A CORRECTION TO SOME EXPERIMENTS TO MEASURE THE REORIENTATION EFFECT

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Received 12 March 1968

The importance of the attenuation of the γ ray angular distribution on the interpretation of reorientation experiments is discussed. The attenuation which arises when the emitting nuclei recoil into vacuum leads to an appreciable uncertainty in some reported quadrupole moments.

A number of experiments [1-6] have been performed to determine the quadrupole moment of the first excited 2^+ state in some nuclei by measuring the reorientation effect of Coulomb excitation [7]. The experimental technique which has been most frequently used to observe this effect is that of measuring the probability of Coulomb excitation for two or more different types of projectiles by detecting γ rays in coincidence with backscattered ions. It is necessary to make a number of small corrections to the experimental data before extracting a quadrupole moment because the effect of the quadrupole moment on the excitation probability is relatively small. In particular one correction arises from the generally anisotropic angular distribution of the γ rays and enters when normalizing the γ-ray yield to 4π geometry. Recent experiments at this laboratory [8] have revealed an interesting phenomenon which can have a large effect on the angular distribution correction.

It has been established [8] that the angular distribution of γ rays following Coulomb excitation in coincidence with back-scattered oxygen ions can be quite strongly attenuated if the target nuclei recoil into vacuum before emitting the γ ray. The explanation is that the recoiling target atom is in general in a highly ionized state upon leaving the target and consequently the nucleus feels a strong magnetic field. The interaction between the magnetic field and the magnetic dipole moment of the nucleus results in a precession of the nuclear spin axis about the total angular momentum vector of the system. If the lifetime of the nuclear state is sufficiently long the nucleus will precess through an appreciable angle before emitting the γ ray with a consequent effect on the γ-ray angular distribution. On the other hand if the recoiling target atom comes to rest in the target before emitting the γ ray then the angular distribution will be unperturbed provided the lifetime of the excited state is shorter than about 1 ns.

The angular distribution of γ rays in coincidence with backscattered ions can be written

$$W(\theta) = 1 + A_2 Q_2 (J_2/J_0)\, P_2(\cos\theta) + A_4 Q_4 (J_4/J_0)\, P_4(\cos\theta)\,. \tag{1}$$

The factors A_2 and A_4 are products of particle parameters and γ-γ angular correlation coefficients [9], Q_2 and Q_4 represent the smearing of the angular distribution due to the finite size of the (cylindrically symmetric) γ-ray detector [10], and J_2/J_0 and J_4/J_0 are factors which account for the attenuation of the angular distribution due to finite size of the annular counter detecting the backscattered particles [11].

When the nuclei emitting the γ rays are recoiling into vacuum the effect of the magnetic interaction is equivalent to a multiplication of the $P_2(\cos\theta)$ and $P_4(\cos\theta)$ terms by factors G_2 and G_4, respectively. In the experiments of ref. 8 in which oxygen ions of 30 to 40 MeV were incident upon targets of 200 to 300 μg/cm^2, the factors G_2 and G_4 are typically in the ranges 0.6 - 1.0 and 0.5 - 1.0, respectively, depending on the nucleus studied. These factors which have been measured for even Cd and Te isotopes are found to change little for initial recoil energies between 12 and 18 MeV.

The experimental situation in part of the reorientation experiments of Stokstad et al. [1,2] on ^{114}Cd and ^{116}Cd is very similar to that of ref. 8. In the latter experiments targets of CdCl$_2$ were used whereas Stokstad et al. used 250-450 μg/cm^2

cadmium on thin carbon foils (≈ 50-100 $\mu g/cm^2$) [12]. In the two experiments similar oxygen bombarding energies were employed. Hence it would appear that in the reorientation experiments the angular distribution of the γ rays emitted following Coulomb excitation by oxygen ions should be corrected for the magnetic attenuation.

The reorientation experiments also measure the probability of Coulomb excitation by α particles. The recoil energy of the Cd ions is then quite low, about 1 MeV, and the great majority of these recoils will be stopped either in the target or in the carbon backing since the range is about 80 $\mu g/cm^2$ in carbon. The γ-ray angular distribution following Coulomb excitation by α particles will then be unperturbed. The range estimation is based on a modification of the theory of Lindhard [13] by Blaugrund [14].

The γ-ray angular distribution factor, unperturbed by the magnetic interaction, for a 7.6×7.6 cm^2 NaI(Tl) crystal at 58° to the incident beam direction and at a distance of 3 cm from the target is, for ^{114}Cd,

$$W(58^{\circ}) = 1 - 0.037 + 0.112 = 1.075. \quad (2)$$

Using the experimental values of G_2 and G_4 for ^{114}Cd, but neglecting relativistic corrections and the fact that some nuclei decay slightly closer to the NaI(Tl) crystal, the angular distribution factor with the magnetic interaction included is

$$W(58^{\circ}) = 1 - 0.037 \times 0.715 + 0.112 \times 0.589 = 1.040\,. \quad (3)$$

Thus the two angular distribution factors differ by about 3.5%, and since the reorientation effect for a quadrupole moment of rotational size is about 12%, the correction can account for about 30% of the observed quadrupole moment of -0.7 b in ^{114}Cd. (In the experiments the probability of Coulomb excitation by oxygen ions was lower than was expected from the α-particle results). The situation in ^{116}Cd is slightly worse because of the smaller factors G_2 and G_4 measured. However, the measurements of Stokstad and Hall [5] to determine the quadrupole moment of ^{126}Te and ^{128}Te are relatively unaffected by the magnetic interaction because of the shorter life-times of the 2^+ states in these nuclei.

It must be emphasized that the correction which has been calculated is only approximate. If the emitting nuclei recoil into vacuum two things are important. One is to know the angular distribution of the γ rays to determine the products $Q_2(J_2/J_0)G_2$ and $Q_4(J_4/J_0)G_4$. The second is to know very accurately the geometry of the experiments. If, in the example of ^{114}Cd given above, the effective center of the NaI(Tl) crystal had been off axis by about 2 mm this could change the angle from 58° to the zero of the $P_2(\cos\theta)$ term. The $P_4(\cos\theta)$ term would be larger and the correction to the quadrupole moment would be about 0.3 b rather than the previous 0.2b. The effective distance of the NaI(Tl) crystal is also very critical because Q_4 changes quite rapidly with distance [10]. (The estimate that the quadrupole moments of ^{126}Te and ^{128}Te are relatively unaffected by the magnetic interaction also depends quite critically on the geometry since the factors G_2 and G_4 lie in the range 0.8 - 0.9).

In conclusions it seems that due to the attenuation of the γ-ray angular distribution for recoil into vacuum a number of quadrupole moments determined by the reorientation effect are in doubt. It is also advisable to avoid the problem of the attentuation by providing the target with a backing thick enough to stop completely the recoiling nuclei.

We should like to thank Professor G. Goldring, Dr. Z. Vager, Dr. A. E. Blaugrund and Mr. M. Goldberg for helpful discussions, and Dr. R. G. Stokstad for supplying us with unpublished information.

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