MASS OF ^{16}NE

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ABSTRACT

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The mass of ^{16}Ne has been measured by the reaction $^{20}Ne(^{4}He,{}^{8}He)^{16}Ne$ at a beam energy of 129 MeV. The target gas of isotopically enriched ^{20}Ne (>99.5% ^{20}Ne) was contained in a gas cell with Havar windows. Reaction products were detected at the focal plane of an Enge split-pole spectrograph by a single-wire gas proportional counter backed by a Si surface barrier detector. Particle identification was determined from 1) energy loss in the gas, 2) total energy and 3) time of flight relative to the cyclotron RF. The reaction was observed at a lab angle of 7.5°. A total of 25 events were obtained at an approximate reaction cross section of 1 nb/sr. The mass excess of ^{16}Ne was found to be 23.984 ± 0.024 MeV. The value is in good agreement with the quadratic isobaric multiplet mass equation although small cubic and quartic coefficients are found for the A=16 isobaric quintet for the fit to the four-parameter IMME.

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I. INTRODUCTION

Mass measurements of nuclei are very important in the study of the structure of the nucleus and the properties of the fundamental forces of nature. In particular, there is a strong interest at this time in the determination of the masses of highly unstable nuclei for which accurate measurements could not be made prior to innovations in particle detectors, electronics and data acquisition systems. The measurement of the mass of ^{8}He by R. E. Tribble et al.[1] in 1977 makes the (^{4}He,^{8}He) reaction particularly attractive to measure the masses of proton-rich nuclei. A typical proton-rich nuclide is ^{16}Ne, having ten protons and six neutrons. As is characteristic of these nuclei, ^{16}Ne is unbound and decays by particle emission; it has a lifetime on the order of 10^{-20} seconds.

The $^{20}Ne(^{4}He,^{8}He)^{16}Ne$ reaction* is one of several reactions which can be used to produce ^{16}Ne. The mechanism for the (^{4}He,^{8}He) reaction is the transfer of a single four-neutron cluster from the target nucleus to the projectile nucleus[2]. This reaction requires the conversion of some of the kinetic energy of the energetic incident alpha particle into binding energy of the reaction products. The rest of the kinetic energy is used to excite the products above their ground states or is transferred directly as kinetic energy. The kinetic energy released in a nuclear reaction in known as the Q-value of the reaction and is equal to the difference in the masses

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*In this notation for a nuclear reaction the first element is the target nucleus, the second is the projectile, the third is the ejectile, and the fourth is the residual nucleus.

of the products and the reactants: $Q = \sum$atomic mass of reactants $- \sum$atomic mass of products. Endoergic reactions such as the one used in this experiment require a minimum kinetic energy of the projectile particle to enable the reaction to take place and are characterized by a negative Q-value. The energy absorbed in the reaction is the difference in the kinetic energy of the reactants and the kinetic energy of the products. The Q-value of the reaction is determined from the measured kinetic energies of the incident particle and the ejectile and the laws of conservation of energy and momentum. The mass of the residual nucleus is then obtained from the Q-value and the masses of the other nuclei involved in the reaction.

The fundamental force holding the nucleus together is the strong nuclear force. However, since the nucleus is composed of neutrons and positively charged protons which tend to repel each other, the electromagnetic force in the form of the Coulomb interaction acts as a pertubation to the dominant strong nuclear interaction. Since the mass of the nucleus is dependent upon the forces acting upon it, mass measurements can provide information about these forces at the nuclear level.

Until relatively recently it was believed that the strong nuclear interaction was charge independent. If this were the case, then the only charge dependent nuclear interaction would be the two-body Coulomb interaction. Since the perturbations due to gravity and the weak nuclear force, the other two fundamental forces of nature, are negligible when compared to the effect of the Coulomb interaction, the deviation of the mass from that predicted by the strong interaction Hamiltonian* can be predicted from a simple two-body electromagnetic interaction Hamiltonian. If the strong nuclear interaction were charge independent then its

Hamiltonian would be dependent upon the atomic mass number, A, the isospin, T, and the other charge independent nuclear quantum numbers, but would be independent of the z-component of the isospin, T_z, which is the charge dependent nuclear quantum number. T_z is given by the relationship $T_z=(N-Z)/2$, where N is the number of neutrons and Z is the number of protons in the nucleus. The Coulomb interaction Hamiltonian, however, would be dependent upon T_z. The isobaric multiplet mass equation (IMME) first suggested by Eugene Wigner in 1957[3] predicts that the mass excesses of an isobaric multiplet, several nuclei with the same isospin and atomic mass number, are given by the equation $\Delta M(A,T,T_z)=a+bT_z+cT_z^2$, where a, b, and c are constants for any given multiplet. The mass excess is the difference between the exact mass and the atomic mass number, $\Delta M=M-A$. The IMME assumes the only significant charge dependent perturbation to be the Coulomb repulsion between the protons in the nucleus which, being a two-body interaction, is quadratic in T_z.

Recent evidence[4,5,6,7] indicates that the strong nuclear interaction may include a small charge dependent component. If this is an n-body interaction then it will introduce correction terms into the quadratic IMME making it an n^{th} order polynomial in T_z. In particular, non-zero d or e coefficients in the five-parameter equation $\Delta M(A,T,T_z)=a+bT_z+cT_z^2+dT_z^3+eT_z^4$ could indicate the existence of a nuclear charge dependent interaction (cdi). If the nuclear cdi were predominantly a two-body interaction then its major effect would be to renormalize the a, b, and c coefficients. Until better calculations of the Coulomb interaction within the nucleus are available, it is difficult to predict the Coulomb interaction contributions to the mass excess accurately enough to distinguish a two-body nuclear cdi from the two-body electromagnetic interaction. Mass measurements of nuclei far from stability where charge dependent interactions play a major role will provide more information on the Coulomb interaction within the nucleus and a more accurate and comprehensive view of the nuclear cdi.

In this thesis, the results of the mass measurement of the T_Z=-2 member of the A=16, isobaric quintet are discussed and the mass of ^{16}Ne is combined with those of the other members of the quintet to obtain the coefficients of the IMME.

II. EXPERIMENTAL PROCEDURE

The mass of ^{16}Ne was determined from the Q-value of the $^{20}Ne(^{4}He, ^{8}He)^{16}Ne$ reaction. A beam of 129.0 MeV alpha particles was obtained from the Texas A&M University 88-inch variable energy cyclotron and transported to the target chamber of the Enge split-pole magnetic spectrograph where it impinged upon a target of ^{20}Ne. The gas cell containing the ^{20}Ne was collimated by slits designed to exclude particles scattered from the entrance and exit foils of the cell from entering the spectrograph for reaction angles > 6°. Had these particles been allowed to enter the spectrograph they would have shown up as background in the spectra obtained from the particle detector making it much more difficult to accurately identify the ^{8}He particles. The gas pressure and spectrograph entrance slit width were varied to produce a target thickness of 0.996 mg/cm^2 (99.5% isotopically enriched ^{20}Ne). The measurement was taken at a laboratory angle of 7.5° with a spectrograph solid angle of 2.6 msr. Reaction products entering the spectrograph were bent and focused by the variable-field magnet. They were detected at the focal plane of the spectrograph by a single-wire proportional counter backed by a Si surface barrier detector. The gas mixture of 90% argon/ 10% methane used in the proportional counter was maintained at one atmosphere pressure by differential pumping. The position sensitive portion of the counter consisted of a gas region with a .3 mil diameter wire strung through the center of it. An electric field was maintained in this region by establishing a potential difference between the wire and the outer case. Particles passing through this region ionized the gas; the electrons were attracted to the wire while the ions were attracted to the case. The resulting voltage pulse, which was proportional to the energy loss of the particles in the gas, was detected from each side of the counter. The parameters obtained from the counter to be used in particle identification were 1) energy loss in the gas, 2) energy loss in the Si detector, 3) time of flight relative to the cyclotron beam burst and 4) position of the particle along the focal plane of the spectrograph. Since these parameters differed for different particles, they were used to identify the type of particle detected. A spectrum of energy loss vs. time of flight seen in Fig. 1 shows the grouping of the different particles produced in this experiment.

In order to predict the mass excess of ^{16}Ne it was necessary to calibrate the focal pane of the spectrograph (position vs. energy) and to determine the energy of the incident ^{4}He particles. The focal plane calibration was obtained from the $^{20}Ne(^{4}He,^{6}He)^{18}Ne$ reaction by observing the change in position of the ^{6}He peak corresponding to the 9.20 MeV excitation state of ^{18}Ne for a change in the magnetic field of the spectrograph. The ^{6}He position spectrum obtained at the same magnetic field as the ground state ^{8}He is shown in Fig. 2. The beam energy was calibrated using the momentum matching technique described in Ref. 8. Basically, the technique involved application of the fact that the magnetic rigidity, the magnetic field multiplied by the radius of the arc traveled by the particle ($B\rho$), varies linearly with the beam energy for a given reaction angle. The slope of the line varies with the Q-value of the reaction. This implies that there is a unique beam energy at which the magnetic rigidity is the same for two reactions with different Q-values. Determination of the cross over point for two reactions with known Q-values provides a very accurate measurement of the beam energy. For this calibration the $^{28}Si(p,p)^{28}Si$ and $^{28}Si(p,d)^{27}Si$ reactions were observed at an angle of 25°.

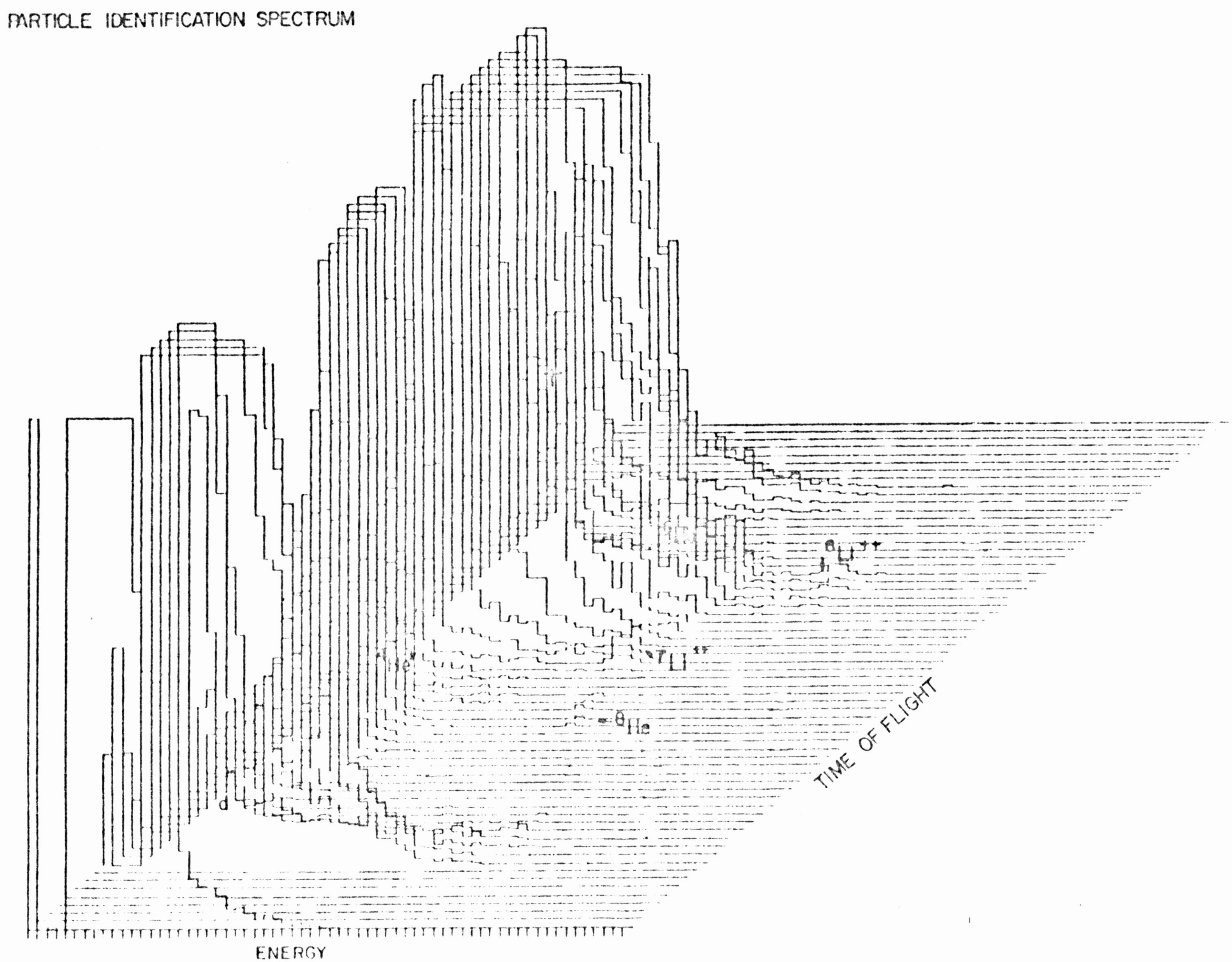

Fig. 1. Particle identification spectrum of energy loss in the Si surface detector vs. time of flight relative to the cyclotron beam burst.

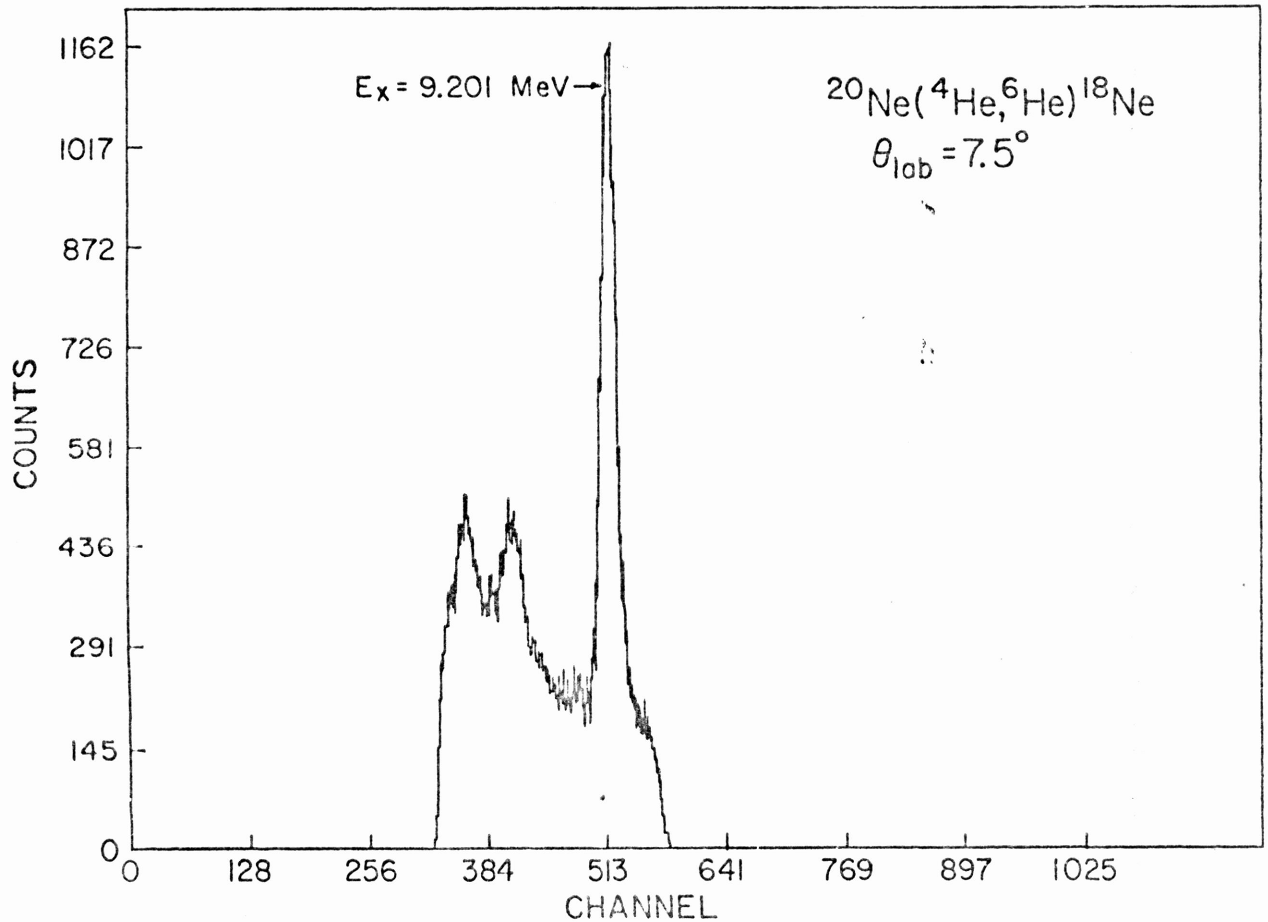

Fig. 2. Position spectrum of ^{6}He corresponding to the 9.201 MeV excitation state of ^{18}Ne.

III. RESULTS

In analyzing the data, care was taken to detect and correct any shifts in the position peak. For each of the 24 separate data runs the ^{6}He calibration peaks was fit with a Gaussian peak shape superimposed on a quadratic background function to detect shifts caused by electronics fluctuations. In cases where the centroid of an individual run differed from the centroid of the sum of all the runs by more than the full width at half maximum of the peak, the ^{8}He position spectrum was renormalized to offset the shift. However, this correction did not affect the ^{8}He centroid by more than its peak width (FWHM).

A total of 25 events were obtained in the ^{8}He position spectrum which is shown in Fig. 3. This corresponds to a reaction cross section of 1 $\pm$ 0.5 nb/sr averaged over the 2.6 msr solid angle. The peak width of 177 keV FWHM results in a centroid uncertainty of 15 keV. Because ^{16}Ne decays by particle emission, it has an inherent energy width given by the Heisenberg uncertainty principle, $\Delta E \Delta t > h$, where h is Planck's constant (6.6256x10-34 joule-sec) and Δt is the decay time. The data from this experiment indicates that the ground state of ^{16}Ne has a natural width of 110 $\pm$ 40 keV.

The Q-value uncertainty was found by adding in quadrature the uncertainties listed in Table I. Factors contributing to the uncertainty in the Q-value were the width of the ^{8}He peak, the width of the ^{6}He calibration peak, the fit to the focal plane calibration data, the beam energy uncertainty, the target thickness, and the uncertainty in the reaction angle. The reaction angle was determined optically to a precision of .1°. A 3% uncertainty was assigned to the dimensions of the gas cell, which included the target and the dead gas regions before and after the

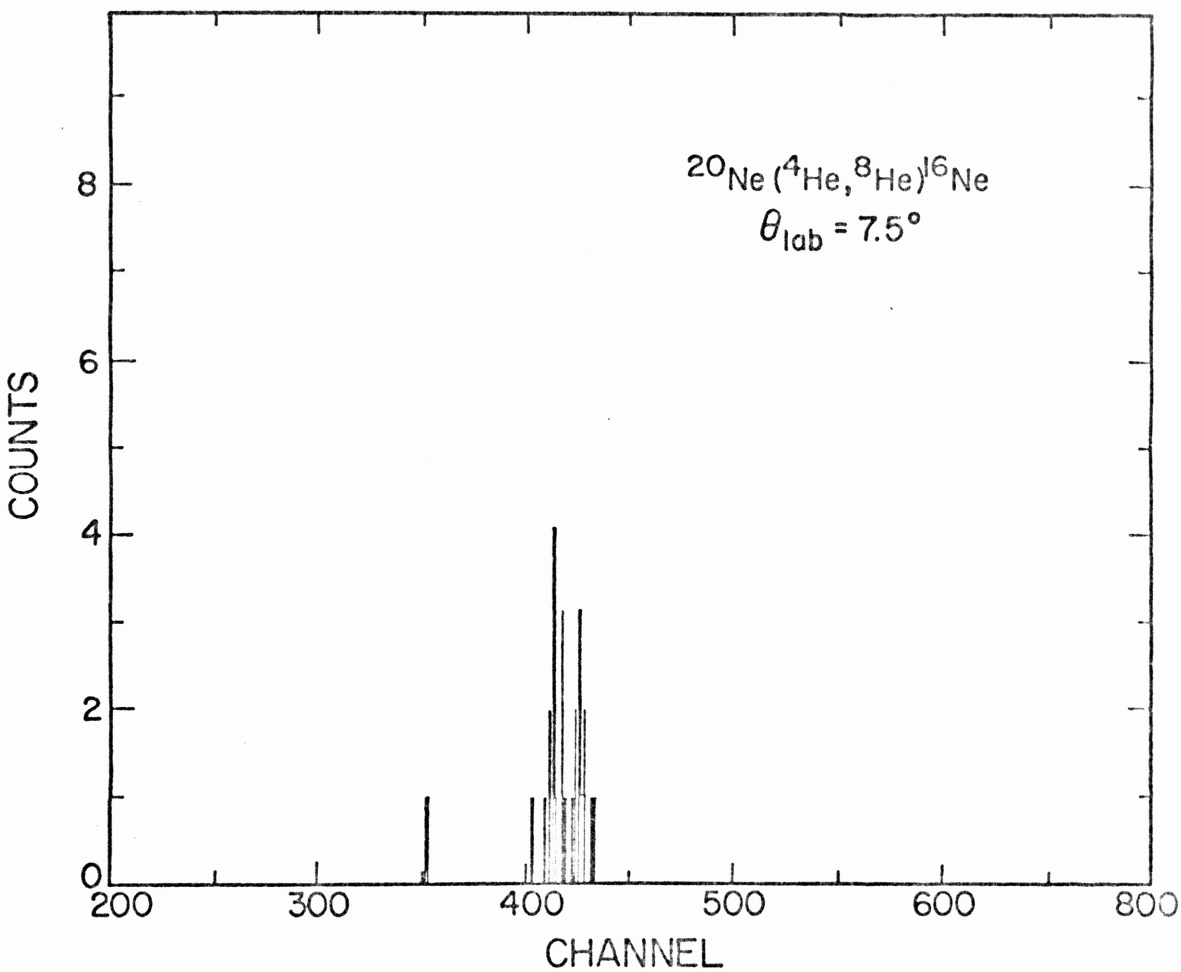

Fig. 3. Position spectrum of ^{8}He events corresponding to the ground state of ^{16}Ne.

target region. The Havar foil window thickness was measured both by the energy loss of alpha particles from an ^{241}Am source through the foil and by weighing the windows on a precision balance. An uncertainty of 10% was assigned to the average value obtained by these methods. The Q-value for the ^{20}Ne(^{4}He,^{8}He)^{16}Ne reaction was found to be -60.197 ± 0.023 MeV. By combining this result with the mass excesses of ^{20}Ne, ^{4}He and ^{8}He listed in Table II, ^{16}Ne is found to have a mass excess of 23.984 ± 0.024 MeV.

The mass excess of ^{16}Ne represents the fourth member of the A=16 isobaric quintet to be measured. Although the mass excess of ^{16}Ne has been measured before[9,10], this measurement is the most accurate to date. The value measured in this experiment is consistent with the values of 23.92 ± 0.08 MeV obtained by KeKelis et al. and 24.051 ± 0.045 MeV obtained by Burleson et al. The fifth member of the quintet, ^{16}F, has not been observed yet because of difficulties in finding a reaction which preferentially populates the T=2 excited state of ^{16}F.

The mass excesses and excitation energies of the members of the A=16 multiplet are listed in Table III. The results for the fit to the quadratic IMME and for the four parameter fit determining the d or e coefficient are found in Table IV. These four members of the quintet are described reasonably well by the quadratic IMME, as the χ^2 of 3.22 indicates. The results for the four parameter fit indicate that there is a positive d or e coefficient. The d coefficient estimation of 6 ± 3 keV is consistent with the fit by KeKelis et al. which indicates that d=8 ± 5 keV. However it is not consistent with zero as the result of Burleson et al. of d=2.5 ± 3.7 is. It is interesting to note that both the d and e coefficients obtained from the results of this experiment are positive and of approximately the same magnitude. However, it is difficult to draw

Table I. Error Estimation.

Source of uncertainty	Uncertainty (keV)
Centroid uncertainty	15
Focal plane calibration	11
Beam energy	6.5
Target thickness	10
Reaction angle	5

Table II. Atomic mass excesses of reaction nuclei.

Nuclei	Mass excess (keV)	Reference
^{20}Ne	-7043.0(0.5)	12
^{4}He	2424.94	12
^{8}He	31595(7)	1,15
^{16}Ne	23984(24)	this work

Table III. Properties of the members of the A=16 isobaric quintet.

Nucleus	T_z	Mass excess (keV)[a]	E_x (keV)	Reference
^{16}Ne	-2	23984(24)	0	this work
^{16}O	0	17984(3)	22721(3)	13
^{16}N	1	15610(7)	9928(7)	13
^{16}C	2	13692(4)	0	14

[a]Ground state mass excesses of ^{16}O and ^{16}N are obtained from ref. 12.

Table IV. Predicted coefficients (in keV) for the IMME parametrized as $\Delta M=a+bT_z+cT_z^2+dT_z^3+eT_z^4$.

a	b	c	d	e	χ^2[b]
17982.5(2.9)	-2577(6)	215.7(2.9)	-	-	3.22
17984(3)	-2597(13)	214(3)	6(3)	-	-
17984(3)	-2573(6)	194(12)	-	5(3)	-

[b]Normalized χ^2.

conclusions about the value of these coefficients until a measurement of the mass excess of the T=2 state of ^{16}F is made which will provide a means of determining how well these coefficients fit the IMME.

IV. CONCLUSIONS

Since any two-body charge dependent interaction would produce the same quadratic equation in first-order perturbation theory, it is to be expected that the quadratic IMME provides a good fit for the mass excesses of an isobaric multiplet. In fact, of the isobaric quintets of which 4 or 5 members are known, only for the A=8 quintet does the quadratic IMME not provide a good fit to the data[11], and only for the A=16 quintet are non-zero d and e coefficients found. This is possible evidence of a nuclear many-body charge dependent interaction which would introduce higher order terms with small coefficients into the quadratic IMME. However, in order to use the IMME as a truly viable test for a nuclear cdi, it is necessary to have accurate predictions of the Coulomb interaction contributions to the mass excess. So far, calculations of these contributions have not been accurate enough, primarily because of the scarcity of information on nuclear radii. Therefore, although there is evidence of the need for a nuclear cdi correction to the strong interaction Hamiltonian, not enough is known about the Coulomb interaction within the nucleus to clearly separate its effects from those of a two-body interaction due to the strong nuclear force. Until this can be done, no clear formulation of the nuclear cdi can be made. Mass measurements of nuclei far from the line of stability are useful in that they provide new information about the nuclear Coulomb interaction and the strong nuclear interaction which can be used in the study of charge dependent interactions within the nucleus.

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