PHYSICAL REVIEW C VOLUME 51, NUMBER 6 JUNE 1995

^{36}Ca β decay and the isobaric multiplet mass equation

A. García,[1,2] E. G. Adelberger,[3,4] P. V. Magnus,[3] H. E. Swanson,[3]
F. E. Wietfeldt,[2] O. Tengblad,[4] and the Isolde Collaboration
[1] *University of Notre Dame, Notre Dame, Indiana 46556*
[2] *Lawrence Berkeley Laboratory, Berkeley, California 94720*
[3] *Nuclear Physics Laboratory, University of Washington, Seattle, Washington 98195*
[4] *PPE Division, CERN, CH-1211 Geneva 23, Switzerland*

(Received 17 February 1995)

We measured the mass of the lowest $T = 2$ state in ^{36}K by observing β-delayed protons following the superallowed ^{36}Ca decay and use this result to make a precise test of the isobaric multiplet mass equation.

PACS number(s): 21.10.Dr, 23.40.−s, 27.30.+t

If the internuclear forces were charge independent, the nuclear states of an isospin multiplet would have identical masses. This degeneracy is broken by any force, such as electromagnetism, that is not an isoscalar. If the isospin-violating interactions are two-body forces between $T = 1/2$ nucleons, the masses of the multiplet members should obey the first-order expression

$$M(A,T,T_z) = a(A,T) + b(A,T)T_z + c(A,T)T_z^2 \ , \quad (1)$$

where the a, b, and c coefficients contain information on the stucture of the states and on the isospin properties of the nuclear force. Any deviations from Eq. (1) would indicate the importance of higher-order processes. For this reason, precise measurements of the masses of isospin quartets and quintets have been carried out over the years [1]. The only clear evidence for a deviation from Eq. (1) occurs in the $A = 9$ $T = 3/2$ quartet where the data require that Eq. (1) be modified by adding a $d(A,T)T_z^3$ term with $d = 5.2 \pm 1.7$ keV [1]. This was explained by a combination of non-Coulombic charge-dependent forces and a swelling of the orbit of the least-bound proton in ^{9}C [2].

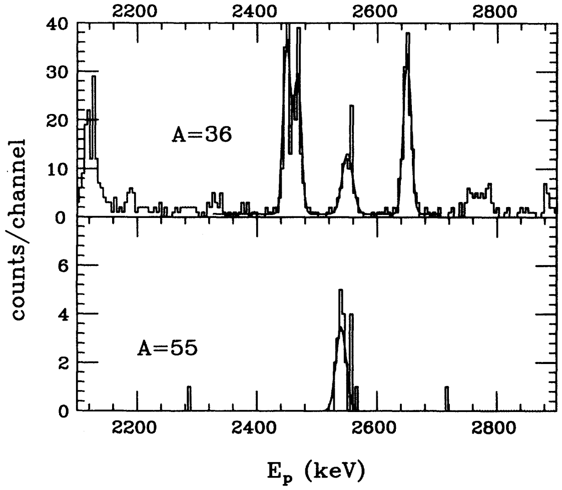

FIG. 1. Upper panel: proton spectrum with an $A = 36$ beam. Lower panel: proton spectrum taken with an $A = 55$ beam. The peak at 2550 keV results from the superallowed decay of ^{36}Ca. The difference in the centroids of the superallowed peaks in the two spectra is not statistically significant; the peak energy was taken from the $A = 36$ spectrum.

Isospin quintets can provide an even more exact test of Eq. (1) than can the quartets. Äystö *et al.* [3] made such a test in $A = 36$. They found that the energy of the delayed proton group corresponding to the isobaric analog transition in ^{36}Ca β decay was $E_p = 2.519 \pm 0.021$ MeV, which, together with the mass of ^{35}Ar, implied that the lowest $T = 2$ level in ^{36}K had a mass excess of -13.168 ± 0.022 MeV. Combining this with existing information on the masses of the other quintet members, Äystö *et al.* found satisfactory agreement with Eq. (1), although the χ^2 probability was only 15%, hinting that the model may not reproduce the data. In fact, the compilers of Ref. [1] noted that the $A = 36$ quintet was the only case where the data required nonzero values for $d(A,T)T_z^3$ and $e(A,T)T_3^4$ extensions to Eq. (1).

In this Brief Report, we present a more precise determination of the mass of the lowest $T = 2$ level in ^{36}K and use it, together with the well-known masses of the analog levels in ^{36}S, ^{36}Cl, and ^{36}Ar, to test the multiplet mass equation. We find good agreement, establishing one of the most precise limits on a possible $d(A,T)$ term. We then use the equation to predict the mass of ^{36}Ca, which we compare to the observed value.

This ^{36}Ca work was a by-product of a study of ^{37}Ca decay [4]. The ^{36}Ca source was produced using a radioactive beam from the ISOLDE on-line isotope separator at CERN with a fluorinated Ti target. We took data with

TABLE I. Mass excesses of the lowest $T = 2$ quintet in $A = 36$.

Nucleus	T_z	Mass excess[a] (keV)
^{36}Ca	-2	-6440 ± 40
^{36}K	-1	-13135.6 ± 2.4 [b]
^{36}Ar	0	-19377.1 ± 1.5
^{36}Cl	1	-25222.4 ± 1.1
^{36}S	2	-30664.0 ± 0.2

[a] Using accepted values for ground-state masses [9] and E_x's [10] unless otherwise noted.
[b] This work plus Ref. [9].

0556-2813/95/51(6)/3487(2)/$06.00

TABLE II. Coefficients of multiplet mass equation for the lowest quintet in $A = 36$.

a (keV)	b (keV)	c (keV)	d (keV)	e (keV)	χ^2/ν	$P(\chi^2,\nu)$[a]
-19378.4 ± 1.0	-6043.8 ± 1.3	200.5 ± 0.7			1.5	0.22
-19377.6 ± 1.5	-6044.5 ± 1.6	199.1 ± 1.9	0.8 ± 1.0		2.4	0.12
-19.3771 ± 1.5	-6043.6 ± 1.3	197.6 ± 2.5		0.6 ± 0.5	1.6	0.21
-19377.1 ± 1.5	-6039.2 ± 3.8	195.4 ± 3.1	-4.2 ± 3.4	2.7 ± 1.8		

[a] Probability of getting a χ^2 as large as that in the previous column.

both $A = 36$ (for ^{36}Ca) and $A = 55$ (for ^{36}CaF) beams. The $A = 36$ beam was dominated by ^{36}K, which produced a β-delayed proton background; the $A = 55$ beam was very pure but had a very low intensity; the fluorine leak lasted for only 8 h of ^{37}Ca data [4,5] and by the time we tuned on $A = 55$ the fluorinization was very inefficient.

The radioactive beam was focused onto a three-element proton telescope that had an energy resolution of about 17 keV. Figure 1 shows the proton spectra obtained with $A = 36$ and $A = 55$ beams. The $A = 55$ spectrum shows a single peak that we associate with the superallowed decay of ^{36}Ca. Most of our statistics are in the $A = 36$ spectrum, which contains additional peaks (two of which are barely resolved) from ^{36}K decay that were not present in the $A = 55$ spectrum. We do not expect proton groups from ^{36}K decay at the position of the ^{36}Ca peak. A previous study of ^{36}K decay [6] saw no proton peaks between $E_p = 2458 \pm 10$ keV and $E_p = 2640 \pm 10$ keV, and ^{35}Cl(p,x) studies [7] saw no resonances that would produce ^{36}K β-delayed protons between $E_p = 2521$ keV and $E_p = 2643$ keV.

We fitted the delayed proton peaks with Gaussians using a variety of regions for the fits, in all cases obtaining consistent results. The proton energy scale was calibrated using groups from ^{37}Ca decay. This calibration reproduced the well-known [8] energies of ^{36}K delayed proton groups with a mean deviation of 0.6 keV, essentially all of which could be explained by the quoted uncertainties [8] in the energies of the ^{36}K peaks. Our superallowed ^{36}Ca peak has $E_p = 2550.2 \pm 2.2$ keV which translates to a total center-of-mass energy of $E_{\mathrm{c.m.}} = 2623.6 \pm 2.3$ keV, where the error is about an order of magnitude smaller than in the previous experiment [3]. This, together with the mass excess of ^{35}Ar, -23048.2 ± 0.8 keV [9], yields $M(^{36}\mathrm{K}, T = 2) = -13135.6 \pm 2.4$ keV. Using the ^{36}K mass excess of -17425 ± 8 keV from Ref. [9], we get $E_x = 4289 \pm 8$ for the excitation energy of the $T = 2$ level in ^{36}K.

Table I shows the masses [9,10] of all members of the $A = 36$ quintet, and Table II shows the fit of these masses to the multiplet mass relation. The agreement is reasonable (the χ^2 probability is only 0.22 and there is still weak evidence for nonvanishing d and e terms). If we fit the multiplet masses to an extension of Eq. (1) containing a T_z^3 term, the ±1.0 keV uncertainty in the d coefficient is lower than for any other other isospin quartet or quintet. Future experiments could improve this test significantly. It would be straightforward to reduce the uncertainty in the mass of ^{36}K$(T = 2)$ to around 1 keV—one simply needs more counts. It will be more challenging to reduce the errors in the ^{36}Ca mass. (If one uses the known masses of the ^{36}S, ^{36}Cl, ^{36}Ar, and ^{36}K members of the multiplet to predict the mass excess of ^{36}Ca, one obtains a value of -6490 ± 5 keV, 50 keV below the measured value of -6440 ± 40 keV.)

With such measurements the $A = 36$ quintuplet would provide easily the most sensitive test of the multiplet mass equation. In fact, the $A = 36$ data already provide what is probably the most significant of all the tests of Eq. (1); the second-order effects of very loosely bound valence particles, which are presumably responsible for the observed d term in the $A = 9$ quartet, should be much smaller for the well-bound states of the upper $1d2s$ shell.

Finally, we note that the *shape* of the superallowed proton group from ^{36}Ca decay, given enough statistics, could be used to search for a fundamental scalar weak interaction via its influence on the angular correlation between the positron and the neutrino [11].

We thank the entire ISOLDE team, especially Helge Ravn, for helping to make this measurement a success. A.G. acknowledges support from the Warren Foundation and the NSF. The University of Washington researchers are partially supported by the DOE.

---

[1] M.S. Antony, J. Britz, J.B. Bueb, and A. Pape, At. Data Nucl. Data Tables **33**, 447 (1985).

[2] G. Bertsch and S. Kahana, Phys. Lett. **33B**, 193 (1970).

[3] J. Äystö, M.D. Cable, R.F. Parry, J.M. Wouters, D.M. Moltz, and J. Cerny, Phys. Rev. C **23**, 879 (1981).

[4] A. García, E.G. Adelberger, P.V. Magnus, H.E. Swanson, D.P. Wells, F.E. Wietfeldt, O. Tengblad, and the ISOLDE Collaboration, Phys. Rev. C **51**, 439 (1995).

[5] A. García, E.G. Adelberger, P.V. Magnus, H.E. Swanson, O. Tengblad, the ISOLDE Collaboration, and D.M. Moltz, Phys. Rev. Lett. **67**, 3654 (1991).

[6] K. Eskola, M. Riihonen, K. Vierinen, J. Honkanen, M. Kortelahti, and K. Valli, Nucl. Phys. **A341**, 365 (1980).

[7] P.M. Johnson, M.A. Meyer, and D. Reitmann, Nucl. Phys. **A218**, 333 (1974).

[8] P.M. Endt and C. van der Leun, Nucl. Phys. **A310**, 1 (1978).

[9] G. Audi and A.H. Wapstra, Nucl. Phys. **A565**, 1 (1993).

[10] P.M. Endt, Nucl. Phys. **A521**, 1 (1990).

[11] E.G. Adelberger, Phys. Rev. Lett. **70**, 2856 (1993).