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Author

Moltz, D.M.

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COMPLETION OF THE MASS 20 ISOSPIN QUINTET BY EMPLOYING
A HELIUM-JET FED ON-LINE MASS SEPARATOR*

D. M. Moltz, J. Äystö[†], M.D. Cable, R. D. von Dincklage[‡],
R. F. Parry, J. M. Wouters and Joseph Cerny

Department of Chemistry and
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

October 1978

Abstract:

Observation of beta-delayed protons from the decay of the mass-separated $T_z = -2$ nuclide ^{20}Mg ($t_{1/2} \sim 95$ ms) establishes the mass-excess of the lowest $T = 2$ (0^+) state in ^{20}Na (13.42 ± 0.05 MeV), thereby completing the mass twenty isospin quintet. All members of this multiplet are bound to isospin-allowed particle decay modes, providing the first test of the isobaric multiplet mass equation for such a quintet. Excellent agreement is observed using only the quadratic form of this equation.

Development of general experimental systems capable of mass analysis of radioactive species with half-lives as short as 50 ms and with simple application to a vast majority of the chemical elements is clearly of great interest in the study of nuclei far from stability. Such an on-line system has been completed which employs a helium-jet to transport activity from the

target area to a Sidenius-type hollow-cathode ion source which is coupled to a mass separator. Use of this separator¹ (termed RAMA for Recoil Atom Mass Analyzer) to detect the decay of ^{20}Mg represents the first exotic nucleus whose decay has been discovered with this type of apparatus. Although one other member of this $A = 4n$, $T_z = -2$ mass series (the rare gas ^{32}Ar) has been recently observed² in experiments at ISOLDE, ^{20}Mg is the lightest nucleon-stable member of this new series of beta-delayed proton emitters.

Detection of the decay of ^{20}Mg establishes the location of the lowest $T = 2$ state in ^{20}Na , thereby completing the second known isospin quintet³ but the first in which all members of the multiplet are bound to isospin-allowed particle decay modes. The mass twenty quintet thus represents an effective test for a possible deviation from the quadratic isobaric multiplet mass equation (IMME):

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

where the coefficients a , b and c are related to reduced diagonal matrix elements of the charge dependent part of the nuclear Hamiltonian.

Deviations from the quadratic form are generally represented by additional terms $d(A, T)T_z^3$ and $e(A, T)T_z^4$. The d and e coefficients are related to off-diagonal matrix elements and can be derived from second order perturbation theory; they are physically represented by phenomena such as isospin mixing, shifts of unbound levels, and charge-dependent many-body nuclear forces. Significant deviations from the quadratic form of the IMME have been reported for the mass 8 quintet^{3,4} (in which ^8C is unbound to prompt nucleon emission); however, this has occurred in only one case (mass nine⁵) of some twenty complete isospin quartets.

The experimental setup for RAMA is illustrated in Fig. 1.

Beams of 70 MeV ^3He ions from the Lawrence Berkeley Laboratory 88-inch cyclotron of intensity 2-7 μA were used to produce ^{20}Mg nuclei via the $^{20}\text{Ne}(^3\text{He}, 3n)$ reaction. The target employed was spark chamber gas (90% Ne and 10% He), which for these experiments necessarily served as the stopping and the transport medium. A 12-unit multiple capillary system collected nuclear reaction recoils from an extended reaction zone and fed a single 6 m stainless steel capillary (i.d. 1.4 mm) which transported the radioactivity to the skimmer. Ethylene glycol was employed as an additive to build up a high molecular weight aerosol; radioactive nuclides attached to this aerosol possess excellent transport and skimming properties. After skimming, the activity entered the hollow cathode ion source which was operated at $\sim 1300^\circ\text{C}$; singly charged ions were extracted at 18 kV and mass analyzed as shown in Figure 1. Other radioactive species readily extracted in good yield from the source to date include isotopes of Na, Al, Si, Te, Dy, Ho, Er and At. The present efficiency of the system (target to focal plane) is $\sim 0.1-0.5\%$.

The detection system for beta-delayed protons on the focal plane of the separator consisted of two vertically symmetric counter telescopes subtending solid angles $\sim 30\%$ of 4π sr. The ΔE detectors ranged in thickness from 22 to 42 μm and the E detectors from 300 to 500 μm . Foils of aluminized polyethylene 2 μm thick placed in front of each telescope collected the activities and protected the counters. A periodic electrostatic deflection of the ion beam between the two telescopes was used for half-life determinations; the predicted ^{20}Mg half-life was ~ 100 ms.

Having $J^\pi = 0^+$ and $T = 2$, ^{20}Mg is expected to undergo superallowed β^+ decay to the 0^+ ($T = 2$) analog state in ^{20}Na in addition to strong allowed transitions to lower-lying 1^+ states.⁶ The quadratic IMME prediction and the proton binding energy in ^{20}Na lead one to expect ~ 4.1 MeV energy for the proton transition from the analog state in ^{20}Na to the ground state of ^{19}Ne .^{7,8} Calibration of the telescopes in this region was accomplished by detecting the well-known⁹ beta-delayed proton emitter ^{21}Mg , produced in much higher yield in the $^{20}\text{Ne}(^3\text{He}, 2n)$ reaction. A proton spectrum arising from the decay of 122 ms ^{21}Mg is shown in Fig. 2(b); the groups at 3.873 and 4.669 MeV provided convenient calibration points.

The proton spectrum arising in the decay of ^{20}Mg after bombardment for 700 mC is shown in Fig. 2(a). Two distinct proton peaks are evident with weighted average energies from three separate experiments giving 4.16 ± 0.05 and 3.95 ± 0.06 MeV. A half-life of 95^{+80}_{-50} ms was observed for these peaks. Substantial detection problems were encountered at the mass twenty position due to both an intense ^{20}Ne beam from the target gas and to very high "background" from the strong β^+ -delayed α -particle emitter ^{20}Na ($t_{1/2} = 446$ ms). ^{20}Na was copiously produced in the competing $^{20}\text{Ne}(^3\text{He}, p2n)$ reaction with resultant activities on the focal plane in the ratios of $(\sim 10^5)$ ^{20}Na 2.16 MeV α -particles per (1) ^{20}Mg proton. Even with telescope techniques, complete removal of ^{20}Na activity was not possible due to real coincidences between positrons in the E counters of the telescopes and α -particles of reduced energy due to the foils (~ 1 -1.5 MeV) in the ΔE counters. Those events in the cross-hatched region at lower energies of the ^{20}Mg spectrum in fact possess the ^{20}Na half-life. It should be noted that

the two peaks attributed to the decay of ^{20}Mg can not arise from the possible beta-delayed proton decay of ^{20}Na since the maximum proton energy available in ^{20}Na decay is 0.99 MeV.

The 4.16 and 3.95 MeV proton groups in Fig. 2(a) can be attributed to the isospin-forbidden proton decay of the lowest 0^+ , $T = 2$ state in ^{20}Na . This ^{20}Na state is fed via a pure Fermi (superalowed) transition ($0^+ \rightarrow 0^+$, $T = 2$) with a calculated log ft of 3.18. All other (allowed) β^+ transitions to states near this excitation energy in the daughter would lead to considerably lower intensities in the delayed proton spectrum. The measured half-life combined with the calculated log ft value yields a branching ratio of $3 \pm 2\%$ for the superallowed transition. A proposed partial decay scheme for ^{20}Mg is shown in Fig. 3. The measured proton energy in the center of mass taken together with the ^{19}Ne mass excess⁷ yields a mass excess of 13.42 ± 0.05 MeV for the lowest 0^+ ($T = 2$) state in ^{20}Na .

The mass values for all of the members of the mass twenty isospin quintet are given in Table I.¹⁰⁻¹³ When these are used to test the isobaric multiplet mass equation, an excellent fit ($\chi^2 = 0.98$) is obtained by using only the quadratic form, reflecting the insignificance of charge dependent mixing in this mass twenty multiplet. The results for the only other complete quintet ($A=8$) clearly indicate a non-quadratic form for the IMME.^{3,4} This deviation has been discussed in terms of the strong Coulombic repulsion associated with the particle-unbound members in this quintet, in addition to the effect of isospin mixing in the $T_z = 0$ member of this multiplet.³ On the other hand, in the $A=20$ quintet, all members

are stable toward isospin-allowed particle decay. Major isospin mixing would be expected to show up in the e coefficient; however, any observation of a nonzero quartic term would require much more accurate measurements of the masses of most of the members in the multiplet. Our results on the mass twenty quintet with its narrow states, then, are in accord with all but one of the numerous measurements on isospin quartets in showing excellent agreement with the simple quadratic mass equation and no evidence for substantial charge dependent effects.

These results also permit an evaluation of the current limits of on-line mass analysis by a RAMA system in terms of production cross-section and half-life. The estimated cross section for the $^{20}\text{Ne}(^3\text{He}, 3n)^{20}\text{Mg}$ reaction is $\sim 30 \mu\text{b}$. With the deduced 3% branching to the analog state, this indicates an effective observable cross section of $\sim 1 \mu\text{b}$ for activities in the ~ 100 ms region. Of course this cross-section value can confidently be expected to be lowered substantially with ion source improvements. Extension of these measurements to observe the decays of other members of this $A = 4n$, $T_z = -2$ mass series, such as ^{24}Si and ^{28}S , is in progress.

We wish to thank the crew and support staff of the 88-inch cyclotron in addition to the many people associated with the RAMA system during its development. To this end, special thanks are due to Dr. R. A. Gough and to Dr. M. S. Zisman for their excellent design and support of the RAMA project.

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Footnotes and References

[†] On leave from: University of Jyväskylä, Finland.

[‡] On leave from: University of Göttingen, W.-Germany.

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Table I. Properties of the A=20 isobaric quintet and coefficients of the IMME^a.

Nucleus	T _Z	Mass Excess M [MeV]	E _x [MeV]	Reference
²⁰ Mg	-2	17.57 (3)	0.0	8
²⁰ Na	-1	13.42 (5)	6.57 (5)	this work
²⁰ Ne	0	9.6908 (23)	16.7325 (23)	10, 11, 12
²⁰ F	1	6.503 (3)	6.519 (3)	13
²⁰ O	2	3.799 (8)	0	7

Predicted coefficients [MeV] for the IMME^a: $M(T_Z) = a + bT_Z + cT_Z^2 + dT_Z^3 + eT_Z^4$

a	b	c	d	e	χ^2
9.6917 (22)	-3.4372 (51)	0.2466 (33)	0	0	.98
9.6909 (23)	-3.4347 (56)	0.2489 (39)	-0.0022 (20)	0	.71
9.6908 (23)	-3.4440 (74)	0.2588 (101)	0	-0.0025 (19)	.33
9.6908 (23)	-3.463 (34)	0.278 (34)	0.005 (9)	-0.007 (9)	-

^aThe numbers in parentheses for the masses and the mass equation coefficients represent the uncertainties in the least significant figures.

Figure Captions

Fig. 1. Schematic view of the on-line mass separator RAMA.

Fig. 2. Spectra of beta-delayed protons from (a) ^{20}Mg and (b) ^{21}Mg .

Both spectra are a combination of three separate runs. Arrows at low and high energy indicate telescope cutoffs. The high detection efficiency results in "sum" peaks due to the simultaneous detection of a proton with its preceding positron. The broad peak ~200 keV above the 4.669 MeV group in the ^{21}Mg spectrum is such a peak.

Fig. 3. Proposed decay scheme for ^{20}Mg .

RAMA-88 schematic

Fig. 1

XBL 758-3797A

XBL 7810-11639

Fig. 2

XBL 7810-11638

Fig. 3

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