NUCLEAR ALIGNMENT IN HEAVY-ION REACTIONS*

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In this Letter we would like to point out the usefulness for spectroscopic purposes of the nuclear alignment obtained in (heavy-ion, xn) reactions. It is well known that in compound-nucleus reactions the incoming particle brings orbital angular momentum to the compound system but only in the $m=0$ substates, taking the beam direction as the axis of quantization.[1] Thus the compound nuclei have their spins aligned in the plane perpendicular to the beam axis; the only deviations are caused by the spins of the target nucleus and projectile. With heavy ions as projectiles, the amount of orbital angular momentum brought in far exceeds the usual nuclear spins, and the resulting compound nuclei should be highly aligned. The evaporation of a few neutrons will leave the initial spin distribution of the compound system largely unaltered and will broaden the distribution in m. However, since evaporated neutrons do not carry off much angular momentum, the nuclei with high angular momenta will be expected to remain highly aligned even after the evaporation process. Thus the final gamma rays (or particles) emitted between discrete states of the residual nuclei will show angular distributions with respect to the beam direction provided that the alignment is not destroyed by some interaction with extranuclear fields.

It has previously been shown[2] that the conversion electrons emitted following proton- and alpha-particle-induced reactions are indeed anisotropic. In a paper to be published elsewhere,[3] we describe the results of a more detailed investigation, with lithium-drifted Ge detectors, of the angular distributions of the discrete gamma-ray cascades observed as the final de-excitation step in some 12 reactions induced by heavy ions (^{4}He to ^{19}F), producing deformed and spherical even-even nuclei in the mass range 160-200. The result of interest here is that very pronounced angular distributions were observed for all these stretched $E2$ cascades. Using the expression $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, we have summarized the results of that work in Fig. 1, where A_4 vs A_2 has been plotted for the observed transitions other than the $2\rightarrow0$. The line in Fig. 1 represents the relationship between A_4 and A_2 expected with a Gaussian distribution, centered at $m=0$, for the population of magnetic substates. Figure 1 shows that (1) the population can be approximately represented by a Gaussian about $m=0$, although significant deviations from this appear; and (2) the A_2 values are large and both A_2 and A_4 are reasonably well clustered about particular values (all data, $I>2$, fall within $A_2=+0.30\pm0.09$, and $A_4=-0.09\pm0.05$). The latter result shows that this alignment will be an extremely useful tool, since it generally persists throughout the entire neutron and gamma-ray cascade.

The gamma decay of nuclei formed in (heavy-ion, xn) reactions offers a very general method of studying the decay schemes of neutron-deficient nuclei over a wide range of the periodic system. Although mainly studies of even-even nuclei have been reported so far, it is now clear that odd-mass and odd-odd nuclei can also be successfully investigated. We feel that the strong alignment produced in these reactions is a very important feature which will be of great value particularly in the study of

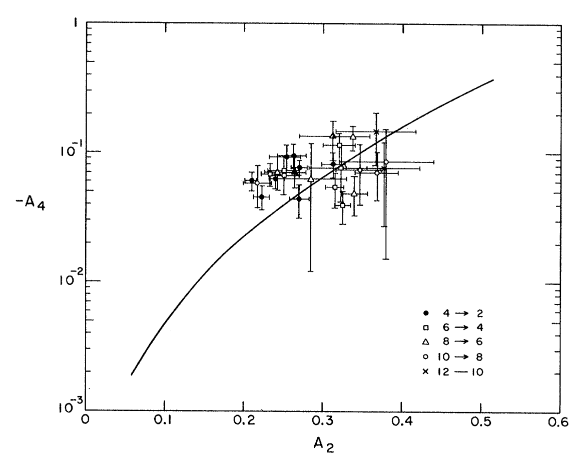

FIG. 1. The coefficients A_4 vs A_2 (see text) are plotted for a number of rotational or vibrational gamma rays observed as the last step of heavy-ion (^{4}He-^{19}F) nuclear reactions. The coefficients for the $2\rightarrow0$ transitions have not been included since they can be attenuated by extranuclear effects. The line represents the relationship between A_4 and A_2 expected for a Gaussian population of magnetic substates centered around $m=0$.

these more complex level schemes. One of the most obvious ways to exploit the alignment is the measurement of angular distributions of the de-excitation gamma rays with respect to the beam direction. We would like to illustrate this with an example taken from a general study of the levels of the neutron-deficient odd-mass Tl nuclei.[4] In the reaction ^{197}Au(^{4}He, $2n$)^{199}Tl we have found, among others, three transitions of 331, 370, and 701 keV which lie above the $\frac{9}{2}^-$ isomeric level at 749 keV. From the energies and intensities of these transitions, we believe they connect two higher levels with the isomeric one in a cascade arrangement with a crossover (see insert in Fig. 2). We have measured the angular distributions of these radiations with respect to the beam direction and find large anisotropies for each transition. From these angular distributions, shown in Fig. 2, definite conclusions about a particular spin sequence can be based both on the signs of A_2 and A_4 and on their magnitudes, whenever the experimental values exceed that for complete alignment ($|m| = \frac{1}{2}$). Also, if two transitions come from the same level, both distributions must be consistent with the same alignment of the state. In the present example, where we know initially only the arrangement of the levels (Fig. 2) and that the transitions must be dipole, quadrupole, or a mixture, the distributions alone unambiguously reduce the number of possible spin sequences from 19 to 5. It is then possible to go further and make probable conclusions based on the expected alignment of the state obtained from the range of A_2 and A_4 values observed above for the even-even nuclei. These considerations reduce the probable number of spin sequences to 3 and these probable spins are shown in Fig. 2. Conversion-coefficient and other data can provide the basis for a choice among these remaining spin sequences. The $E2$-$M1$ amplitude mixing ratio for the mixed transitions can then be derived in cases where the alignment of the initial state can be deduced (e.g., when there is also a pure transition coming from the same state), or probable ranges can be defined in less favorable cases. It can be seen that in this example a considerable amount of spectroscopic information can be obtained from the measurement of the angular distributions of these three transitions.

This high degree of alignment can also be used in the measurement of electromagnetic

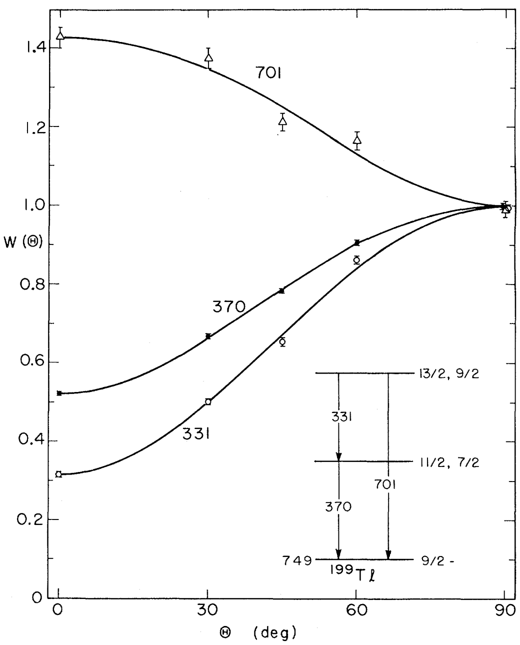

FIG. 2. The curves are the observed angular distributions with respect to the beam direction of three gamma rays produced in the reaction ^{197}Au(^{4}He, $2n$)^{199}Tl. The placement of these gamma rays above the 749-keV, $\frac{9}{2}^-$ isomeric level in ^{199}Tl is shown in the insert along with the probable spins based on the angular distributions. The measured coefficients are as follows: 331 keV, $A_2 = -0.58 \pm 0.03$, $A_4 = -0.02 \pm 0.03$; 370 keV, $-A_2 \geq 0.36 \pm 0.02$, $-A_4 \geq 0.03 \pm 0.02$; 701 keV, $A_2 = +0.26 \pm 0.04$, $A_4 = -0.03 \pm 0.04$.

moments and hyperfine interactions of nuclear states by the method of perturbed angular distributions. This type of experiment requires a target structure which preserves the spin orientation of the reaction product for a period longer than the lifetime of the nuclear state of interest. The lower limit to the usable lifetime is set by the minimum time to get appreciable precession of the nuclear moment in the effective field, the upper limit by the relaxation of time of the nuclei in their particular environment. In these studies the large recoil velocity of the product nucleus is very valuable in getting the nucleus quickly into a suitable environment for the experiment. Thus for short-lived levels in the 10^{-11}- to 10^{-9}-sec range, the product nuclei can be recoiled into a ferromagnetic lattice to obtain large effective magnetic fields to perturb the correlation. This technique has already been used in Coulomb excitation experiments,[5] and should find general application in reaction experiments also. For half-lives in the 10^{-9}- to 10^{-3}-sec range, the same ferromagnetic environment can be used for resonance destruction of the angular distribution.[6] For this range of lifetime one needs to take advantage of the rf-amplitude enhancement in a ferromagnetic lattice while for longer lifetimes this may not be necessary.[7] For conventional spin-rotation measurements in an external magnetic field, the recoil atoms should go into nonmagnetic cubic metals, to avoid as far as possible attenuating interactions. Experiments along these lines are clearly feasible, and preliminary work is in progress.

In summary, our results have shown that a large and reasonably uniform degree of alignment is present throughout the neutron and gamma-ray cascades following heavy-ion nuclear reactions. This has been demonstrated to be very useful for spin and multipolarity assignments in spectroscopic studies of the de-exciting product nuclei. It promises to be useful also for studies of the nuclear moments and hyperfine interactions of levels in the product nuclei. Taken together with (1) the wide variety of nuclei that can be produced in compound-nucleus reactions, (2) the broad population of levels in a given product nucleus, and (3) the large uniform recoil velocities of compound nuclei, it makes the use of these reactions a general and powerful tool in nuclear spectroscopy.

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DYNAMICS OF THE GEOMAGNETIC TAIL

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In a paper recently published,[1] Ness has reported the experimental evidence of a magnetically neutral sheet behind the earth at a distance of (20-30)R_e (earth radii). This sheet separates regions of oppositely directed magnetic fields in the magnetic tail (Fig. 1). It has been proposed by Ness[1] and subsequent authors that the dynamics of this sheet may have an essential role in geomagnetic phenomena. This suggests as a model the analysis of the stability of a pinch containing a neutral sheet.[2] In fact, theory and laboratory experiments[3-5] clearly show that this configuration is violently unstable as it breaks up into separate pinches (Fig. 2), lying on the neutral sheet, which tend to repel each other. Considering the order of magnitude of the sheet thickness (600 km), and the energy of the electrons there contained, we see immediately that collisional effects (such as resistivity) cannot play a role in the dynamics of the neutral sheet. For this, we can take up the stability analysis of a collisionless pinch,[2,6] with the intention

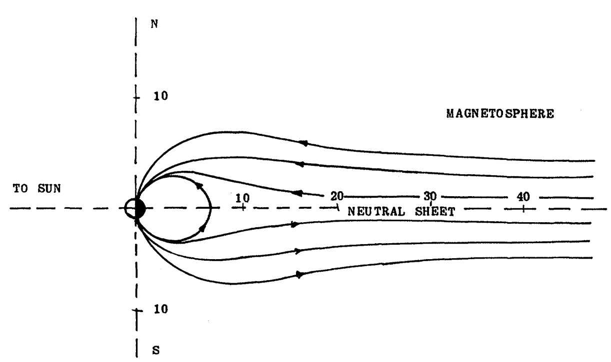

FIG. 1. Projection of magnetic field topology on noon-midnight meridian plane in the vicinity of the neutral sheet (unperturbed configuration). Distance in earth radii.