whose predicted masses are considerably in error (^{11}Li was predicted unbound by 2.5 MeV), it can be seen that their predictions as to which nuclei should be nucleon stable

and the masses thereof are quite accurate. As they note (7), their predicted masses for neutron-deficient nuclei near the limits of stability may be over-estimates since the small proton binding energy encountered in these cases reduces the Coulomb energy of the nuclei; the relevant data in Table I are generally in accord with this statement. A more stringent test of their relationship must await measurements nearer the edge of stability. If it proves to be correct, quite a large number of neutron-excess nuclei remain to be discovered, since, for example, they predict nucleon-stable carbon isotopes of even N through ^{24}C (and possibly ^{26}C) and neon isotopes through ^{38}Ne (23).

HIGH ISOSPIN STATES

$T = 3/2$ States in $T_z = \pm 1/2$ Nuclei.

Prior to 1964 very few $T = 3/2$ states were known; perhaps the best early measurement is of the lowest $T = 3/2$ state in ^{15}N , the analogue of the ^{15}C g.s., which lies at 11.61 MeV and was observed by Bartholomew et al.

(49) in proton scattering experiments on ^{14}C . Since 1964 many $T = 3/2$ states have been observed by direct reaction techniques, by resonance reactions in which the resonance may be isospin allowed or forbidden, and as states populated in the

decay of the $4n+1$ mass series of delayed proton emitters.

Table III (50-103) lists the observed $T = 3/2$ states in the $T_z = \pm 1/2$ nuclei for $5 \leq A \leq 39$. For completeness, an attempt has been made to tabulate $T = 3/2$ states corresponding to the ground state and to any excited states of the analogue $T_z = 3/2$ nucleus. If an author has reported several measurements of a given $T = 3/2$ state, the most recent one is generally the only one tabulated. Weighted values for the excitations are listed whenever more than one measurement of a particular $T = 3/2$ state is available. The large amount of data presented in Table III precludes a discussion of each measurement and only some of the generally used techniques will be mentioned. Data concerning analogue states observed in the decay of beta-delayed proton emitters are included in this table but will not be discussed further, since a complete discussion of this topic has been given by McPherson (104).

Direct Reaction Experiments.

A powerful technique for observing $T = 3/2$ states has been the use of two-nucleon transfer reactions such as (p,t) , $(p,^3\text{He})$, $(^3\text{He},n)$ or $(^3\text{He},p)$. Especially valuable has been the simultaneous observation of (p,t) and

(p, ^3He) reactions employed on targets with $T_z = +1/2$ which can produce $T = 3/2$ states in the residual $T_z = -1/2$ and $+1/2$ nuclei through pickup of the two nucleons in an $S=0$, $T=1$ configuration. Since the configuration of at least the lowest $T = 3/2$ state is generally simply related to that of the target, transitions to these states are normally enhanced with respect to transitions to nearby states of lower isospin (and generally quite complex configurations) at these high excitations. So long as the $T_z = +3/2$ nucleus is known, the approximate location of the analogue state(s) can be predicted by taking the mass difference between the ground states of the isobars with $T_z = 3/2$ and $T_z = 1/2$ and adding to this the appropriate Coulomb energy corrected for the neutron-hydrogen atom mass difference.

After analysis of the energy spectra, the angular distributions of transitions to the level(s) in the region of excitation suspected of containing the analogue state are extracted. First, the observed angular momentum transfer in the transition to the suspected analogue state should lead to a spin and parity assignment consistent with that established for the analogue state in the $T_z = 3/2$ isobar. Second, within the framework of

charge independence of nuclear forces, these specific transitions proceed from the same initial to identical final states through only $S = 0$, $T = 1$ pickup of two nucleons. Hence, in the limit of no isospin mixing in the final states, these transitions should possess identical cross sections apart from a constant factor arising from isospin-coupling and phase-space considerations (see reference (105)). Observation of the expected close similarity in the angular distributions of transitions to suspected analogue states then confirms their assignment.

As an illustration of this procedure, consider (p,t) and $(p,^3\text{He})$ reactions induced by 43.7 MeV protons on ^9Be in an experimental search for $T = 3/2$ states in ^7Be and ^7Li as reported by Detraz, Cerny & Pehl (50). Figure 3(a) presents energy spectra from the $^9\text{Be}(p,t)^7\text{Be}$ and $^9\text{Be}(p,^3\text{He})^7\text{Li}$ reactions. The strong transitions to previously unobserved states at 10.97 MeV in ^7Be and 11.28 MeV in ^7Li were suspected of being transitions to the analogue states; the angular distributions to these states, with the $(p,^3\text{He})$ cross sections multiplied by 0.989 to correct for phase space and isospin coupling factors, are shown in Figure 3(b). Virtually identical cross sections are observed, as

is expected for transitions to $T = 3/2$ states, and the angular distribution has a characteristic $L = 0$ shape consistent with transitions to the lowest $T = 3/2$ state in mass seven, theoretically predicted to be $3/2^-$. This technique of simultaneous observation of (p,t) and $(p,^3\text{He})$ transitions to $T = 3/2$ states has also been applied by the Berkeley group to $T = 3/2$ states in residual nuclei of mass 11 (56), 13 (25), 19 (73), 23 (73) and 37 (33), and by Hardy & Skyrme to masses 25 and 29 (80).

Several experiments locating $T = 3/2$ states with high accuracy utilizing $(^3\text{He},n)$ or $(^3\text{He},p)$ reactions have been carried out at the California Institute of Technology. Early measurements on $T = 3/2$ states in ^9Be by Lynch, Griffiths & Lauritsen (52) and in ^9B by Dietrich (55) have been followed by those of Barnes and his co-workers on $T = 3/2$ states in mass 13 (58, 60, 61), 17 (67, 68) and 21 (74, 75). Figure 4 presents an energy spectrum of the $^{11}\text{B}(^3\text{He},n)^{13}\text{N}$ reaction obtained by Adelberger & Barnes (61) clearly showing the transition to the lowest ^{13}N $T = 3/2$ state at 15.07 MeV.

Single neutron pickup and single proton stripping reactions on $T = 1$ target nuclei have also been utilized to locate $T = 3/2$ states in this mass

region. For example, Hensley (74) has employed the $^{22}\text{Ne}(^3\text{He},\alpha)^{21}\text{Ne}$ reaction and Butler et al. (33) the $^{22}\text{Ne}(d,t)^{21}\text{Ne}$ reaction to observe $T = 3/2$ states in ^{21}Ne , while Dubois (78) utilized the reaction $^{22}\text{Ne}(^3\text{He},d)^{23}\text{Na}$ to investigate $T = 3/2$ levels in ^{23}Na and Lawergren (85) employed the $^{26}\text{Mg}(d,n)^{27}\text{Al}$ reaction to observe the lowest $T = 3/2$ state in ^{27}Al .

Other types of direct reactions can, of course, populate these $T = 3/2$ states. For example, the isospin selection rules are satisfied in such reactions as (p,n) or $(^3\text{He},t)$ on $T_z = 1/2$ targets, although the $T = 3/2$ states may not be sufficiently selectively excited to make these reactions a particularly useful tool. The excitation of the lowest mass 9 $T = 3/2$ states via the $^9\text{Be}(^3\text{He},^3\text{He}')^9\text{Be}$ and $^9\text{Be}(^3\text{He},t)^9\text{B}$ reactions has been investigated

(106) and, in fact, only a weak population of these states was observed.

Isospin-forbidden Resonance Reactions.

Highly accurate measurements of the location, width and decay modes of $T = 3/2$ states in $4n+1$ nuclei are possible through twice-isospin forbidden resonance reactions such as $^{12}\text{C} + p \rightarrow ^{13}\text{N}(T=3/2) \rightarrow ^{12}\text{C} + p$ and once-isospin forbidden reactions such as $^{12}\text{C} + p \rightarrow ^{13}\text{N}(T=3/2) \rightarrow ^{13}\text{N}(T=1/2) + \gamma$. The

initial measurement of a twice T-forbidden elastic scattering reaction appears to be the $^{16}\text{O}(p,p)^{16}\text{O}$ investigations of Hardie, Dangle & Oppliger (70) leading to $T = 3/2$ states in ^{17}F which were analogues of the first and second excited states of ^{17}N . Although this field is extremely active, a pathbreaking program of investigating $T = 3/2$ states through proton-induced compound nucleus resonance reactions has been carried out by Temmer and his associates. They have studied elastic and several inelastic proton groups, and in some cases alpha groups, in experiments establishing accurate excitations and widths for $T = 3/2$ states in ^{13}N (107, 108), ^{17}F (62), and ^{25}Al and ^{29}P (84). One of the most striking aspects of these results is that the widths of the lowest $T = 3/2$ states have all been ≤ 2 keV, even though the states lie at fairly high excitations.

As an example of their work, Figure 5 presents elastic scattering excitation curves for protons on ^{12}C showing the resonance corresponding to the $^{13}\text{N}(T=3/2)$ state, as reported by Temmer & van Bree (108). Analysis of these data yields a total width for this state of $\Gamma = 1.9 \pm 0.6$ keV. This width arises from isospin-mixing with nearby states of the same spin and parity in

both the target state ($T=1$ admixture) and the compound resonance ($T=1/2$ admixture) induced by the Coulomb interaction (and charge-dependent nuclear forces). These widths can, in principle, be calculated if appropriate wave functions for both target and compound states are available. A rough preliminary estimate of the width of this $^{13}\text{N}(3/2^-, T=3/2)$ state has been reported by Ginocchio (108) who calculated, in second order perturbation theory, the effect of Coulomb mixing using p-shell wave functions. He obtained an expected width of 1.4 keV which is in good agreement with the measured width.

Once T-forbidden resonance reactions have also been investigated. For example, Youngblood, Morrison & Segel (91) utilized the proton capture reaction $^{28}\text{Si}(p,\gamma)^{29}\text{P}$ to investigate the $T=3/2$ state of ^{29}P by detecting the residual ^{29}P activity in a chopped beam experiment; and Miller & Kavanagh (59) and Dietrich et al. (64) observed the gamma decay of the lowest mass thirteen $T = 3/2$ states populated in the $^9\text{Be}(\alpha,\gamma)^{13}\text{C}$ and $^{12}\text{C}(p,\gamma)^{13}\text{N}$ reactions, respectively.

$T = 2$ States in $T_z = 0, 1$ Nuclei

The first excited states with isospin two units greater than that of the ground state were observed by Garvey, Cerny & Pehl (109) following a

suggestion by Garvey & Bayman (110). These authors utilized the (p,t) reaction on ^{26}Mg , ^{46}Ti and ^{54}Fe to populate the lowest $T = 2$ states in the $T_z = 0$ nuclei ^{24}Mg , ^{44}Ti and ^{52}Fe . Following these measurements, many $T = 2$ states have been investigated both by direct reaction and by isospin-forbidden compound nucleus resonance techniques.

Table IV (111-120) lists the observed $T = 2$ states in $T_z = 0, 1$ nuclei for $12 \leq A \leq 60$. When known, $T = 2$ states corresponding to the ground state and any excited states of the analogue $T_z = 2$ nucleus are presented. Weighted values for the excitations are given whenever more than one measurement of a particular $T = 2$ state is available.

Direct Reaction Experiments.

The only direct reaction utilized to date in the population of $T = 2$ states in this mass region has been the previously discussed two-nucleon transfer reaction. For the present case, simultaneous measurement of (p,t) and (p, ^3He) reactions employed on a $T = 1$ target and proceeding through pickup of an $S = 0$, $T = 1$ nucleon pair are capable of identifying the $T = 2$ states in the $T_z = 0, 1$ product nuclei. Figure 6 presents energy spectra from the $^{42}\text{Ca}(p,t)^{40}\text{Ca}$

and $^{42}\text{Ca}(p, ^3\text{He})^{40}\text{K}$ reactions which led to the identification of the $T = 2$ states at 11.97 MeV in ^{40}Ca and 4.37 MeV in ^{40}K (111). Angular distribution data established the expected 0^+ spin and parity; after correction for phase space and isospin coupling, the (p, t) and $(p, ^3\text{He})$ angular distributions were quite comparable. Many further measurements of $T = 2$ states using simultaneous studies of (p, t) and $(p, ^3\text{He})$ reactions have been carried out at Berkeley investigating residual masses 16, 20 and 52 (112, 120); masses 12, 24, 40 and 56 (111); and masses 32 and 36 (73). The only other reported $T = 2$ state found in a pickup reaction was the ^{24}Na $T = 2$ state investigated by Kingston et al. (119) in the $^{26}\text{Mg}(p, ^3\text{He})^{24}\text{Na}$ reaction.

A program of two-nucleon stripping investigations of $T = 2$ states is in progress at Cal Tech. Adelberger & McDonald (114) have utilized the $(^3\text{He}, n)$ reaction on ^{18}O and ^{22}Ne to measure the lowest $T = 2$ states in ^{20}Ne and ^{24}Mg . In addition, Hensley, Nettles & Barnes (113) have reported data from the $^{14}\text{C}(^3\text{He}, p)^{16}\text{N}$ reaction measuring the excitation of two $T = 2$ states in ^{16}N .

The simple configurations of the high isospin states generally account for their selective population at these high

excitations (the previously mentioned fact that these states are normally "sharp", since the only energetically-allowed particle decays are isospin-forbidden, is a further aid in their observation). One additional aspect of interest in these direct reaction experiments is the nature of the agreement between the experimental data on the population of $T = 2$ states and theoretical spectroscopic factors calculated for them. Table V (121), taken from a forthcoming paper by Towner & Hardy (122), presents a comparison of predicted relative intensities with experimental results for several (p,t) reactions. Spectroscopic amplitudes were calculated assuming simple configurations (i.e., j^n) for the states involved. Distorted wave calculations were performed using a program based on the theory of Rook & Mitra (123) with the same set of average optical model parameters being used for all four reactions. As can be seen from the table, rather good agreement between experiment and theory is found.

As noted in Table IV, no $T = 2$ states are currently known in the $4n+2$ mass series. This situation arises since two nucleon transfer techniques cannot be applied in locating these states due to the absence of stable odd-odd $T = 1$ targets. This would appear to be a fruitful area for ($^3\text{He}, ^3\text{He}'$) and

($^3\text{He}, t$) investigations on $T_z = 1$ targets, such as the $^{22}\text{Ne}(^3\text{He}, ^3\text{He}')^{22}\text{Ne}$ ($T=2$) and $^{22}\text{Ne}(^3\text{He}, t)^{22}\text{Na}$ ($T=2$) reactions. Unfortunately, one must be prepared for low cross section experiments (see earlier discussion). Also, the present lack of sufficient data and theoretical analysis to anticipate angular distributions of interest and then confirm angular momentum transfers to these highly excited states must be considered.

The existence of known $T = 2$ states in the lighter nuclei enables one to investigate the differing selection rules arising in certain direct two-nucleon transfer reactions induced on self-conjugate nuclei; these selection rules depend upon whether the charge symmetry or the charge independence of nuclear forces is assumed. As pointed out by Kroll & Foldy (124) (also see the review by MacDonald (3)), such direct reactions as $^{14}\text{N}(d, \alpha)^{12}\text{C}^*$ ($T=1$) are forbidden in either a charge-symmetric or a charge-independence framework, though (d, α) transitions to a $T = 2$ state in ^{12}C would be charge-symmetry allowed but charge-independence forbidden. Since nuclear forces are known to be almost charge independent, one would not expect to see transitions to the $T = 2$ state (except those arising through $T = 0$ impurities in its wave function).

Some data on this point are available. Ball & Cerny (106) have investigated the $^{14}\text{N}(d,\alpha)^{12}\text{C}^*$ (27.5 MeV, 0_+ , $T = 2$) reaction at forward angles induced by 55 MeV deuterons. As expected, no transitions to a state in this region were observed. An upper limit of 3.3 $\mu\text{b/sr}$ average cross section for the population of this 0_+ , $T = 2$ state can be set from these data, while an upper limit of 2.1 $\mu\text{b/sr}$ can be set for the $^{14}\text{N}(d,\alpha)^{12}\text{C}^*$ (17.77 MeV, 0_+ , $T = 1$) transition which is forbidden in either framework. [Over these angles the average cross sections to the ^{12}C ground (0_+ , $T = 0$) and $^{12}\text{C}^*$ (4.43 MeV, 2_+ , $T = 0$) states were 68 and 346 $\mu\text{b/sr}$, respectively.]

Isospin-forbidden Resonance Reactions.

The initial measurement of a $T=2$ state through isospin-forbidden compound nucleus reactions was reported by Hanna and his colleagues at Stanford (118) through investigation of the $^{24}\text{Mg}(T=2)$ state via the once- T -forbidden capture reaction $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}^*(T=1)$ and the twice- T -forbidden elastic scattering reaction $^{23}\text{Na}(p,p_0)^{23}\text{Na}$. The isospin-forbidden particle decay of this $T=2$ state had been observed earlier by McGrath, Cosper, & Cerny (125) in a particle-particle coincidence experiment by populating the state in the isospin-allowed $^{26}\text{Mg}(p,t)^{24}\text{Mg}$ reaction and then observing its proton and alpha decay. Decay scheme data from both of these experiments are presented in Fig. 7(a). Some results from the resonance experiment (118) are presented in Fig. 7(b), which shows the data on the $^{23}\text{Na}(p,\gamma)^{24}\text{Mg}$ reaction. A gamma cascade in isospin from the 15.43 MeV, $0^+ T=2$ state is observed ($T=2 \rightarrow 1 \rightarrow 0$). Fig. 7(b) (top) presents the capture as observed in the $T=1 \rightarrow 0$ part of the cascade, proceeding through the two 1^+ , $T=1$ levels at 10.03 and 10.80 MeV to the ground state. Presented in Fig. 7(b) (bottom) are the observed primary capture gamma rays leading to the 10.03 and 10.80 MeV levels, as well as angular

correlations which confirm the zero spin of the $T=2$ state. As was the case for the $T = 3/2$ states discussed earlier, this $T=2$ state is extremely sharp ($\Gamma < 2$ keV) even though it lies at very high excitation.

Two other experiments observing $T=2$ states as compound nucleus resonances have been reported, both investigating $^{20}\text{Ne}(T=2)$. Bloch, Pixley, & Truöl (116) investigated this state in the twice- T -forbidden $^{19}\text{F}(p,p_0)^{19}\text{F}$ reaction while the Stanford group (115) utilized elastic scattering investigations as well as the once- T -forbidden proton capture reaction. At the present time the particle decay of this sharp $T=2$ state ($\Gamma=2.1 \pm 0.5$ keV) appears very complex since Γ_{p_0}/Γ is only $6.2 \pm 0.4\%$ (116) and no strong particle-decay groups have yet been observed (by contrast, see Fig. 7(a), Γ_{p_0}/Γ for the decay of the ^{24}Mg $T=2$ states is $\sim 60\%$). Preliminary data on the decay of the $^{20}\text{Ne}(T=2)$ state as observed in particle-particle coincidence experiments by the Berkeley group (126) [$^{22}\text{Ne}(p,t)^{20}\text{Ne}^*(T=2)(p \text{ or } \alpha, ^{19}\text{F} \text{ or } ^{16}\text{O})$] find strong alpha-particle groups in the decay leading to both the 6.05 and/or 6.13 MeV and the 6.92 and/or 7.12 MeV levels of ^{16}O , although these results are in contradiction to those of reference (115). Only a

qualitative estimate of the amplitude of the isospin impurities which result in the observed proton width in the decay of the $^{20}\text{Ne}(T=2)$ state can be given at present. Bloch et al. estimate from their data (116) that the amplitude of the $T = 1$ or 0 impurity in this state is $\sim 1.5\%$ which, interestingly, is of the same order of magnitude as the amplitude that MacDonald (3) calculated for the total isospin impurities in the ground states of light nuclei near this mass.

Complete results on the particle and gamma decay of these high isospin states ($T=3/2$ or 2) should lead to a better understanding of the charge dependence of nuclear forces, though as yet very little theoretical analysis of these experiments has been reported. Alpha-particle decay widths of $T=2$ states in nuclei with $T_z=0$ should be especially interesting from the point of view of isospin mixing because in first order only the isotensor part of the charge-dependent perturbation can mix a $T = 0$ amplitude into the $T = 2$ states (compare MacDonald (3)). However, as also arises in the case of proton or alpha-particle decay of $T = 3/2$ states, isospin forbidden proton decays may arise from both the isovector and the isotensor part of the charge-dependent interaction.

Although an experiment searching for the forbidden $\Delta T = 2$ transitions in the gamma-ray decay of these $T = 2$ states is in progress at Stanford (127), no results on this study have yet been reported.

COMPLETE ISOBARIC MULTIPLETS

The completion of isobaric multiplets of four or more members permits an exploration of the model-independent isobaric multiplet mass equation which, as noted earlier, is based on the assumption of charge independence of nuclear forces: $M(A, T, T_z) = a(A, T) + b(A, T)T_z + c(A, T)T_z^2$. The first experimental test of this relationship was reported by Cerny and colleagues (18) who utilized the $^{12}\text{C}(^3\text{He}, ^6\text{He})^9\text{C}$ reaction to measure the mass of ^9C , thereby completing the mass 9 $T = 3/2$ quartet. Within the relatively large experimental error of the ^9C mass measurement, the IMME was found to correctly relate all four masses.

To date, isospin quartets of mass 7, 9, 13, 17, 21, and 37 have been completed, although no complete isospin quintets are known. Data on the completed quartets are presented in Table VI utilizing the weighted values for the relevant $T = 3/2$ states from Tables I - IV and additional masses from reference (21). These data are treated in two ways. First, the masses of the $T = 3/2$ states in

the $T_z = 3/2$, $1/2$ and $-1/2$ members of the quartets are used in the IMME to predict the masses of the $T_z = -3/2$ members, which are then compared with experiment. Second, values of the $b(A,T)$ and $c(A,T)$ and a possible $d(A,T)$ coefficient (which would appear in a $d(A,T)T_z^3$ term arising in the next stage of the perturbation theory treatment of the masses of a multiplet) are tabulated for later comparison.

From the results in Table VI, it can be seen that there is very good first order agreement between the predicted and experimental mass excesses within the generally large experimental errors, which indicates that the IMME is accurate over a fairly wide range in atomic number. [A relatively large disagreement can be seen in the mass 21 quartet data. However, there are conflicting experimental results on the $T = 3/2$ states in ^{21}Ne and ^{21}Na , and it appears best at present to urge experimental re-measurement of all the relevant states. This is of particular interest since the present data lead to a unique discrepancy between this IMME predicted ^{21}Mg mass and the predictions of Kelson & Garvey (7) on neutron-deficient nuclei (compare Table I to Table VI and see Table VII and its discussion).] The data on mass seven are particularly interesting, in that agreement is

found even though all four members of the quartet are unbound to isospin-allowed decay modes (increasingly so as one goes from ${}^7\text{He}$ to ${}^7\text{B}$) so that their wave functions could be quite different. The only [other than mass 21] apparent discrepancy in these comparisons in Table VI arises in the much more accurate mass nine data, resulting in a non-zero $d(A,T)$ term. Unfortunately, no explicit theoretical estimates of the expected magnitude of the $d(A,T)$ (or higher) term(s) are available. It can be seen from the last column of Table VI, times $c(A,T)$, however, that this coefficient is no greater than $\bar{Z}\alpha$ / where $\bar{Z}$ is the average atomic number of an isospin quartet and α is the fine structure constant. Theoretical predictions of the magnitude of the expected second order corrections would be quite valuable.

A more sensitive procedure for investigation of the charge independence of nuclear forces through use of the IMME was first pointed out by Wilkinson (128) and applied in the $1p$ shell. This procedure requires a detailed study of the mass and/or isospin dependence of the $b(A,T)$ and $c(A,T)$ coefficients and has more recently been discussed by Janecke (129).

At present no complete isospin quintets are known nor are more than three members of any quintet established (these three members occur in the $T_z = 2, 1$ and 0 nuclei). Since completion of isospin quintets would provide a more rigorous test of the IMME, the development of experimental procedures capable of locating $T = 2$ states in the $T_z = -1$ nuclei and measuring the masses of the $T_z = -2$ nuclei (none of which are presently known) are of quite some importance. Two possible general procedures for locating $T = 2$ states in the $T_z = -1$ nuclei suggest themselves. One is the utilization of the ($^3\text{He}, ^6\text{He}$) reaction on available stable odd Z targets, which satisfies the isospin selection rules. (If we take the mass 20 system as an example, this would be the $^{23}\text{Na}(^3\text{He}, ^6\text{He})^{20}\text{Na}^*(T=2)$ reaction.) Unfortunately, this type of investigation is hampered by the very low experimental cross sections, the uncertainty of selective population of the sought $T = 2$ state, and the present lack of systematic angular distribution data in ($^3\text{He}, ^6\text{He}$) reactions. The other, and possibly more fruitful, approach would be the investigation of the decay schemes of the $T_z = -2$ nuclei. Although nothing is presently known about these nuclei (e.g., ^{20}Mg , ^{24}Si , ^{28}S , etc.), they should constitute a new class of beta-delayed proton emitters.

Their decay scheme should include a pure super-allowed Fermi transition to the 0^+ , $T = 2$ state in the daughter $T_z = -1$ nuclei which is then unstable to moderate energy proton emission. For instance, the $(^3\text{He}, 3n)$ reaction on $4n, T_z = 0$ nuclei could produce these new isotopes. (In our example, this would be

$^{20}\text{Ne}(^3\text{He}, 3n)^{20}\text{Mg} \xrightarrow{\beta^+} ^{20}\text{Na}^* (T=2) \rightarrow ^{19}\text{Ne} + p.$) The experimental difficulty in

this procedure would occur in detecting new delayed-proton emitters in the presence of more intense proton groups arising from members of the $4n + 1$ series of known delayed-proton emitters also produced and probably in higher yield.

(e.g., ^{21}Mg from the $^{20}\text{Ne}(^3\text{He}, 2n)^{21}\text{Mg}$ reaction, ^{17}Ne from the $^{20}\text{Ne}(^3\text{He}, \alpha 2n)^{17}\text{Ne}$

reaction, etc.). Finally, to complete the quintet, the mass of the $T_z = -2$

member could be reasonably accurately measured through the $(^4\text{He}, ^8\text{He})$ four

neutron transfer reaction (13) (here $^{24}\text{Mg}(^4\text{He}, ^8\text{He})^{20}\text{Mg}$).

MASS PREDICTIONS OF UNKNOWN NEUTRON-DEFICIENT NUCLIDES

The preceeding section has shown the IMME to be quite accurate for

first order prediction of the masses of the $T_z = -3/2$ members of isospin quartets.

Enough additional data, in Tables I, III and IV and the 1964 mass tables (21),

exist on partially complete quartets and quintets (and one case of a septet)

to permit prediction via the IMME of the masses of many undiscovered light

neutron-deficient isotopes. These mass predictions are tabulated in Table VII along with the relevant predictions of Kelson & Garvey (7). The latter predictions (except for ^{38}Ti) arise from a relation based fundamentally on the charge symmetry of nuclear forces and are expected to be very reliable.

The decay schemes of a few of the $T_z = -3/2$ nuclei listed are known (^{25}Si , ^{29}S , ^{33}Ar), but their masses have not been measured. Noting the table, one finds the expected excellent overall agreement between these mass predictions of reference 7 and those predicted by the use of the IMME. The largest discrepancy between the two occurs in the case of the highly unbound nuclide ^{11}N .

In general, these data support the conclusions of Kelson & Garvey as to the expected stability of the listed nuclei, but do permit a more precise discussion of two nuclei, ^{19}Na and ^{23}Al . Based on the IMME prediction, the separation energy of a proton from ^{19}Na is -0.27 ± 0.15 MeV so that ^{19}Na is probably proton unstable. On the other hand, the IMME prediction of the proton separation energy of ^{23}Al is $+0.28 \pm 0.135$ MeV so that ^{23}Al is most probably proton stable and should be the first bound nuclide in this $T_z = -3/2$, $4n + 3$ mass series.

In conclusion, we note the tremendous growth of our knowledge on high isospin nuclei and excited nuclear states over the past several years. As developing experimental techniques further explore the limits of nucleon stability, the usefulness of the Garvey-Kelson mass relationship will be better evaluated as a guide to additional work. One hopes that the rapidly accruing information on the locations, widths and decay modes of the high isospin nuclear states will shortly lead to an enhanced understanding of the strength of the charge dependence of nuclear forces as they appear in nuclei.

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TABLE I

NUCLEON-STABLE NUCLEI FAR FROM STABILITY

Nuclide	T_z	Decay ^a	Refs.	Mass-Excess (MeV $\pm$ keV)	Refs.	Garvey-Kelson Mass-Prediction ^b (MeV $\pm$ keV)
^8He	2	$\beta^-[\text{n}]$	11,12	31.60 ± 115	13,14 ^c	29.7^6
^{11}Li	5/2	$((\beta^-[\text{n}]))$		<41.1	15	43.6^6
^{12}Be	2	$(\beta^-)[\text{n}]$	16(15)	<28.3		25.0^6
^{14}B	2	$((\beta^-[\text{n}]))$		<24.6	15	24.2^6
^{15}B	5/2	$((\beta^-[\text{n}]))$		<32.7	15	bound to $^{14}\text{B} + \text{n}$ by 2.90 MeV ⁶
^9C	-3/2	$(\beta^+)[\text{p}](2\alpha)$	17	28.916 ± 5	18,19	28.88 ± 22^7
^{16}C	2	$(\beta^-)[\text{n}]$	20	13.693 ± 16	21	
^{18}N	2	β^-	22	13.1 ± 400	22	
^{13}O	-3/2	$(\beta^+)[\text{p}]$	24	23.11 ± 70	25	23.52^7
^{22}F	2	β^-	26	4.5 ± 600	26	
^{17}Ne	-3/2	$(\beta^+)[\text{p}]$	27,28,29	16.47 ± 250	29,30	16.63^7
^{26}Na	2	β^-	31	-7.69 ± 300	21	
^{27}Na	5/2	$((\beta^-[\text{n}]))$		<0.38	32	-6.7^{23}
^{28}Na	3	$((\beta^-[\text{n}]))$		<8.45	32	bound to $^{27}\text{Na} + \text{n}$ by 4.8 MeV
^{21}Mg	-3/2	$(\beta^+)[\text{p}]$	31	10.62 ± 120	33	10.79^7
^{30}Al	2	β^-	31	-17.15 ± 250	21	-17.1^{23}

TABLE I, continued

Nuclide	T_z	Decay ^a	Refs.	Mass-Excess (MeV $\pm$ keV)	Refs.	Garvey-Kelson Mass-Prediction ^b (MeV $\pm$ keV)
²⁵ Si	-3/2	(β^+)[p]	31			See Table VII
³⁴ P	2	β^-	31	-24.83 $\pm$ 200	21	-24.8 ²³
²⁹ S	-3/2	(β^+)[p]	31			See Table VII
⁴⁰ Cl	3	β^-	31	-27.50 $\pm$ 500	21	-27.5 ²³
³³ Ar	-3/2	(β^+)[p]	31			See Table VII
³⁷ Ca	-3/2	(β^+)[p]	31	-13.24 $\pm$ 50	33	-13.17 $\pm$ 55 ⁷

^aBeta-delayed emission of nucleons is denoted by []. Unobserved elements of any decay scheme are enclosed in (), while conjectured decay schemes are enclosed in (()).

^bThe particular reference from which the prediction was taken is given as a superscript.

^cA mass-excess for ⁸He of 31.0 $\pm$ 0.4 MeV is given in this report, superceding the earlier result of the same authors reported in Phys. Letters, 22, 487 (1966).

TABLE II
NUCLEON-UNSTABLE NUCLEI FAR FROM STABILITY

Nuclide	T_z	Mass-Excess; Width (MeV $\pm$ keV; keV $\pm$ keV)	Ref.	Garvey-Kelson ⁶ Prediction
^5H	3/2	Not observed	5,39-41	
^7H	5/2	Not observed	42	
^7He	3/2	26.11 $\pm$ 30; 160 $\pm$ 30	43	
^9He	5/2	Not observed	42,44	
^{10}He	3	Not observed	15,44	unbound to $^8\text{He} + 2n$ by 10 MeV
^{10}Li	2	Not observed	15	Unbound to $^9\text{Li} + n$ by ~ 2.0 MeV
^5Be	-3/2	Not observed	45	
^{13}Be	5/2	Not observed	15	unbound to $^{12}\text{Be} + n$ by 2.7 MeV
^{14}Be	3	Not observed	46	unbound to $^{12}\text{Be} + 2n$ by 2.4 MeV
^7B	-3/2	27.94 $\pm$ 100; 1400 $\pm$ 200	47	
^{16}Ne	-2	Not observed	48	See Table VII

TABLE III

T = 3/2 LEVELS IN $T_z = \pm 1/2$ NUCLEI^{a, b}

$T_z = +1/2$				$T_z = -1/2$		
A	Nucleus	Excitation (MeV $\pm$ keV)	Refs.	Nucleus	Excitation (MeV $\pm$ keV)	Refs.
5	⁵ He	Not observed	40	⁵ Li	Not observed	40
7	⁷ Li	11.28 $\pm$ 40	47,50	⁷ Be	10.98 $\pm$ 30	47,50,51
9	⁹ Be	14.392 $\pm$ 5 (16.973 $\pm$ 2)	52 53,54	⁹ B	14.656 $\pm$ 5	19,55
11	¹¹ B	(12.94 $\pm$ 50) ^c	56	¹¹ C	(12.47 $\pm$ 60) ^c	56
13	¹³ C	15.107 $\pm$ 3 (18.460 $\pm$ 30; 18.659 $\pm$ 15; 18.681 $\pm$ 15; 19.122 $\pm$ 5)	25,57,58 ^d ,59 60	¹³ N	15.066 $\pm$ 4 (18.415 $\pm$ 6, 18.980 $\pm$ 16)	25,61-64 65-67
15	¹⁵ N	11.61	49	¹⁵ O		
17	¹⁷ O	11.075 $\pm$ 6 (12.469 $\pm$ 5; 12.948 $\pm$ 5; 12.996 $\pm$ 5; 13.635 $\pm$ 5)	67 67	¹⁷ F	11.197 $\pm$ 4 (12.553 $\pm$ 5; 13.062 $\pm$ 6; 14.312 $\pm$ 12)	29,62,68,69 62,68-70
19	¹⁹ F	7.432 $\pm$ 14 (7.660 $\pm$ 35) ^e	71,72 73	¹⁹ Ne	(7.606 $\pm$ 35) ^e	73

TABLE III continued

$T_z = +1/2$				$T_z = -1/2$		
A	Nucleus	Excitation (MeV $\pm$ keV)	Refs.	Nucleus	Excitation (MeV $\pm$ keV)	Refs.
21	^{21}Ne	8.856 $\pm$ 6 (9.138 $\pm$ 6; 9.962 $\pm$ 6)	33,74 33,74	^{21}Na	8.969 $\pm$ 7 (9.217 $\pm$ 6)	28,33,75,76 75,76
23	^{23}Na	7.900 $\pm$ 21 (8.640 $\pm$ 21; 10.248)	73,77,78 77-79	^{23}Mg	7.770 $\pm$ 40	73
25	^{25}Mg	7.796 $\pm$ 13	80,81	^{25}Al	7.915 $\pm$ 5 (7.987 $\pm$ 5)	28,80,82-84 83,84
27	^{27}Al	6.815 $\pm$ 2 (10.478 $\pm$ 3; 10.507 $\pm$ 2)	85,86 86,87	^{27}Si		
29	^{29}Si	8.294 $\pm$ 10	80,88,89	^{29}P	8.375 $\pm$ 5	80,84,90,91
31	^{31}P	6.380 $\pm$ 10 (7.150 $\pm$ 10; 9.42)	92 92-94	^{31}S		
33	^{33}S	5.483 $\pm$ 15	95	^{33}Cl	5.555 $\pm$ 19	96,97
35	^{35}Cl	(7.54; 7.84)	98,99	^{35}Ar		
37	^{37}Ar	5.010 $\pm$ 30	33	^{37}K	5.047 $\pm$ 3	33,97,100,101
39	^{39}K			^{39}Ca		

^aA few $T=5/2$ states in $T_z=3/2$ nuclei are known. The lowest $T=5/2$ state in ^{37}Cl lies at 10.24 MeV (102) and $T=5/2$ states in ^{39}Ar exist at 9.089 ± 0.020 and 9.461 ± 0.020 MeV (103).

^b $T=3/2$ states which correspond to any excited states of the $|T_z|=3/2$ nuclei are enclosed in parentheses.

TABLE III continued

^cThese states are the $J^\pi=1/2^-$ analogs of the ^{11}Be first excited state.

^dThe best excitation of Hensley and Barnes for this state is 15.104 ± 0.003 MeV.

^eThis level is the analogue of the ^{19}O first excited state ($3/2^+$) lying at 96 keV excitation.

TABLE IV

T = 2 LEVELS IN $T_z = 0$ AND $T_z = 1$ NUCLEI^{a,b,c}

$T_z = 0$				$T_z = 1$		
A	Nucleus	Excitation (MeV $\pm$ keV)	Refs.	Nucleus	Excitation (MeV $\pm$ keV)	Refs.
12 ^d	¹² C	27.50 $\pm$ 100	111	¹² B	12.67 $\pm$ 70	111
16	¹⁶ O	22.90 $\pm$ 100 (24.70 $\pm$ 100)	112 112	¹⁶ N	9.928 $\pm$ 7 (11.701 $\pm$ 7)	112,113 113
20	²⁰ Ne	16.732 $\pm$ 2.4 (18.430 $\pm$ 5)	112,114-116 112,117	²⁰ F	6.523 $\pm$ 35 (8.05 $\pm$ 100)	73,112 112
24	²⁴ Mg	15.436 $\pm$ 5	109,114,118	²⁴ Na	5.979 $\pm$ 28	73,111,119
28	²⁸ Si			²⁸ Al		
32	³² S	12.017 $\pm$ 45	73	³² P	5.071 $\pm$ 40	73
36	³⁶ Ar	10.858 $\pm$ 35	73	³⁶ Cl	4.295 $\pm$ 30	73
40	⁴⁰ Ca	11.97 $\pm$ 65	111	⁴⁰ K	4.37 $\pm$ 70	111
44	⁴⁴ Ti	9.35 $\pm$ 120	109	⁴⁴ Sc		
48	⁴⁸ Cr			⁴⁸ V		
52	⁵² Fe	8.54 $\pm$ 100	109,120	⁵² Mn	2.79 $\pm$ 100	120
56	⁵⁶ Ni	9.90 $\pm$ 100	111	⁵⁶ Co	3.57 $\pm$ 100	111
60	⁶⁰ Zn			⁶⁰ Cu		

^aAt the present time, no T=2 states are known in $T_z=-1$ nuclei and none are known in any nuclei of mass $4n+2$. The only other states of this general type known are the lowest T=3 levels in ³⁸Ar ($T_z=1$) and ³⁸Cl ($T_z=2$) which lie at 18.775 ± 0.045 and 8.216 ± 0.025 MeV, respectively (73).

TABLE IV. continued

^b This table has been extended through mass 60 to encompass all the $T=2$ states in $T_z=0,1$ nuclei which can be observed using established techniques.

^c $T=2$ states which correspond to any excited states of the $T_z=2$ nuclei are enclosed in parentheses.

^d No $T=2$ states in $T_z=0, 1$ nuclei are known below mass 12.

TABLE V

COMPARISON OF PREDICTED RELATIVE INTENSITIES WITH EXPERIMENTAL RESULTS

FOR SEVERAL (p,t) REACTIONS^a

Target Nucleus	Predicted $\frac{d\sigma}{d\Omega}(0^+, T=2)$ $\frac{d\sigma}{d\Omega}(0^+, T=0)$ (at 40 MeV)	Experimental $\frac{d\sigma}{d\Omega}(0^+, T=2)$ $\frac{d\sigma}{d\Omega}(0^+, T=0)$	Bombarding Energy (MeV)	Ref.
²² Ne	0.25	0.23	43.7	112
²⁶ Mg	0.24	0.19	46.0	121
³⁸ Ar	0.13	0.19	45.0	73
⁵⁴ Fe	0.18	0.22	43.7	120

^aThe comparison is made at the second maximum ($\sim 30^\circ$) in the angular distributions.

TABLE VI

ISOBARIC MULTIPLY MASS EQUATION PREDICTIONS AND CALCULATED COEFFICIENTS

$T_z = -3/2$ Nucleus	Experimental Mass-Excess (MeV)	Predicted Mass-Excess (MeV)	$\underline{b}(A,T)$ (MeV)	$\underline{c}(A,T)$ (keV)	$[\underline{d}(A,T)]$ (keV)	$\bar{Z}\alpha c$ (keV)
${}^7\text{B}$	27.94(100) ^a	27.80(150)	-0.562(50)	242(45)	-24(30)	6
${}^9\text{C}$	28.916(5)	28.961(29)	-1.332(7)	277(11)	7.6(5)	9
${}^{13}\text{O}$	23.11(70)	23.102(16)	-2.180(5)	255(4)	-1(12)	12
${}^{17}\text{Ne}$	16.47(250)	16.517(26)	-2.882(7)	243(10)	8(42)	15
${}^{21}\text{Mg}$	10.62(120)	10.928(29)	-3.658(9)	243(8)	51(21)	19
${}^{37}\text{Ca}$	-13.24(50)	-13.20(90)	-6.189(30)	182(30)	7(17)	25

^aAll errors are in parentheses and are in keV.

TABLE VII

PREDICTED MASSES FOR UNKNOWN NEUTRON-DEFICIENT ISOTOPES OF $A \leq 40$

A	Nucleus	T_z	Estimated Mass-Excess from the IMME (MeV $\pm$ keV)	Garvey-Kelson Mass Prediction ⁷ (MeV)
11	^{11}N	-3/2	25.03 $\pm$ 235 ^a	25.77 ^a
16	^{16}Ne	-2	25.15 $\pm$ 600	24.67
19	^{19}Na	-3/2	12.88 $\pm$ 150 ^b	12.87
20	^{20}Mg	-2	17.45 $\pm$ 280	17.40
23	^{23}Al	-3/2	6.63 $\pm$ 135	6.71
24	^{24}Si	-2	10.68 $\pm$ 230	10.72
25	$^{25}\text{Si}^c$	-3/2	3.78 ₁ $\pm$ 43	3.77
29	$^{29}\text{S}^c$	-3/2	-3.12 ₈ $\pm$ 34	-3.02
32	^{32}Ar	-2	-2.39 $\pm$ 420	-2.28
33	$^{33}\text{Ar}^c$	-3/2	-9.41 ₂ $\pm$ 73	-9.36
36	^{36}Ca	-2	-6.41 $\pm$ 320	-6.48
38	^{38}Sc	-2	-4.64 $\pm$ 1070 ^d	-4.70
38	^{38}Ti	-3	10.94 $\pm$ 1750	10.82
40	^{40}Ti	-2	-9.08 $\pm$ 680	-9.07

^aFor the lowest p-shell state (1/2-).^bThe available data predict the first excited state of ^{19}Na ; this ground state mass-excess has been obtained by assuming that the spacing of these levels in ^{19}Na is the same as in ^{19}O .^cThe decay schemes, but not the masses, of ^{25}Si , ^{29}S , and ^{33}Ar are known.^dThis prediction requires the additional assumption that the $T=3$ state in ^{38}Sc lies at the same excitation as in the analog nucleus ^{38}Cl .

FIGURE CAPTIONS.

Figure 1. A particle-identifier spectrum resulting from the bombardment of uranium by 5.3 GeV protons showing the existence of the previously unknown isotopes ^{11}Li , ^{14}B and ^{15}B .

Figure 2. Two independent ^6He energy spectra from the $^{40}\text{Ca}(^3\text{He}, ^6\text{He})^{37}\text{Ca}$ reaction at 55.9 MeV; the data from both systems were kinematically corrected to 11.2 deg. Each block is one count and the block width is 100 keV.

Figure 3. (a) Energy spectra for the reactions $^9\text{Be}(p, t)^7\text{Be}$ and $^9\text{Be}(p, ^3\text{He})^7\text{Li}$ at 32.5 deg.

(b) Angular distribution for the $T = 3/2$ states at 10.97 MeV in ^7Be and 11.28 MeV in ^7Li . The cross sections for the ^7Li state have been corrected for phase space and isospin coupling by the factor of 0.989.

Figure 4. Energy spectrum from the $^{11}\text{B}(^3\text{He}, n)^{13}\text{N}$ reaction showing the transition to the lowest $T = 3/2$ state in ^{13}N .

Figure 5. Elastic scattering curves for protons on ^{12}C at lab. angles of 65° , 145° and 165° . The largest steps taken were 2 keV, 1-keV steps being taken across the resonance.

Figure 6. Energy spectra from the $^{42}\text{Ca}(p,t)^{40}\text{Ca}$ and $^{42}\text{Ca}(p,^3\text{He})^{40}\text{K}$ reactions

showing the lowest $T = 2$ states in the product nuclei.

Figure 7. (a). Level diagram showing the $0_+, T = 2$ state at 15.43 MeV in ^{24}Mg

and the observed particle- and γ -decay modes. Percentage branching

ratios are given for the particle decays.

(b). Top half: Spectra of gamma rays obtained on and off the $0_+, T = 2$

resonance of ^{24}Mg . The insert shows the yield curve of the 10.03-MeV

gamma ray obtained with a target 4 keV thick.

Bottom half: Spectra of coincident gamma rays obtained on and off resonance.

The insert shows the angular correlations for the 5.40- to 10.03-MeV and

5.40- to 8.66-MeV cascades.

XBL 676-3299

Fig. 1

MUB-9797

Fig. 2

Fig. 3

XBL 682-106

Fig. 4

XBL682-1773

Fig. 5

MUB-7417

Fig. 6

Fig. 7

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