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MASSES OF LIGHT NUCLEI FAR FROM STABILITY*

by

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1. Introduction

In this review I would like to indicate the progress that has been made in mass determinations of light nuclei far from the valley of beta-stability. Generally, high-isospin nuclei of mass $5 \leqslant A \leqslant 40$ will be covered which have been studied by in-beam multi-neutron transfer reactions induced by conventional projectiles and heavy ions, as well as through fragmentation reactions initiated by GeV protons. Recent attempts to utilize heavy-ion transfer reactions for accurate mass measurements of various nuclides through the $f_{7/2}$ shell are also summarized.

Many accurate masses are now known for $T_z = (N-Z)/2 = -3/2$ nuclei from ^7B to ^{37}Ca and these results can be compared to various theoretical mass relations. The available data on these neutron-deficient nuclides are used to evaluate the mass predictions of Kelson and Garvey (1) as well as to test the isobaric multiplet mass equation (since these $T_z = -3/2$ nuclides complete isospin quartets). On the neutron-excess side of stability, considerable progress has been made in establishing additional neutron-rich, nucleon-stable isotopes, though relatively few accurate masses are known. Figure 1 presents an overview of the current situation in the elements through sulfur by indicating all nuclei known to be nucleon stable as well as the predicted limits of stability from the nuclidic mass relationship of Garvey, Kelson and co-workers (1,2).

In the following discussion only nuclei which are at least three neutrons lighter than (or three neutrons heavier than) the lightest (heaviest) stable isotope of each element will be considered. This in general means that complex multi-nucleon transfer reactions are required to produce the nuclei of interest. With this basis, then, those particular neutron-excess nuclides whose masses can be accurately measured by simple charge-exchange reactions on neutron-rich targets [e.g., ^{18}N via $^{18}O(t,{}^3He)$ (3) or ^{26}Na via $^{26}Mg({}^7Li,{}^7Be)$ (4)] will also be omitted.

2. Neutron-Deficient Light Nuclei

Table I (5-10) presents a summary of the known neutron-deficient nuclei which meet the restrictions noted above. As yet no nuclei with $T_z = -2$ or greater have been characterized. The results of all the various mass measurements on both nucleon-stable and -unstable nuclei are included in the table; a weighted average is also shown.

A general approach employed for accurate mass-measurements of neutron-deficient nuclei has been to utilize the $({}^3He,{}^6He)$ and

TABLE I

Masses of known $T_z = -3/2$ nuclei far from stability

Nuclide	Nucleon-stable	Reaction	Lab	Mass-excess (MeV ± keV)	Reference[a]	Adopted mass-excess (MeV ± keV)
^{7}B	No	^{10}B(^{3}He,^{6}He)	LBL-67	27.94 ± 100	5	27.94 ± 100
^{9}C	Yes	^{12}C(^{3}He,^{6}He)	LBL-64	28.99 ± 70	5	28.910 ± 3[b]
		^{7}Be(^{3}He,n)	CIT-67	28.916 ± 5	5	
		"	CIT-69	28.907 ± 4	6	
		^{12}C(^{3}He,^{6}He)	MSU-70	28.911 ± 9	7	
^{13}O	Yes	^{16}O(^{3}He,^{6}He)	LBL-66	23.11 ± 70	5	23.105 ± 10
		"	LBL-70	23.107 ± 15	8	
		"	MSU-70	23.103 ± 14	7	
^{17}Ne	Yes	^{16}O(^{3}He,2n)	BNL-67	16.47 ± 250	5	16.479 ± 49
		^{20}Ne(^{3}He,^{6}He)	LBL-70	16.479 ± 50	8	
^{19}Na	No	^{24}Mg(p,^{6}He)	LBL-69	12.974 ± 70	9	12.974 ± 70
^{21}Mg	Yes	^{24}Mg(^{3}He,^{6}He)	LBL-68	10.889 ± 40	8	10.908 ± 16
		"	MSU-70	10.912 ± 18	7	
^{23}Al	Yes	^{28}Si(p,^{6}He)	LBL-69	6.766 ± 80	9	6.766 ± 80
^{25}Si[c]	Yes	^{28}Si(^{3}He,^{6}He)	LBL-70	3.817 ± 50	8	3.831 ± 12
		"	MSU-71	3.832 ± 12	10	
^{37}Ca	Yes	^{40}Ca(^{3}He,^{6}He)	LBL-68	-13.23 ± 50	5	-13.23 ± 50

[a] Whenever possible, reference is made to review articles.

[b] See ref. 6.

[c] These measurements assume that only the ^{25}Si ground state is populated.

$(p,{}^6He)$ reactions. These reactions possess high negative Q-values (~ -24 to -38 MeV) and low cross-sections (~ 0.06 to 3 μb). Until recently, most of these investigations were performed at Berkeley using counter-telescope techniques; however, this past year a group at Michigan State University has begun similar measurements using a magnetic spectrograph with a position-sensitive detector in the focal plane (7).

Figure 2 presents the experimental approach used in the Berkeley measurements. Due to the low cross-sections for these reactions, two four-counter semiconductor-telescope, particle-identifier systems are employed. Basically, in each telescope two particle-identifications of all events of interest are performed and compared using signals from the two successive differential-energy-loss detectors--denoted $\Delta E2$ and $\Delta E1$, respectively--and the third E detector. (The fourth detector rejects any events traversing the first three.) Further, to eliminate background due to pile-up within a single beam burst, time-of-flight measurements over the 51 cm flight path between the target and the $\Delta E2$ counter as well as subnanosecond pile-up detection using the signal from this counter are utilized. Those events in each system which are of interest are sent via an analog-to-digital converter, multiplexer system to an on-line computer. Six parameters are recorded for each event: $\Delta E2$, $\Delta E1$, E(total), particle identification, time-of-flight and pile-up detection. The details of our set-up and calibration procedures are discussed elsewhere (see 8, 9 and references therein). It appears that such an overall system is capable of studying highly endothermic nuclear reactions with cross-sections as low as 10 nb/sr.

Figures 3 and 4 present ${}^6He$ energy spectra from the ${}^{20}Ne({}^3He,{}^6He){}^{17}Ne$ and ${}^{28}Si({}^3He,{}^6He){}^{25}Si$ reactions (11) induced by 62.6 MeV ${}^3He$ ions from the Berkeley 88-inch cyclotron. In both cases the $({}^3He,{}^6He)$ reactions on ${}^{12}C$ and ${}^{16}O$ are also shown; since the masses of ${}^9C$ and ${}^{13}O$ are accurately known (particularly the former--see Table I), these reactions provide a valuable reference standard. Both the reactions on ${}^{20}Ne$ and ${}^{28}Si$ have cross-sections ~ 0.5 to 1 μb/sr. Transitions to several excited states of ${}^{17}Ne$ can be seen in Fig. 3.

Although the $({}^3He,{}^6He)$ reaction can be used to study all the members of the $T_Z = -3/2$, $A = 4n+1$ mass series through the calcium isotopes (and in fact only the ${}^{29}S$ and ${}^{33}Ar$ masses are presently unknown), a different reaction is required to investigate the comparable $T_Z = -3/2$, $A = 4n+3$ mass series (since only ${}^7B$ and ${}^{11}N$ can be reached via the above reaction). For this latter mass series the $(p,{}^6He)$ reaction can be utilized, and Fig. 5 presents ${}^6He$ energy spectra from this reaction induced by 54.7 MeV protons on several targets (9). The $(p,{}^6He)$ reaction on ${}^{24}Mg$ and ${}^{28}Si$ was used to determine the masses of ${}^{19}Na$ and ${}^{23}Al$ given in Table I, while the ${}^{14}N(p,{}^6He){}^9C$ reaction was used as a calibration. Cross sections at forward angles for production of ${}^9C$, ${}^{19}Na$, and ${}^{23}Al$ are 160, 120, and 60 nb/sr, respectively. These measurements established ${}^{23}Al$ as the first nucleon-stable member of this mass series. No further measurements of members of this $T_Z = -3/2$, $A = 4n+3$ mass series have been reported, though ${}^{15}F$, ${}^{27}P$, ${}^{31}Cl$, and ${}^{35}K$ remain measurable by this technique.

Table II (12-14) compares the measured mass-excesses of all these $T_Z = -3/2$ nuclei to various theoretical predictions. First, since these nuclides complete isospin quartets in which the other three members are accurately known, one can investigate two aspects of the isobaric multiplet mass equation (IMME), $\Delta M = \underline{a} + \underline{b}\ T_Z + \underline{c}\ T_Z^2$. (This relation among the masses of an isobaric multiplet is derived by treating any two-body charge-dependent forces as a first-order perturbation to a charge-independent nuclear Hamiltonian. See, e.g., refs. 5, 12). One of these aspects is its predictive ability: in Table II are shown the predicted mass-excesses for these nuclides obtained from using the known masses of the other three members of the various quartets in the IMME. In general excellent first-order agreement can be noted over the entire mass range, regardless of whether the $T_Z = -3/2$ nuclide is nucleon-bound or -unbound. Such results suggest that the IMME can be reliably used to predict the masses of other undiscovered light, neutron-deficient isotopes.

Since the isobaric multiplet mass equation does so well, considerable recent interest has been attached to determining at what level and in which isobars significant deviations from this quadratic form appear. This deviation is normally parameterized by an additional term $\underline{d}\ T_Z^3$ in the mass equation (it arises as the next term in a second order perturbation treatment (see, e.g. ref. 15)). Values for $\underline{d}$ for these isobars are also given in Table II. Apart from the accurate non-zero value for the A=9 isobar, all the values of $\underline{d}$ are essentially consistent with zero, including the equally accurate result for A=13 (the uncertainty noted in footnote f of the table precludes taking the A=25 data to be of comparable importance). These results are in agreement with two recent theoretical treatments (16,17), both of which find generally small values for $\underline{d}$ ($\lesssim$ 1 keV). At present, the A=9 result appears to be anomalous, and experimental remeasurement as well as more theoretical work seem necessary to clarify the situation.

In addition, Table II also compares the experimental masses to the predictions of Kelson and Garvey (1) which arise from a relation based fundamentally on the charge symmetry of nuclear forces. One in general finds excellent overall agreement between their predictions and experiment (by far the largest discrepancy occurs for ^{13}O). Finally, the relevant masses are compared with those predicted from a systematic study of Coulomb displacement energies in the $1d_{5/2}$ shell (14); in this case extremely good agreement can be seen between the predicted and experimental masses.

3. Neutron-Excess Light Nuclei

Table III (18-24) presents a summary of the known <u>nucleon-stable</u>, neutron-excess nuclei--which meet the restrictions noted in the Introduction--along with their mode of production. All available mass-excesses are tabulated; however, when only the nucleon-stability of a series of isotopes has been established, then solely the heaviest known neutron-stable isotope is listed (see also Fig. 1).

Although few accurate mass-excesses for very neutron-rich nuclei are available (the ^{29}Mg measurement will be discussed in the next section), the nucleon-stability of many such isotopes has been determined. The various approaches for investigating these latter nuclei are indicated in Table III and its references, but a particular

TABLE II

Experimental and predicted mass-excesses of neutron-deficient nuclides

T_z = -3/2 Nuclide	Experimental mass-excess (MeV ± keV)	IMME[a] prediction (MeV ± keV)	d (keV ± keV)	Kelson-Garvey[b] (MeV)	$d_{5/2}$ - shell Coul. calc.[c] (MeV ± keV)
^{7}B	27.94 ± 100	27.87 ± 150	-11 ± 30		
^{9}C	28.910 ± 3	28.956 ± 22[d]	8.0 ± 3.7[d]	28.88	
^{13}O	23.105 ± 10	23.102 ± 14	-0.5 ± 2.9	23.52	
^{17}Ne	16.479 ± 49	16.514 ± 21	5.8 ± 8.9	16.63	
^{19}Na	12.974 ± 70	e	e	12.87	12.965 ± 25
^{21}Mg	10.908 ± 16	10.940 ± 24	5.3 ± 4.9	10.79	10.916 ± 7
^{23}Al	6.766 ± 80	6.699 ± 77	-11.2 ± 18.5	6.71	6.743 ± 25
^{25}Si[f]	3.831 ± 12	3.796 ± 17	-5.8 ± 3.5	3.77	3.828 ± 8
^{37}Ca	-13.23 ± 50	-13.198 ± 91	5.3 ± 17.3	-13.17	

[a] Required data were taken from refs. 5, 8, and 12 insofar as possible. Also see ref. 13.

[b] See ref. 1.

[c] See ref. 14.

[d] See ref. 6.

[e] The lowest T = 3/2 state in ^{19}Ne has not been established.

[f] These results assume that only the ^{25}Si ground state was populated in the ^{28}Si(^{3}He,^{6}He)^{25}Si reaction.

TABLE III

Nucleon-stable, neutron-excess nuclides far from stability

Nuclide[a]	T_z	Reaction	Lab	Mass-excess (MeV ± keV)	Ref.[b]	Garvey et al.[c] (MeV)
^{8}He	2	^{26}Mg(^{4}He,^{8}He)^{22}Mg	LBL-66	31.60 ± 115	5	29.7
		^{16}O,^{12}C(π^-,^{8}He)	JINR-66		5	
^{11}Li	5/2	^{238}U + 5.3 GeV p	LBL-66	$\leqslant$ 41.1[d]	5	42.0
^{12}Be	2	^{15}N(p,4p)^{12}Be	BNL-65	$\leqslant$ 28.3[d]	5	25.0
^{15}B	5/2	^{238}U + 5.3 GeV p	LBL-66		5	stable
^{16}C	2	^{14}C(^{3}H,p)^{16}C	AWRE-61	13.693 ± 16	5	13.67
^{19}C	7/2	^{197}Au + 3 GeV p	PPA-70		18	33.7 [e]
^{21}N	7/2	^{232}Th + 174 MeV ^{22}Ne	JINR-70		19	stable
^{24}O	4	" "	"		19	"
^{25}F	7/2	" "	"		19	"
^{25}Ne	5/2	^{181}Ta + 180 MeV ^{22}Ne	JINR-71	(−2.3 ± 300)[f]	20	−1.9
^{26}Ne	3	^{232}Th + 174 MeV ^{22}Ne	JINR-70	$\leqslant$ 5.8[d]	21	−0.9
^{27}Na	5/2	^{238}U + 24 GeV p	CERN-68	−7.0 ± 500	22	−6.6
^{31}Na	9/2	" "	CERN-69		22	stable
^{29}Mg	5/2	^{26}Mg(^{11}B,^{8}B)^{29}Mg	AERE-71	(−12.33 ± 160)[f]	23	−12.56

[a] The heaviest known neutron-stable isotope is tabulated. Lighter isotopes are listed only if their mass-excess has been determined.

[b] Whenever possible, reference is made to review articles.

[c] See ref. 2.

[d] A limit is given only when the mass of the (1 or 2)-neutron decay channel is known.

[e] See ref. 24.

[f] Preliminary values are enclosed in parentheses.

new technique deserves mention. Volkov and collaborators at Dubna (19,21) have recently identified eleven new neutron-rich isotopes through multi-nucleon transfer reactions of heavy ions on thorium targets; the reaction products were identified using a combined magnetic analysis-counter-telescope detection system.

Also listed in Table III are the mass predictions of Garvey, Kelson and collaborators (2) based on an independent-particle model; where appropriate, either the expected neutron-stability or the predicted mass-excess of the various nuclides is given. In general, excellent agreement between their prediction of nucleon-stability and experiment is observed (see also Table II of ref. 5). Hopefully, it will soon be possible by the techniques of Volkov et al. (19,21) and those of Klapisch et al. (22) to establish experimentally the limits of neutron stability, at least in the elements through sodium, and thereby provide a severe test of this mass relationship. Additional accurate mass data for neutron-excess nuclei are required to test their detailed predictions. Although generally good agreement can be noted in Table III, the predicted mass of ^{8}He is considerably in error, and both ^{11}Li and ^{19}C, though observed to be nucleon stable, were in fact predicted to be unbound (2).

4. Future Prospects

In this section I would like to indicate some useful extensions of present techniques for accurate mass measurements as well as to mention a few of the newer approaches being attempted, particularly those using heavy ions as projectiles.

On the neutron-deficient side of stability, two lines of development are of interest: the determination of masses of nuclei with $T_z = -2$ and greater below mass 40, and the measurement of masses of $Z > N$ nuclei in the $f_{7/2}$ shell, since almost nothing is known concerning these latter nuclides above the titanium isotopes. Of immediate value would be the determination of the masses of all the $T_z = -1/2$ nuclides in the $f_{7/2}$ shell. This would permit accurate mass predictions for many highly neutron-deficient nuclei in that shell following the procedure used by Kelson and Garvey (1) in the lighter nuclei.

Table IV (25-28) presents a few representative reactions capable of reaching these neutron-deficient nuclei. Such multi-neutron transfer reactions as (^{4}He,^{8}He) and (^{3}He,^{8}He) can produce very neutron-deficient nuclides, though at present only a limit can be set for their yield. Hopefully, the increasing use of large solid-angle magnetic spectrometers will soon make these investigations feasible. The ^{40}Ca(^{12}C,t)^{49}Mn ($T_z = -1/2$) reaction has been successfully observed (26), so that either similar heavy-ion transfer reaction measurements, or extension of the (^{3}He,^{6}He) and (p,^{6}He) studies discussed in Section 2, could determine the masses of all the $T_z = -1/2$ nuclei in the $f_{7/2}$ shell. In addition, a recent attempt to study the $T_z = -1$ nuclide ^{50}Fe is listed in the table.

Many masses of neutron-rich isotopes are yet unknown. Table IV presents two quite recent, potentially general studies capable of producing such nuclides. A four-neutron transfer ^{18}O(^{18}O,^{14}O)^{22}O reaction is under investigation at Brookhaven, and measurements of the three-neutron transfer (^{11}B,^{8}B) reaction have been successfully

TABLE IV

Recent in-beam transfer reactions employed in attempts to determine accurate masses of light high-isospin nuclei far from stability

Nuclide	Reaction	Beam Energy (MeV)	Q-value (MeV)	$d\sigma/d\Omega$ (μb)	Ref.
(^{20}Mg)^a	^{24}Mg(^{4}He,^{8}He)^{20}Mg	96	-61	$\lesssim 0.025$	25
^{49}Mn	^{40}Ca(^{12}C,t)^{49}Mn	27.5	-12	~ 1.0	26
(^{50}Fe)^a	^{40}Ca(^{16}O,^{6}He)^{50}Fe	65	-23	< 0.3	27
(^{22}O)^{a,b}	^{18}O(^{18}O,^{14}O)^{22}O	60	-23	< 0.5	28
^{29}Mg	^{26}Mg(^{11}B,^{8}B)^{29}Mg	114.5	-18	~ 3.6	23

[a] Reactions leading to nuclides enclosed in parentheses can at present only set upper limits for their production via this mechanism.

[b] ^{22}O is known to be nucleon stable.

reported at Harwell. Figure 6 presents an energy spectrum from the ^{26}Mg(^{11}B,^{8}B)^{29}Mg reaction due to Scott and collaborators (23). Although these are only preliminary results, exploitation of this reaction will give valuable mass information over much of the nuclidic chart; such data will be extremely useful in verifying the quantitative predictions of various mass relations such as those of Garvey et al. (2).

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(Captions)

Fig. 1. Nucleon-stable nuclei through the sulfur isotopes. Unfilled squares represent the predictions of Garvey, et al.

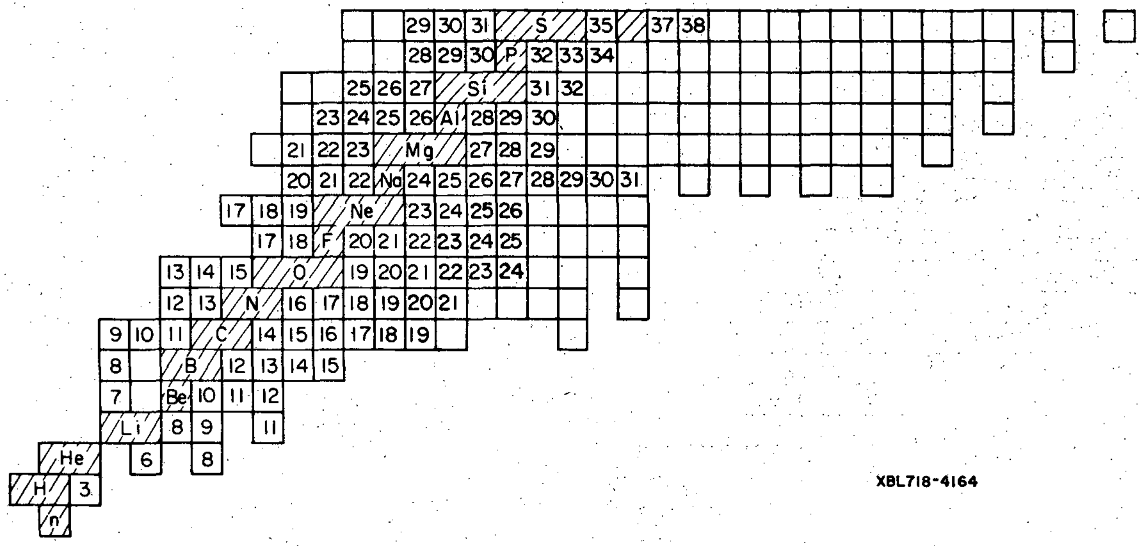
Fig. 2. An abbreviated diagram of the experimental layout for one of the two similar detection systems employed in the Berkeley measurements.

Fig. 3. The (^{3}He,^{6}He) reaction induced by 62.6 MeV ^{3}He ions on both a CO_2 target and a ^{20}Ne-CO_2 mixture.

Fig. 4. The (^{3}He,^{6}He) reaction induced by 60.0 and 62.6 MeV ^{3}He ions on a self-supporting and a ^{12}C-backed SiO_2 target, respectively.

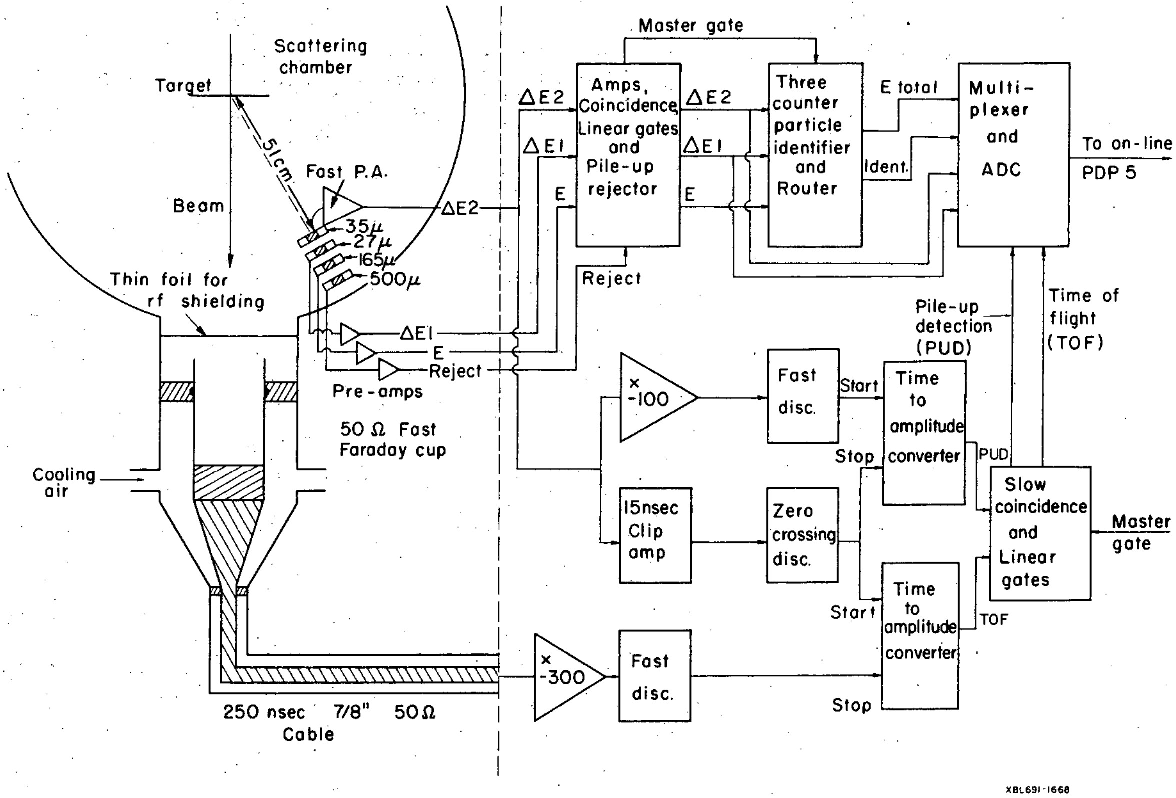
Fig. 5. The energy spectra from the (p,^{6}He) reaction on natural silicon (top), ^{24}Mg (middle), and adenine (bottom). Each block is one count and the block width is 80 keV. Data from detection system 2 only are shown for the last two targets, while data from both systems are combined to produce the ^{28}Si(p,^{6}He)^{23}Al spectrum.

Fig. 6. Energy spectra from the ^{26}Mg(^{11}B,^{8}B)^{29}Mg reaction. The top spectrum shows the data at an angle of 10°, while the inset is the spectrum at 9° with tighter gates around the ^{8}B region of the identifier spectrum. The bottom spectrum shows the data from both angles kinematically compensated to 10°.



XBL718-4164

Fig. 1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Target
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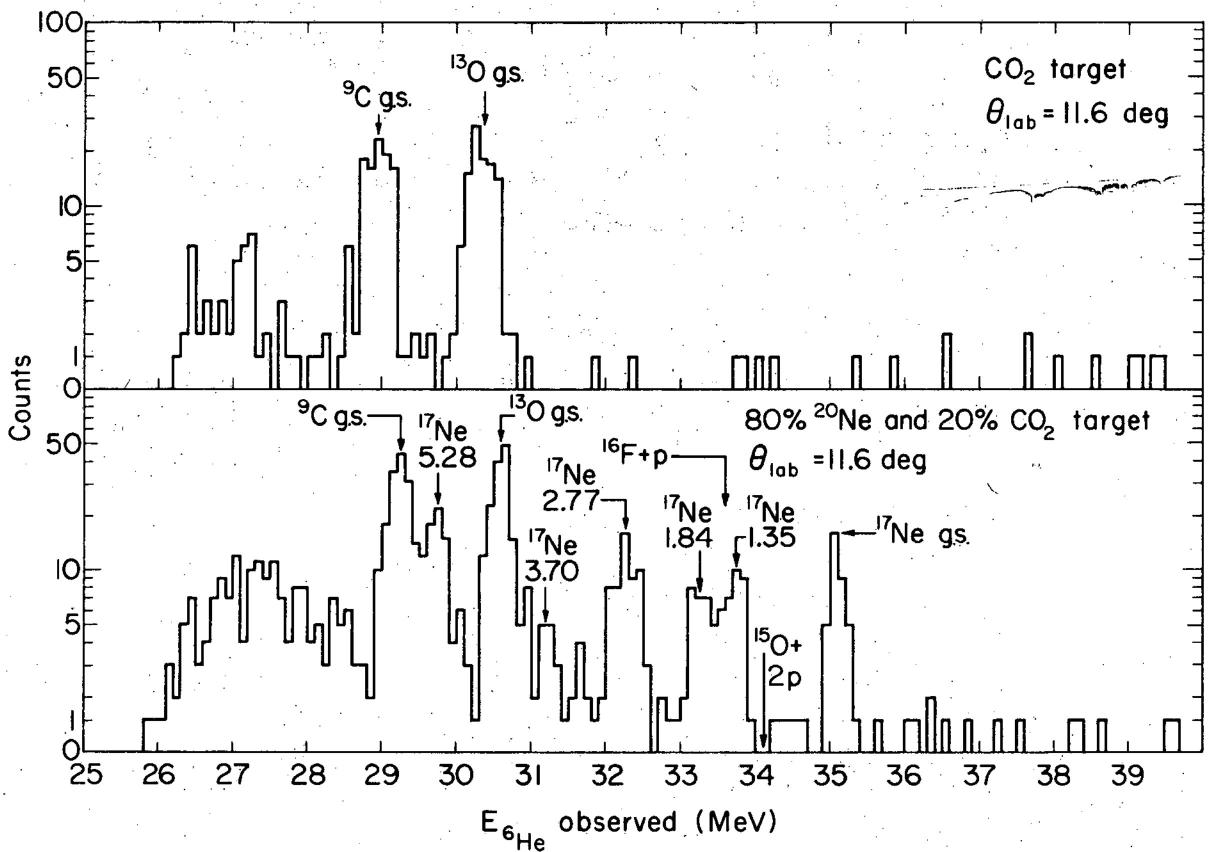
Fast P.A.
Beam
35μ
27μ
165μ
500μ
Thin foil for rf shielding
ΔE2
ΔE1
E
Reject
Pre-amps
50 Ω Fast Faraday cup
Cooling air
Amps, Coincidence Linear gates and Pile-up rejector
Three counter particle identifier and Router
E total
Ident.
Multi-plexer and ADC
To on-line PDP 5
Pile-up detection (PUD)
Time of flight (TOF)
× -100
Fast disc.
Start
Stop
Time to amplitude converter
PUD
Slow coincidence and Linear gates
Master gate
15nsec Clip amp
Zero crossing disc.
TOF
× -300
Fast disc.
250 nsec 7/8" 50Ω Cable
XBL691-1668

Fig. 2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50
10
5
1
0
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80% ^{20}Ne and 20% CO$_2$ target
θ_{lab} = 11.6 deg
^{9}C g.s.
^{17}Ne 5.28
^{13}O g.s.
^{17}Ne 2.77
^{16}F+p
^{17}Ne 3.70
^{17}Ne 1.84
^{17}Ne 1.35
^{17}Ne g.s.
^{15}O+ 2p
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E$_{^6He}$ observed (MeV)
XBL7012-4225

Fig. 3

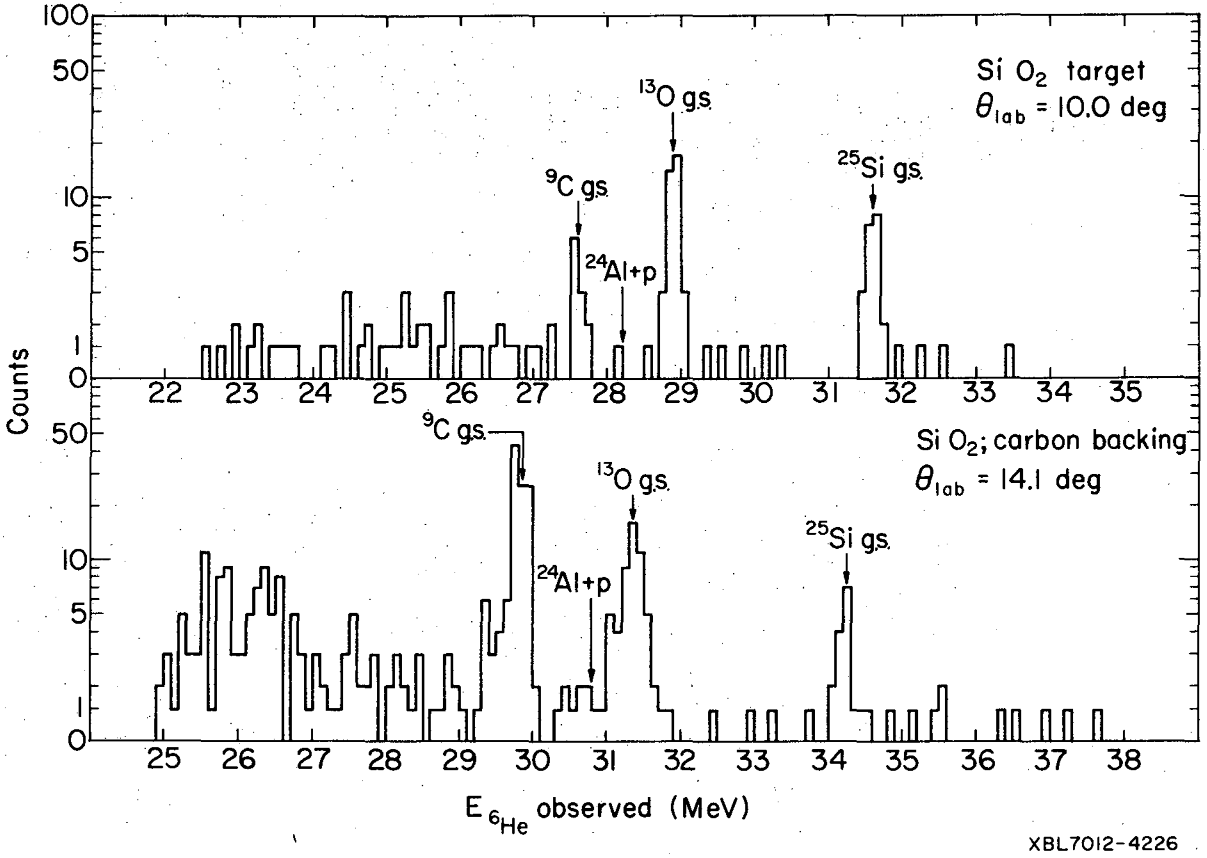
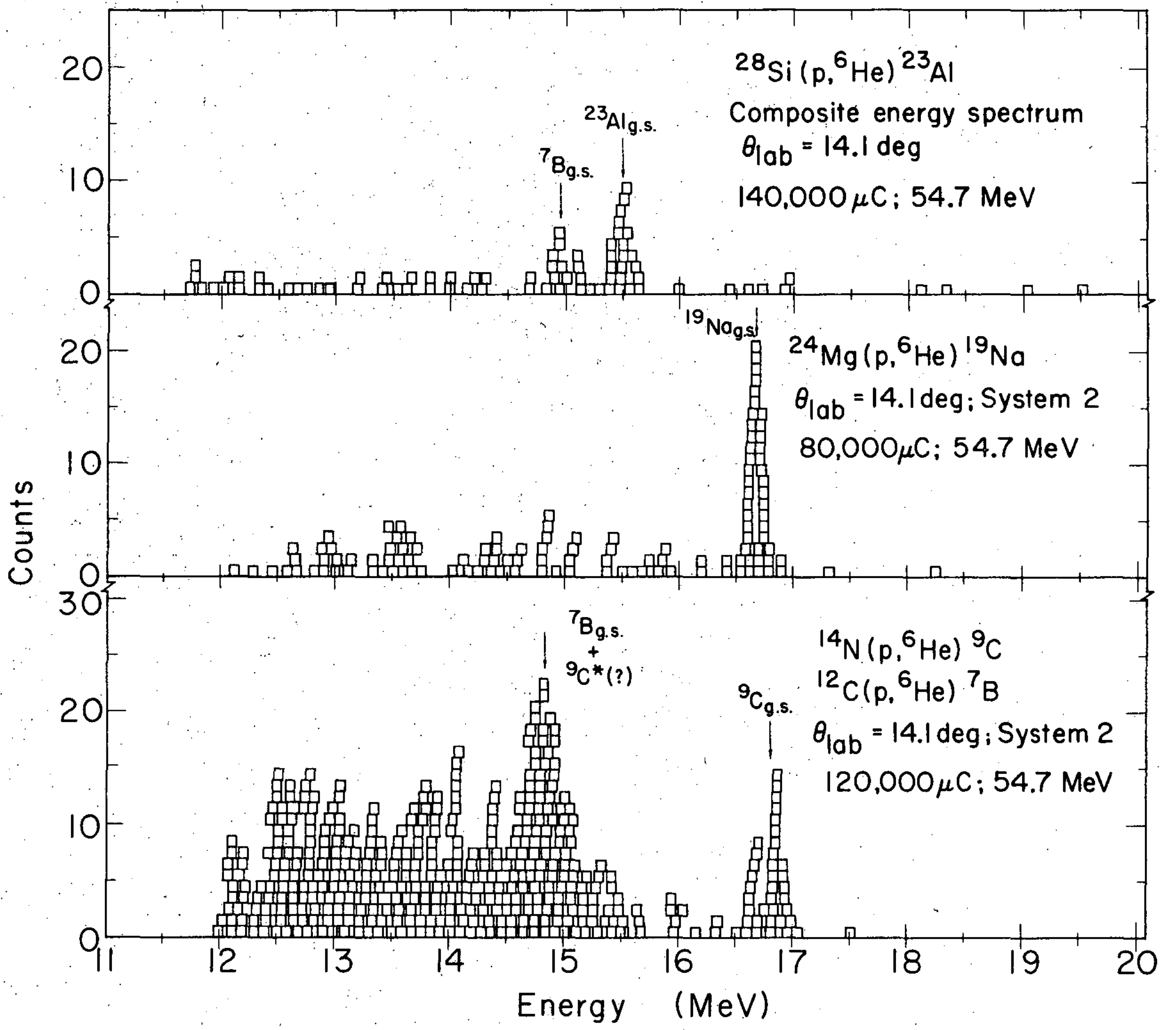
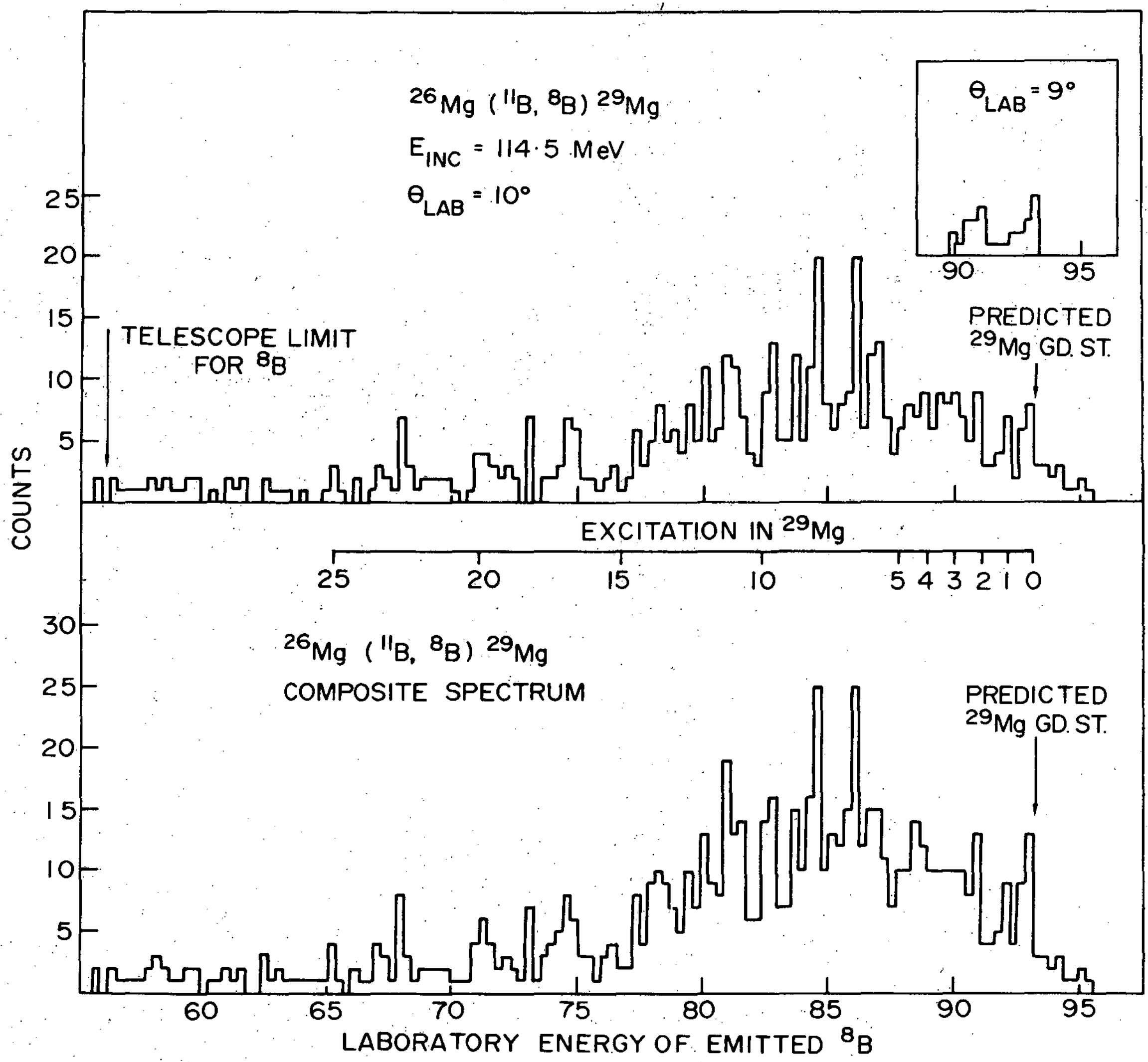

Si O$_2$ target
θ_{lab} = 10.0 deg
^{13}O gs
^{9}C gs
^{25}Si gs
^{24}Al+p
Si O$_2$; carbon backing
θ_{lab} = 14.1 deg
^{9}C gs
^{13}O gs
^{24}Al+p
^{25}Si gs
Counts
100
50
10
5
1
0
22 23 24 25 26 27 28 29 30 31 32 33 34 35
25 26 27 28 29 30 31 32 33 34 35 36 37 38
E $_{^6He}$ observed (MeV)
XBL7012-4226

Fig. 4



XBL 691-1667

Fig. 5



XBL 718-1295

Fig. 6

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