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Completion of the Mass-20 Isospin Quintet by Employing a Helium-Jet-Fed On-Line Mass Separator

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Observation of β-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 $\pm$0.05 MeV), thereby completing the mass-20 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 separator[1] (termed RAMA, for recoil-atom mass analyzer) to detect the decay of ^{20}Mg represents the first discovery of the decay of such an exotic nucleus 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 observed[2] in experiments at ISOLDE, ^{20}Mg is the lightest nucleon-stable member of this new series of β-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 quintet[3] but the first in which all members of the multiplet are bound to isospin-allowed particle-decay modes. The mass-20 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 coefficients d and e 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 ^{8}C is unbound to prompt nucleon emission); however, this has occurred in only one case[5] (mass 9) of some twenty complete isospin quartets.

The experimental setup for RAMA is illustrated in Fig. 1. Beams of 70-MeV ^{3}He ions from the Lawrence Berkeley Laboratory 88-in. cyclotron, of intensity 2–7 μA, were used to produce ^{20}Mg nuclei via the reaction ^{20}Ne(^{3}He,$3n$). 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 twelve-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–

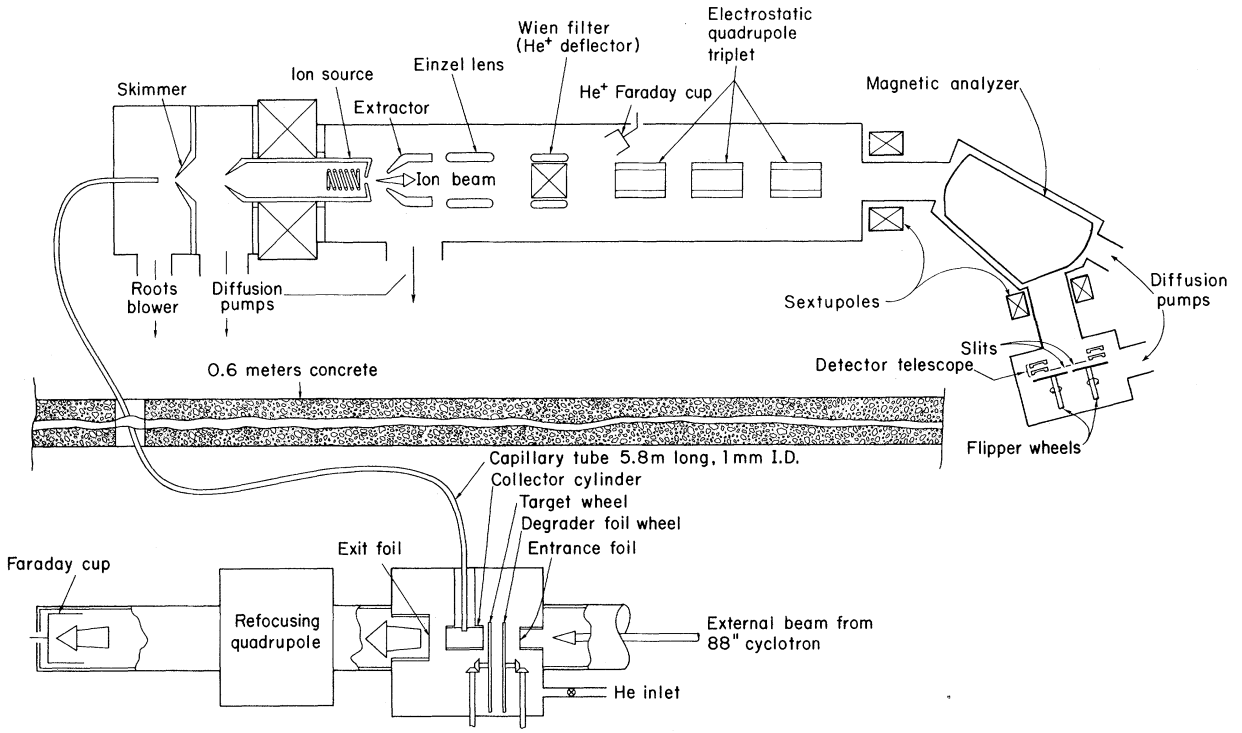

FIG. 1. Schematic view of the on-line mass separator RAMA.

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 ~1300°C; singly charged ions were extracted at 18 kV and mass analyzed as shown in Fig. 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 ~0.1–0.5%.

The detection system for β-delayed protons on the focal plane of the separator consisted of two vertically symmetric counter telescopes subtending solid angles ~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 and 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[6] ^{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-known[9] β-delayed proton emitter ^{21}Mg, produced in much higher yield in the reaction ^{20}Ne(^{3}He, $2n$). 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-line of 95^{+80}_{-50} ms was observed for these peaks. Substantial detection problems were encountered at the mass-20 position due to both an intense ^{20}Ne beam from the target gas and 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 reaction ^{20}Ne(^{3}He, $p2n$) with resultant activities on the focal plane in the ratios of ~10^5 ^{20}Na 2.16-MeV α particles per ^{20}Mg proton. Even with

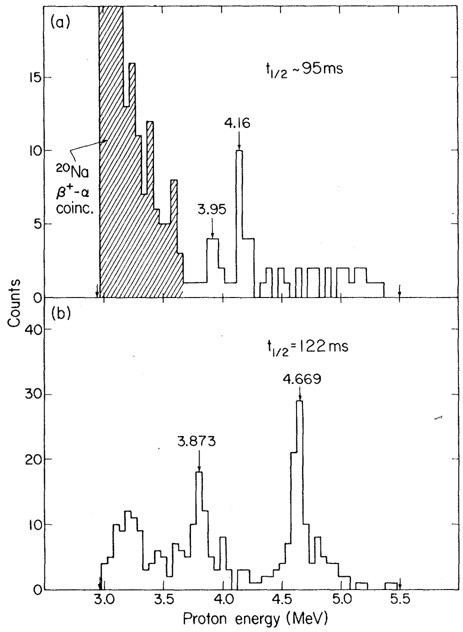

FIG. 2. Spectra of β-delayed protons from (a) ^{20}Mg and (b) ^{21}Mg. Both spectra are a combination of three separate runs. Arrows at low and high energies indicate telescope cutoffs. The high detection efficiency results in "sum" peaks due to the simultaneous detection of a proton with its preceding positron. The broad peak ~200 keV above the 4.669-MeV group in the ^{21}Mg spectrum is such a peak.

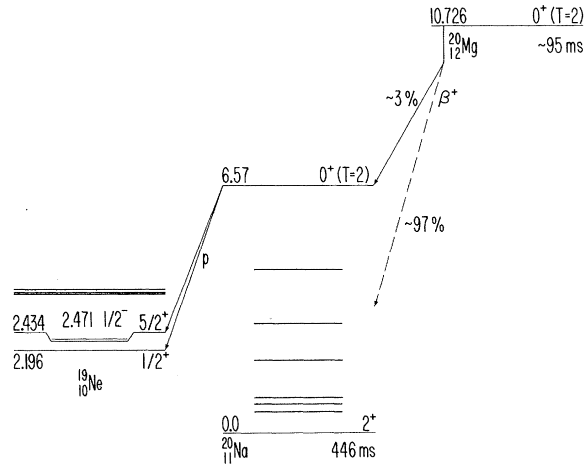

FIG. 3. Proposed decay scheme for ^{20}Mg.

telescope techniques, complete removal of ^{20}Na activity was not possible because of 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 β-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 (superallowed) transition ($0^+ \rightarrow 0^+$, $T=2$) with a calculated logft 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 logft 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 system taken together with the ^{19}Ne mass excess[7] 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-20 isospin quintet are given in Table I.[10-13] When these are used to test the isobaric multiplet mass equation (Table II), 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-20 multiplet. The results for the only other complete quintet ($A=8$) clearly indicate a nonquadratic 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

TABLE I. $A=20$ isobaric quintet and coefficients of the IMME.

Nucleus	Ref.	Mass excess (MeV)
^{20}Mg	8	17.57(3)
^{20}Na	This work	13.42(5)
^{20}Ne	10–12	9.6908(23)
^{20}F	13	6.503(3)
^{20}O	7	3.799(8)

TABLE II. Predicted coefficients (in MeV) for the IMME: $M(T_z) = a + bT_z + cT_z^2 + dT_z^3 + eT_z^4$.

a	b	c	d	e	χ^2
9.6917(22)	−3.4372(51)	0.2466(33)	0	0	0.98
9.6909(23)	−3.4347(56)	0.2489(39)	−0.0022(20)	0	0.71
9.6908(23)	−3.4440(74)	0.2588(101)	0	−0.0025(19)	0.33
9.6908(23)	−3.463(34)	0.278(34)	0.005(9)	−0.007(9)	⋯

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-20 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 reaction $^{20}Ne(^{3}He, 3n)^{20}Mg$ is ~30 μb. With the deduced 3% branching to the analog state, this indicates an effective observable cross section of ~1 μb 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.

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