PHYSICAL REVIEW C, VOLUME 60, 031301

The $0^+_{g.s.} \rightarrow 2^+_1$ transition in ^{38}Ca and isospin symmetry in $A=38$ nuclei

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(Received 6 May 1999; published 4 August 1999)

The $B(E2;0^+_{g.s.} \rightarrow 2^+_1)$ value for ^{38}Ca has been measured via the technique of intermediate energy Coulomb excitation using a beam of radioactive ^{38}Ca nuclei. The present result is used to test isospin purity in the mass 38 system by comparing the isoscalar multipole matrix element M_0 extracted from the $0^+_{g.s.} \rightarrow 2^+_1$ transitions in ^{38}Ca and ^{38}Ar to the corresponding matrix element obtained from the $T=1$ states of the $T_z=0$ nucleus ^{38}K. A discrepancy between the two values of M_0 is found, suggesting that isospin symmetry is broken in $A=38$ nuclei. Similar discrepancies occur for $A=34$ and 42. Experiments for addressing these discrepancies are proposed. [S0556-2813(99)50109-X]

PACS number(s): 23.20.Js, 27.30.+t, 21.10.Hw

The advent of methods for producing radioactive beams and the development of experimental techniques for exploiting these beams have provided new avenues for detailed studies of the isospin symmetry in nuclei. While isospin symmetry is broken by the Coulomb force, the approximate conservation of isospin has been assumed in many nuclear structure calculations, such as the shell model calculations of Brown, Chung, and Wildenthal [1,2]. In the present work, we report on a measurement of $B(E2;0^+_{g.s.} \rightarrow 2^+_1)$ in the short-lived ($T_{1/2}=0.44$ s) nucleus ^{38}Ca using the method of intermediate energy Coulomb excitation of radioactive beams (a review of this technique is given in [3]). This measurement enables us to examine the isospin purity of the mass 38 system. As pointed out in [4], we can test isospin purity by extracting the isoscalar multipole matrix element M_0 from the present result on ^{38}Ca and the previously measured $B(E2;0^+_{g.s.} \rightarrow 2^+_1)$ value in the mirror nucleus ^{38}Ar and comparing it to the isoscalar matrix element obtained from the corresponding transition between $T=1$ states in the $N=Z$ nucleus ^{38}K. Our data suggest that these two values of M_0 are not equal and that isospin symmetry is broken to a surprisingly large degree in the mass 38 system. We demonstrate here that an examination of previous measurements on the mass 34 and 42 systems also reveals similar effects. Finally, we discuss experiments which would provide further information on this apparent breakdown in isospin symmetry.

To produce the ^{38}Ca beam, a 80 MeV/nucleon ^{40}Ca beam from the K1200 cyclotron at the National Superconducting Cyclotron Laboratory irradiated a 202 mg/cm^2 target of ^{9}Be located at the midacceptance target position of the A1200 fragment separator [5]. The energy spread of the resulting ^{38}Ca fragments was limited to $\pm 1\%$ with an aperture. Isotope separation was obtained by placing a thin, achromatic wedge (^{27}Al, 64 mg/cm^2) at the second dispersive image of the A1200. A ''cocktail'' beam containing several fragment species was used to perform the experiment in order to study other nuclei in the vicinity simultaneously. This could be done because the counting rate was not a limiting factor and the fragment identification, which is described below, was unambiguous. After passing through the secondary target (^{197}Au, 184.1 mg/cm^2), the secondary beams were stopped in a cylindrical fast-slow plastic phoswich detector (called the ''zero-degree detector,'' or ZDD) which allowed charge identification of the secondary beam particles. The time of flight between a thin plastic scintillator located after the A1200 focal plane and the ZDD was recorded for each secondary beam particle and provided positive mass identification. About 20% of the mixed beam was ^{38}Ca ($\approx 12\,000$ ^{38}Ca particles/s). The average energy of the incoming ^{38}Ca particles was 56.1 MeV/nucleon. The ZDD had an opening angle of $\theta_{lab}=4.0°$ with respect to the secondary target; Coulomb excitation is the dominant excitation process in this range of scattering angles. The secondary target was surrounded by an array of 38 position sensitive NaI(Tl) γ-ray detectors arranged in three concentric rings around the target and shielded from background photons by 16.5 cm thick lead walls. A more detailed description of the experimental and analysis procedures can be found in Ref. [6], which also illustrates the Doppler-shift correction technique used for analysis of the γ-ray spectra.

The Doppler-corrected γ-ray energy spectrum for ^{38}Ca (recorded under the condition that a ^{38}Ca fragment was detected in the zero-degree detector) is shown in Fig. 1(a). The spectrum includes a strong peak at 2.206(10) MeV, a weaker peak at 3.685(21) MeV, and a weak peak at 1.448(25) MeV. The 2.206 MeV peak corresponds to the $2^+_1 \rightarrow 0^+_{g.s.}$ transition in ^{38}Ca. There are two nearly degenerate states in ^{38}Ca near 3.685 MeV, one having $J^\pi=2^+$ and the other $J^\pi=3^-$ [7]. The possibility that the observed 3.685 MeV γ-ray peak could correspond to transitions from either or both of these states to the ground state must be considered. Finally, it has been demonstrated previously that the 2^+ state at 3.685 MeV deexcites to the 2.206 MeV state via a 1.479 MeV γ ray [7]. We identify the weak peak at 1.448(25) MeV as this connecting transition.

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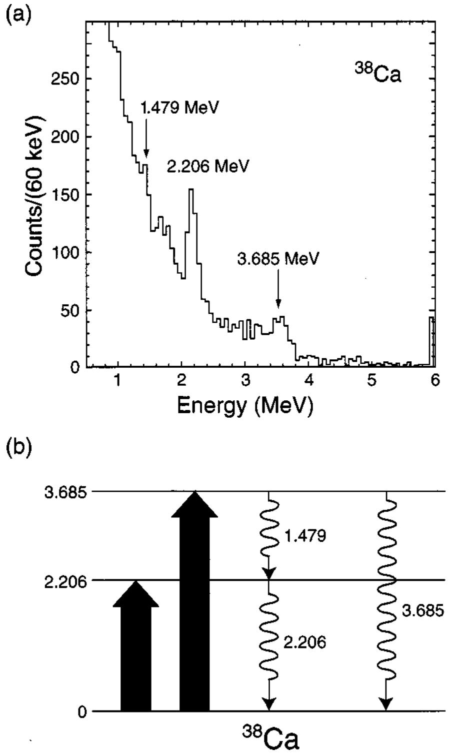

FIG. 1. (a) Doppler-shifted γ-ray spectrum gated on ^{38}Ca. (b) The excitations (solid arrows) and γ rays (wavy lines) considered in the present work.

The goal of the analysis of the γ-ray spectrum is to extract matrix elements for the $0^+_{\rm g.s.}\rightarrow J^\pi$ excitations observed here. Beyond the issues usually addressed in the analysis of intermediate energy Coulomb excitation data [3], there are two additional issues that are particular to the present experiment. First, it is not immediately clear which of the states at 3.685 MeV is being populated. Indeed, both may be populated with comparable intensities. Second, the 2.206 MeV state is fed by deexcitations from the state(s) at 3.685 MeV, as illustrated in Fig. 1(b). The yield of the 2.206 MeV γ ray must be adjusted for this feeding before a $B(E2;0^+_{\rm g.s.}\rightarrow 2^+_1)$ matrix element can be extracted.

The first issue may be addressed via an analysis of the cross section of the state(s) at 3.685 MeV. In the analysis of intermediate energy Coulomb excitation data, the extraction of a cross section from a peak in the γ-ray spectrum involves the number of counts in the peak, the detection efficiency, the integrated beam current (that is, the total number of incident ^{38}Ca nuclei), and the angular distribution of the γ rays. This last factor comes into play because the γ-ray detection efficiency is angle dependent. As a result, the cross section determination is dependent on the multipolarity of the γ ray. If the observed 3.685 MeV peak results entirely from the $3^-\rightarrow 0^+_{\rm g.s.}$ $E3$ transition, then the experimental cross section for production of this γ ray is 19 ± 5 mb. The 3^- state may also deexcite to the 2.206 MeV 2^+ state via an $E1$ transition, so the cross section for *population* of the 3^- state would be greater than or equal to the 3.685 MeV γ-ray production cross section.

The extraction of reduced transition matrix elements $B(E\lambda;0^+_{\rm g.s.}\rightarrow \lambda^\pi)$ from the experimental cross sections is made using the relativistic theory of Winther and Alder [8] as described in [3]. If it is assumed that the 3.685 MeV 3^- state is populated with the cross section given above, then we would have $B(E3;0^+_{\rm g.s.}\rightarrow 3^-)=(2.0\pm 0.5)\times 10^5\ e^2\ {\rm fm}^6$. However, the recommended upper limit for $E3$ transitions in this mass region given by Endt [9] is 50 Weisskopf units (W.u.) which yields $B(E3;0^+_{\rm g.s.}\rightarrow 3^-)=4.3\times 10^3\ e^2\ {\rm fm}^6$ for $A=38$. We therefore conclude that population of the 3^- state accounts for less than 3% of the population of the 3.685 MeV doublet, and that the 3.685 MeV γ ray corresponds to the transition from the 3.685 MeV 2^+ state to the ground state.

To extract $B(E2;0^+_{\rm g.s.}\rightarrow 2^+)$ for the 3.685 MeV 2^+ state, the cross section for the population of this state must be obtained. The population cross section is the sum of the cross sections for the 1.479 MeV and 3.685 MeV γ rays. The 3.685 MeV γ-ray cross section is 17 ± 5 mb, assuming an $E2$ $2^+\rightarrow 0^+$ transition. The 1.479 MeV γ ray is somewhat more problematic, since there is uncertainty regarding its multipolarity ($M1$, $E2$, or a mixture). With the statistical error bar and the uncertainty in the angular distribution (due to the multipolarity) included, the cross section for the 1.479 MeV γ ray is 3.3 ± 2.2 mb. The resulting cross section for populating the 3.685 MeV 2^+ state is 20.5 ± 5.0 mb, which gives $B(E2;0^+_{\rm g.s}\rightarrow 2^+)=122\pm 30\ e^2\ {\rm fm}^4=3.2\pm 0.8$ W.u.

It is worth noting that the γ-ray branching ratio for the 3.685 MeV 2^+ state given by the present data (16 ± 12% to the 1.479 MeV γ-ray) is significantly different from that reported by Shapiro *et al.* in 1970 [10] from the ^{36}Ar(^{3}He, $n\gamma$) reaction (48% to the same γ ray). However, their neutron gating spectrum has a large background, causing their branching ratio results to be unreliable.

To determine the $B(E2;0^+_{\rm g.s.}\rightarrow 2^+_1)$ value for the 2.206 MeV state, we must find the cross section for direct population of this state. That is, the cross section for production of the 2.206 MeV γ-ray must have the cross section for production of the 1.479 MeV feeding γ ray subtracted from it. The cross section for the 2.206 MeV γ ray is 23.2 ± 4.0 mb. If we subtract the 1.479 MeV γ-ray cross section from the 2.206 MeV gamma-ray cross section, we obtain the cross section for direct population of the 2.206 MeV 2^+ state to be 19.4 ± 4.4 mb. The Alder-Winther analysis then yields $B(E2;0^+_{\rm g.s.}\rightarrow 2^+)=96\pm 21\ e^2\ {\rm fm}^4=2.52\pm 0.56$ W.u. for the 2.206 MeV state.

The cocktail beam also included significant amounts of the stable nucleus ^{36}Ar, for which it is known that $B(E2;0^+_{\rm g.s.}\rightarrow 2^+_1)=298\pm 30\ e^2\ {\rm fm}^4$ [7]. The result determined here for ^{36}Ar ($310\pm 31\ e^2\ {\rm fm}^4$) is consistent with the adopted value, lending confidence to our result for ^{38}Ca.

The 3.685 MeV 2^+ state appears to be a member of a deformed band built on the 3.057 MeV 0^+ state. This band is a ''mirror'' of the deformed band in ^{38}Ar built on the 0^+ state at 3.377 MeV [11]. At first, it may seem surprising that the $B(E2;0^+_{\rm g.s.}\rightarrow 2^+)$ value for the 3.685 MeV state in ^{38}Ca is comparable to $B(E2;0^+_{\rm g.s.}\rightarrow 2^+)$ for the 2.206 MeV state. However, the $E2$ transitions within the deformed band in ^{38}Ar are quite strong (the $4^+\rightarrow 2^+$ transition in this band has a strength of 30 W.u.), so modest mixing between the ground state and the 3.057 MeV 0^+ state could account for the observed $B(E2;0^+_{g.s.} \rightarrow 2^+)$ value for the 3.685 MeV state.

The result on the 2.206 MeV 2^+ state provides the opportunity to examine isospin symmetry in the mass 38 multiplet. If isospin symmetry is satisfied within a mass multiplet, then the matrix elements of the corresponding electromagnetic transitions in each isobar are related in a straightforward way. A measurement of the matrix element $B(E2;J_i \rightarrow J_f)$ using Coulomb excitation or some other electromagnetic probe provides information on the contribution of the protons to the transition. If the proton multipole matrix element is defined as

$$M_p = \langle J_f || \Sigma_p r_i^\lambda Y_\lambda(\Omega_i) || J_i \rangle, \quad (1)$$

then

$$B(E\lambda;J_i \rightarrow J_f) = (M_p)^2/(2J_i+1). \quad (2)$$

The relationship between multipole matrix elements in the neutron or proton and isospin representations yields [4]

$$M_p(T_z) = (1/2)[M_0(T_z) - M_1(T_z)], \quad (3)$$

where $M_0(T_z)$ and $M_1(T_z)$ are the isoscalar and isovector multipole matrix elements, respectively. The assumption of isospin conservation gives the relationships between matrix elements in different isobars:

$$M_0(T_z') = M_0(T_z), \quad (4)$$

$$M_1(T_z') = M_1(T_z) T_z'/T_z. \quad (5)$$

If two nuclei are mirrors, then $T_z' = -T_z$ and

$$M_0(T_z) = M_p(T_z) + M_p(-T_z). \quad (6)$$

Equation (6) also implies that for the corresponding transition between $T=1$ states in a $T_z=0$ nucleus

$$M_p(T_z=0) = M_0(T=1)/2. \quad (7)$$

That is, given the assumption of isospin symmetry the value of M_0 extracted from the M_p values in two mirror $T_z = \pm 1$ nuclei should be equal to the value $M_0 = 2M_p$ obtained for the $0^+_{T=1} \rightarrow 2^+_{T=1}$ transition in the $T_z=0$ nucleus. According to [4], this comparison provides an experimental test of isospin purity for $A=4n+2$ multiplets.

For $A=38$, a comparison of M_p values in ^{38}Ca and ^{38}Ar yields $M_0=3.41(18)$ W.u., while the value of M_0 extracted from the compilation of Ref. [7] for the corresponding transition in ^{38}K (between the 0.13 and 2.40 MeV $T=1$ states) is 2.44(50) W.u. The large experimental uncertainty in the value of M_0 obtained for ^{38}K prevents us from drawing a definitive conclusion that isospin symmetry is violated in the mass 38 system. However, the suggestion of broken isospin symmetry is tantalizing enough to provide a strong motivation for improving the experimental value of M_p in ^{38}K. The value of this quantity used here is taken from measurements of the lifetime of the $2^+_{T=1}$ state (the compilation of [7] gives 72 ± 17 fs) and the branching ratio from this state to the $0^+_{T=1}$ state (given as $6 \pm 2\%$ in [7]). However, the error bar quoted in [7] for the lifetime does not provide a complete picture of the experimental situation. Three measurements of the lifetime of the $2^+_{T=1}$ state have been reported [12–14], all using the Doppler shift attenuation method. The results for these three experiments vary widely—54 ± 25 fs [12], 90 ± 25 fs [13], and 76 ± 50 fs [14] (the value given by [12] would yield $M_0 = 2.81 \pm 0.80$ W.u., which is equal to the ^{38}Ca-^{38}Ar value, within the error bar). All three measurements were made prior to 1976, so the γ rays were detected with Ge(Li) detectors which were much smaller than the large-volume high-purity Ge detectors generally used for γ-ray spectroscopy today. In addition, the Compton suppression technology now widely used was not available then. Both these factors are important for measurements of the 2 MeV γ rays which deexcite the $2^+_{T=1}$ state of ^{38}K.

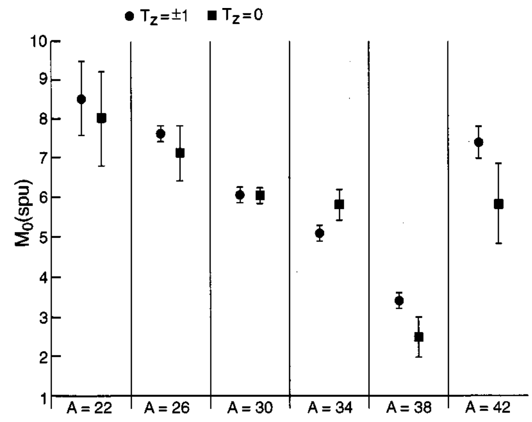

FIG. 2. A comparison of isoscalar multipole matrix elements M_0 extracted from the comparison of M_p values for $0_{g.s.} \rightarrow 2^+_1$ transitions in $T=1$ nuclei to the M_0 values taken from transitions between $T=1$ states in $T_z=0$ nuclei. This comparison allows a test of isospin purity in $A=4n+2$ systems.

Comparisons between M_0 values taken from $T_z = \pm 1$ nuclei and the $T=1$ states of the $T_z=0$ isobars for $4n+2$ nuclei in the mass range $A=22-42$ are shown in Fig. 2 (data are taken from [7] and the present work). In addition to the case of $A=38$, the error bars for the M_0 results from $T_z = \pm 1$ and $T_z=0$ nuclei do not quite overlap in two other cases ($A=34$ and 42); once again suggesting that isospin symmetry might be violated at a surprisingly large level in these mass multiplets. As in the $A=38$ system, this provides a motivation for remeasuring the M_p values in the nuclei involved. This is particularly true for the $T_z=0$ isotopes, where the error bars are large for reasons similar to those in ^{38}K.

In summary, the $B(E2;0^+_{g.s.} \rightarrow 2^+_1)$ value for ^{38}Ca has been measured via the technique of intermediate energy Coulomb excitation. The isoscalar multipole matrix element M_0 was obtained from a comparison of the ^{38}Ca and ^{38}Ar results and compared to the result for M_0 extracted from the transition between the 2^+ and 0^+ $T=1$ states in the $T_z=0$ nucleus ^{38}K to test for isospin purity in the mass 38 system. The two results for M_0 do not agree, suggesting that isospin symmetry is broken to a surprisingly large degree in the $A=38$ mass multiplet. An examination of M_0 values in other mass multiplets reveals similar discrepancies in the $A=34$ and 42 systems. These results provide a strong motivation for more precise measurements of $2^+_{T=1}\rightarrow 0^+_{T=1}$ transitions in the $T_z=0$ nuclei of masses 34, 38, and 42.

We wish to thank A. M. Bernstein for bringing the isospin purity issue to our attention. This work was supported by the National Science Foundation through Grant Nos. PHY-9523974 and PHY-9528844.

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