PHYSICAL REVIEW C VOLUME 22, NUMBER 3 SEPTEMBER 1980

Isospin quintets in the 1p and s-d shells

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(Received 19 February 1980)

The pion double-charge exchange reaction (π^+,π^-) has been used to measure the ground-state masses of ^{12}O, ^{16}Ne, ^{24}Si, and ^{32}Ar. The mass excesses were found to be 32.059(48), 24.051(45), 10.682(52), and −2.181(50) MeV, respectively. These are the first reported measurements of the masses of ^{24}Si and ^{32}Ar and the values for ^{12}O and ^{16}Ne are improved over previous results. Good agreement with the isobaric multiplet mass equation $M = a + bT_z + cT_z^2$ is obtained for the known members of all four quintets.

[NUCLEAR REACTIONS Pion double-charge exchange, ^{9}Be(π^+,π^-)^{9}C, ^{12}C(π^+,π^-)^{12}O, ^{13}C(π^+,π^-)^{13}O, ^{16}O(π^+,π^-)^{16}Ne, ^{24}Mg(π^+,π^-)^{24}Si, ^{32}S(π^+,π^-)^{32}Ar, E=180 MeV, measured Q and $d\sigma/d\Omega$ (5°).]

To first order the masses of isobaric multiplets of nuclear states can be described by the isobaric multiplet mass equation (IMME)[1]:

$$M(A,T,T_z) = a(A,T) + b(A,T)T_z + c(A,T)T_z^2 \ . \tag{1}$$

This form results from assuming only two-body charge-dependent forces. The coefficients of M are related to the diagonal reduced matrix elements of the charge-dependent part of the nuclear Hamiltonian. Deviations from this simple quadratic form are expected if there are significant three-body charge-dependent forces involved in the Hamiltonian.[2] Second-order effects such as isospin mixing of the lower T_z members of the multiplet may also result in higher-order terms in the IMME. These additional terms, $dT_z^3 + eT_z^4$, are related to the off-diagonal matrix elements. Accurate measurements of the masses of $T=\frac{3}{2}$ quartets have shown that the quadratic form of the IMME works very well for 21 of 22 complete quartets, the only exception being the ground-state $A=9$ quartet.[3]

For $T=2$ quintets, only two[4-6] ($A=8, 20$) have had all members measured with sufficient accuracy to test the IMME. For $A=8$, significant terms of $dT_z^3 + eT_z^4$ are required to fit the data. These terms probably arise from shifts in the energy levels of two quintet members due to isospin-allowed particle-decay widths. Measured values for the $A=20$ quintet, which is bound to isospin-allowed particle decay, show agreement with the quadratic IMME. The present measurements of the ground-state masses of ^{24}Si and ^{32}Ar complete the $A=24$, 32 quintets allowing further tests of the IMME for cases of no isospin-allowed particle decay channels open.

The pion double-charge exchange reaction (π^+,π^-) recently studied by Seth[7] using the EPICS spectrometer facility at LAMPF,[8] provides an excellent method for measuring the masses of $T_z=-2$ nuclei. The spectrometer uses a set of multiwire proportional drift chambers at a focus before the dipole magnets to allow software momentum matching of the spectrometer to the momentum-dispersed beam. We have modified the EPICS system by placing an additional dipole bending magnet after the pion scattering target on the rotating arm of the spectrometer and before the spectrometer entrance (Fig. 1). This allowed a twenty degree separation angle between the outgoing π^+ beam and the scattered π^- beam from 0° double charge exchange (DCX), which led to a considerable count rate reduction in the chambers ($F_1 - F_4$) and enabled the first systematic measurements of angular distributions for DCX at forward angles.

Energy excitation functions of $d\sigma/d\Omega$ (5°) and

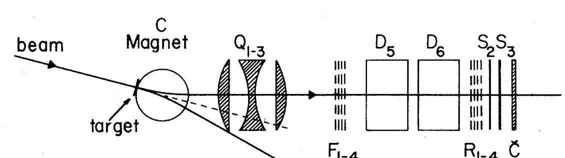

FIG. 1. Schematic view of the EPICS system as modified for DCX.

TABLE I. Targets, target thicknesses, and differential cross sections for (π^+,π^-) at 180 MeV and 5° lab angle.

	Thickness (mg/cm^2)	Cross section (μb/sr)	Chemical composition	Isotope purity (%)	Q value (MeV)
^{9}Be	296	0.15 ± 0.03	Be	100	−17.564 ± 0.042
^{12}C	227	0.40 ± 0.05	C	99	−32.056 ± 0.048
^{13}C	356	0.10 ± 0.03	C	90	−19.965 ± 0.050
^{16}O	157	0.34 ± 0.04	MgO	100	−28.785 ± 0.045
^{24}Mg	235	0.11 ± 0.03	MgO	100	−24.610 ± 0.052
^{32}S	250	0.084 ± 0.025	S	95	−23.837 ± 0.050

TABLE II. Properties of $T=2$ levels of isospin quintets in this study.

A	J^π	T_z	Nucleus	E_x (keV)	Mass excess (keV)	Ref.
12	0^+	2	^{12}Be	g.s.	25 078(15)	11
		1	^{12}B	12 710(20)	26 080(20)	12
		0	^{12}C	27 595.0(24)	27 595.0(24)	13
		−1	^{12}N	unknown	unknown	
		−2	^{12}O	g.s.	32 059(48)	this
16	0^+	2	^{16}C	g.s.	13 695(7)	10
		1	^{16}N	9 928(7)	15 610(7)	14
		0	^{16}O	22 721(3)	17 984(3)	14
		−1	^{16}F	unknown	unknown	
		−2	^{16}Ne	g.s.	24 051(45)	this
24	0^+	2	^{24}Ne	g.s.	−5 949(10)	10
		1	^{24}Na	5 969.0(16)	−2 448.5(18)	15
		0	^{24}Mg	15 436.4(6)	1 505.8(9)	15
		−1	^{24}Al	5 595(10)	5 903(9)	16
		−2	^{24}Si	g.s.	10 682(52)	this
32	0^+	2	^{32}Si	g.s.	−24 092(7)	15
		1	^{32}P	5 073.1(9)	−19 231.6(12)	15
		0	^{32}S	12 050(4)	−13 965(5)	15
		−1	^{32}Cl	5 033(10)	−8 295.6(52)	17
		−2	^{32}Ar	g.s.	−2 181(50)	this

TABLE III. Coefficients of the IMME and reduced χ^2 from least-squares fit.

A	a (MeV)	b (MeV)	c (MeV)	d (MeV)	e (MeV)	χ^2
12	27.5949(24)	−1.7478(118)	0.2441(62)			0.367
	27.5950(24)	−1.7628(273)	0.2434(63)	0.0044(72)		
16	17.9836(29)	−2.5949(89)	0.2233(57)			0.462
	17.9840(30)	−2.5995(112)	0.2220(60)	0.0025(37)		
24	1.5057(9)	−4.1757(36)	0.2222(31)			1.150
	1.5059(9)	−4.1767(37)	0.2194(38)	0.0028(21)		0.603
	1.5058(9)	−4.1818(75)	0.2235(66)	0.0060(47)	−0.0021(27)	
32	−13.9657(25)	−5.4686(25)	0.2027(23)			0.307
	−13.9663(37)	−5.4682(31)	0.2034(41)	−0.0005(22)		0.571
	−13.9651(40)	−5.4648(55)	0.1996(65)	−0.0033(43)	0.0019(25)	

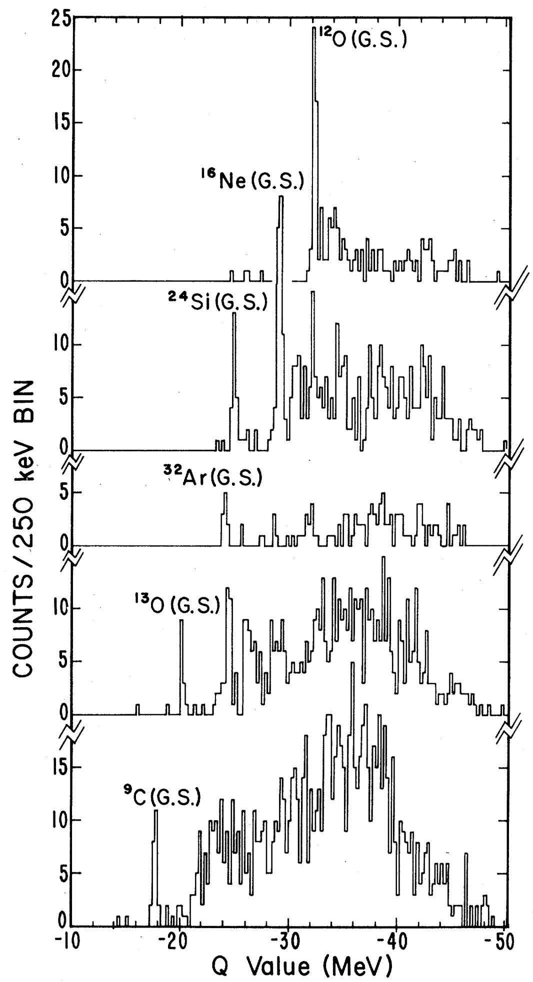

FIG. 2. Q-value spectra from targets of ^{9}Be, ^{13}C, ^{32}S, ^{24}MgO, and ^{12}C, for DCX leading to the final states as labeled.

angular distributions for the nonanalog, analog transitions $^{16,18}O(\pi^+, \pi^-)^{16,18}Ne$ and $^{24,26}Mg(\pi^+, \pi^-)^{24,26}Si$ have been measured.[9] For the nonanalog transitions the largest count rates (a product of pion flux, cross section, and survival fraction) were seen at 180 MeV and 5°, the most forward angle measured. By measuring missing masses (Q values) for the DCX reaction (π^+, π^-), at this energy and angle, on targets of ^{12}C, ^{24}MgO, and ^{32}S to the ground states of ^{12}O, ^{16}Ne, ^{24}Si, and ^{32}Ar, we have determined the mass excesses of these residual nuclei relative to those of the target nuclei.

The linearity of the missing mass calculations was determined by using pion scattering to the ground state, 4.439 and 7.654 MeV states of ^{12}C. Two settings of the spectrometer were used in order to cover the entire focal plane region used in the mass measurements. The missing mass calculation (the spectra obtained are shown in Fig. 2) was linear to 10 keV over the focal plane region used in these measurements. Absolute calibration was done by measuring the ground-state masses of ^{9}C and ^{13}O,[10] using ^{9}Be and ^{13}C targets. The systematic error introduced because of uncertainties in the calibration was ±18 keV. Since the magnets were not changed for any of the mass measurements, there were no systematic errors introduced due to magnet setting reproducibility.

Target thickness corrections to measured Q values were made by using measurements of the energy loss in each target for pion elastic and inelastic scattering at 35°, again using the same magnet settings for all targets. Relative energy losses between the targets were determined to better than ±10 keV for all targets. Both the channel and spectrometer magnetic fields were monitored periodically throughout the run. Fluctuations in the spectrometer fields contributed the largest systematic errors of ±30 keV.

The targets used were 10×20 cm with thicknesses from 157 to 356 mg/cm^2. These thicknesses with the intrinsic spectrometer resolution of ~200 keV combined for an overall resolution of ~300 keV (full width at half maximum). With 10 to 30 counts in the ground-state peaks the statistical errors obtained for all the Q values were less than 40 keV (σ). Although not important to the mass measurements the differential cross sections for these reactions are presented in Table I because of their general interest.

The resulting mass excesses and errors, including all systematic contributions discussed in the text for ^{12}O, ^{16}Ne, ^{24}Si, and ^{32}Ar, are 32 059(48) 24 051(45), 10 682(52), and −2181 (50 keV, respectively. The values of ^{12}O and ^{16}Ne may be compared with those of Kekelis *et al.*[18] of 32 100(120) and 23 920(80) keV, respectively. Our results plus those for the other known quintet members are summarized in Table II.

These masses were used to determine the coefficients of the IMME. The values were fitted to all orders in T_z with a least-squares program and the fitted coefficients are listed in Table III. The reduced χ^2 values show that there is no evidence for higher-order terms; i.e., when such terms are extracted they are consistent with zero. This constitutes further evidence for a nuclear force which gives a quadratic IMME.

The authors gratefully acknowledge the excellent technical support of the LAMPF MP-10 staff and, in particular, Noby Tanaka. This work was supported by the Medium Energy Division of the U.S.D.O.E. and the Robert A. Welch Foundation.

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