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Beta-Gamma Emission through Virtual States*

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The possibility of observing a combined beta-gamma transition through a virtual intermediate nuclear state in competition with a direct forbidden beta decay is investigated. Such a transition is coherent with ordinary inner bremsstrahlung associated with the direct transition and can therefore be observed through the distortion of the gamma-ray spectrum from the form predicted for inner bremsstrahlung alone. Favorable circumstances occur particularly when the intermediate state of the daughter nucleus is nearly degenerate with the ground state of the parent. The K-capture transition in Ni^{59} appears to offer the best possibility for such an observation. The direct observation of negative-helicity gamma rays with appropriate spectrum would be another way of directly establishing the alternate decay mode.

THERE are several cases known wherein the direct beta transition from the ground state of a nuclide to the ground state of the daughter nuclide is highly forbidden. In some cases there exist one or more excited states of the daughter nuclide intermediate in energy between the ground states of daughter and parent for which the beta transition is less strongly forbidden and a decay branch then takes place through a beta-gamma cascade. Except for a discussion several years ago by Longmire,[1] little attention has been paid to an alternate decay branch wherein the transition takes place through a virtual transition through an intermediate nuclear state higher in energy than the ground state of the parent. Such a process is reminiscent of double-photon emission except that here one of the photons is replaced by the products of a beta transition. In this note we wish to present some remarks concerning the possibility of detecting a decay branch through such an intermediate state.

It is clear that a favorable situation requires that the ordinary direct beta transition be at least forbidden or strongly inhibited (e.g., C^{14}, P^{32}) and that a suitable intermediate state (or states) exist for which the beta transition is much less forbidden or inhibited. Furthermore, the required gamma transition should be of low multipolarity. Consider, for example, the situation illustrated in Fig. 1 where the ground state of one nuclide and the two lowest levels of its daughter are depicted. The direct beta transition AC between the ground states is second forbidden, but the alternate nuclear beta-gamma branch ABC involves an allowed beta transition followed by an $M1$ or $E2$ gamma transition. The ABC transition could be identified by the fact that a gamma ray is emitted; the gamma-ray spectrum is continuous, since energy is not conserved in the intermediate state. Unfortunately, the direct AC transition is accompanied by electronic inner bremsstrahlung, and therefore also gives rise to a continuous spectrum of gamma rays. In fact, since the inner bremsstrahlung branch (which we shall call the electronic beta-gamma transition) also leads to the same final states as does the ABC transition there will be coherence and hence interference between the two branches. The electronic beta-gamma branch will usually have a larger amplitude than the nuclear beta-gamma branch in spite of the difference in degrees of forbiddenness of the beta transition involved, since nuclear gamma-ray matrix elements are much smaller than electronic matrix elements for comparable energy and multipolarity. This makes the discrimination of a nuclear beta-gamma transition with respect to the electronic very difficult unless the dependence of the matrix elements on the gamma-ray energy are quite different.

A marked difference in energy dependence is possible in the particular circumstance that the state B is nearly degenerate with the state A, for in this case the ABC transition matrix element contains an energy denominator $(\Delta+E_m-E_\gamma)$, where Δ is the energy difference of the states A and B, E_m is the maximum

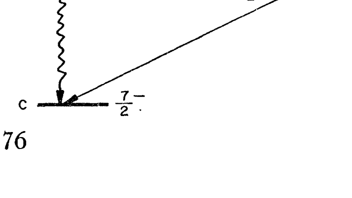

FIG. 1. Typical scheme for a nuclear beta-gamma transition.

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[1] C. L. Longmire, Phys. Rev. **75**, 15 (1949). Longmire considers particularly cases where the beta transition may be absolutely forbidden. In the $V-A$ form of the beta interaction no such absolutely forbidden beta transitions exist.

energy which the gamma ray can have, and E_γ is the energy of the gamma ray. With Δ small compared to E_m this leads to a strong peaking of the matrix element as E_γ approaches E_m, while the electronic beta-gamma process matrix element shows no such peaking. Under these circumstances, one might expect a distortion of the high energy portion of the gamma-ray spectrum from the form to be expected when the nuclear beta-gamma transition is not taken into account.

From the point of view of simplicity of experimental detection and from the contribution of phase space factors to the transition probability, one finds that a K-capture transition has decided advantages over an electron or positron emission decay, if one is to search for the effect under discussion. A search of the table of nuclides has revealed one case in which the desired special conditions are most nearly fulfilled, namely the (8×10^4 yr) K-capture transition in Ni^{59}. The energy level diagram is just that shown in Fig. 1 and the energy difference Δ is approximately 0.03 MeV as compared with a total transition energy (E_m) of 1.06 MeV.[2]

To estimate how large the nuclear beta-gamma transition contribution might be in this particular case, we have calculated the transition probability assuming that this is the only branch for the transition (that is, neglecting the internal bremsstrahlung branch, and hence also the interference between the two branches). We omit the details of the calculation and quote only the result

$$d\lambda_{c\gamma,n}=\frac{\pi\ln 2}{(fT_{1/2})_{AB}}\psi^2(0)\left(\frac{E_m-E_\gamma}{\Delta+E_m-E_\gamma}\right)^2\frac{\Gamma_\gamma E_\gamma^3 dE_\gamma}{(E_m+\Delta)^3}. \quad (1)$$

Here, $d\lambda_{c\gamma,n}$ is the transition probability per unit time for emission of a gamma ray in the energy range E_γ to $E_\gamma+dE_\gamma$, Γ_γ is the gamma-ray width of the level B in Co^{59}, $(fT_{1/2})_{AB}$ is the fT value of the "allowed" beta transition from level A in Ni^{59} to level B in Co^{59}, which of course cannot be measured directly, and $\psi^2(0)$ is the square of the K-electron wave function at the nucleus. All energies are in units of the electron rest energy, lengths are in electron Compton wavelengths $\hbar/mc$, and times are in seconds. On integrating over all gamma-ray energies, the total transition probability per unit time is approximately

$$\lambda_{c\gamma,n}\simeq\frac{\pi\ln 2}{4(fT_{1/2})_{AB}}\psi^2(0)\Gamma_\gamma E_m, \quad (2)$$

where we have neglected Δ in comparison with E_m. To estimate $\lambda_{c\gamma,n}$, we take $\Gamma_\gamma=10^{-9\pm2}mc^2$, $\log_{10}(fT_{1/2})_{AB}=5.3\pm0.7$, $E_m=2mc^2$, $\psi^2(0)=3\times10^{-3}(mc/\hbar)^3$ and find

$$\lambda_{c\gamma,n}\simeq10^{-17\pm2}\ \text{sec}^{-1}.$$

Saraf[3] has measured the gamma-ray spectrum associated with the decay of Ni^{59} and shown that about one decay in one thousand is accompanied by a gamma ray. Since the spectrum has the general shape expected from inner bremsstrahlung, we may estimate that the transition probability per unit time associated with the electronic beta-gamma process to be

$$\lambda_{c\gamma,e}\simeq4\times10^{-16}\ \text{sec}^{-1}.$$

Comparing this with the value obtained above and noting the difference in energy distribution of the gamma rays for the two processes as indicated in Fig. 2, there would appear favorable prospects for experimentally detecting the effects of the nuclear beta-gamma transition if sufficient energy resolution and adequate counting statistics can be achieved at the high-energy end of the spectrum. Of course it should be emphasized that interference effects[4] are not included in this calculation and hence it is not clear whether these make the prospects better or worse.

The experimental detection of a distortion of the gamma-ray spectrum at high energies would be considerably simplified if there were a unique spectral shape for the inner bremsstrahlung spectrum. Unfortunately this is not the case for a forbidden spectrum.

It is of interest to note that Cutkosky[5] has shown that the inner bremsstrahlung accompanying K capture is completely circularly polarized with positive helicity. On the other hand, the gamma arising from the nuclear transition is unpolarized.[6] Consequently, if it were possible to detect only those gamma rays which have negative helicity, these would arise only from the nuclear beta-gamma transition, would be free of interference with inner bremsstrahlung, and would indeed have the spectrum given by Eq. (1) above. In view of the low efficiency of gamma-ray polarization

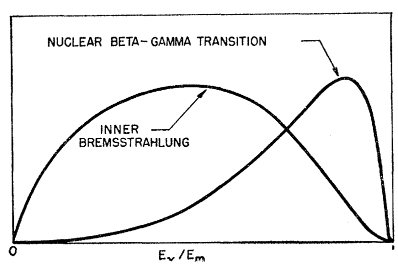

FIG. 2. Typical spectrum of gamma rays expected from the electronic (inner bremsstrahlung) and nuclear beta-gamma transitions separately (without interference terms). The ordinates are on an arbitrary scale and the relative magnitudes of the two curves are not significant. The inner bremsstrahlung curve is that measured by Saraf (reference 3) for Ni^{59}, while the nuclear beta-gamma spectrum is that computed from Eq. (1) with $\Delta/E_m=0.03$.

[2] There is a second possible intermediate state lying slightly above the state B in Co^{59} for which the gamma transition would be $E2$. We have ignored the possible contribution of this state in the analysis which follows, but if the $E2$ matrix element were sufficiently large it might also make a contribution.

[3] B. Saraf, Phys. Rev. **102**, 466 (1956).

[4] Interference effects are currently being calculated by Dr. K. Lassila.

[5] R. E. Cutkosky, Phys. Rev. **107**, 330 (1957).

[6] K. Lassila (private communication.)

analyzers, an experiment of this character would not be easy.

We conclude by noting that we have considered those nuclear beta-gamma processes in which the beta transition precedes the gamma transition. The inverted transition is also possible but such transition matrix elements are not marked by the peaking at high energies in the gamma-ray spectrum in the case of near degeneracy and hence would be much more difficult to detect experimentally. Of course many intermediate states could contribute in principle to a particular transition, but the effect of states distant in energy is relatively small.[7]

[7] On the basis of the results here presented, Dr. M. Schmorak of Brookhaven National Laboratory has undertaken a careful measurement of the gamma-ray spectrum from Ni^{59}. A detailed analysis of his data must await completion of the calculation of the interference terms between the nuclear and electronic beta-gamma processes.

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Decay of At^{212}; the $Bi^{209}(\alpha,n)At^{212}$ Reaction*

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At^{212} was produced by the $Bi^{209}(\alpha,n)At^{212}$ reaction by bombarding Bi^{209} with a beam of 19-MeV helium ions from the Purdue cyclotron. The At^{212} was observed to decay by alpha emission with a half-life of 0.20 ± 0.04 sec. The kinetic energy of the alpha particles emitted in the decay was measured using Au-Si surface-barrier charged particle spectrometers. The alpha-decay energy was found to be 7.87 ± 0.07 MeV. The relative excitation function of the $Bi^{209}(\alpha,n)At^{212}$ reaction was also obtained in the center-of-mass energy range from 17.87 to 18.86 MeV. The hindrance factor for the At^{212} decay is calculated using the experimentally measured At^{212} alpha-decay energy.

INTRODUCTION

Many reactions involving bismuth as the target nucleus have been studied. In particular, the $(\alpha,2n)$ and $(\alpha,3n)$ reactions on bismuth were studied by Kelly and Segrè.[1] The thresholds for the $(\alpha,2n)$ and $(\alpha,3n)$ reactions are at about 20 and 30 MeV, respectively. The At^{211} and At^{210} nuclei formed from the above reactions have half-lives of 7.2 and 8.3 h, respectively.[1,2] The (α,n) reaction on Bi^{209} is more difficult to observe due to its short half-life (0.2 sec) and low cross section.

The decay of At^{212} is interesting in that it crosses a closed neutron shell ($N=126$). This hinders the decay and gives rise to a half-life which is considerably longer than would be predicted on the basis of the observed alpha-decay energy. The alpha-decay energy can be estimated from the following data: electron capture decay energy of $At^{212}\sim1.8$ MeV, alpha decay energy of $Po^{212}=8.949$ MeV, and electron capture decay energy of $Bi^{212}\sim2.75\pm\sim0.15$ MeV.[2] These values give an At^{212} alpha-decay energy of ~8.0 MeV. Using this value in the energy-lifetime relation, a hindrance factor (λ_{ee}/λ; where λ_{ee} is the partial-decay constant expected for ground-state transitions in even-even nuclei and λ is the measured partial-decay constant) of ~2200 is obtained. This is an unusually large hindrance factor and it was suggested[2] that either the estimated decay energy of At^{212} was too large or the $\frac{1}{4}$ sec half-life which had been previously measured was not the ground-state alpha decay of At^{212}.

Two half-life measurements of At^{212} had been made previously. In the unpublished work of Weissbluth, Putnam, and Segrè[3] the half-life was measured as 0.25 sec. Winn[4] obtained a half-life of 0.22 ± 0.03 sec for the At^{212} decay using a ZnS screen mounted on a 4-ft light pipe. No measurement of the alpha energy was made.

During the course of the present measurements, an alpha-decay energy for At^{212} of 7.61 MeV was reported by Griffioen and Macfarlane.[5]

In the present experiments, Au–Si surface-barrier charged particle counters were used as detectors and energy spectrometers for the alpha particles emitted in the decay of At^{212}. Solid-state counters were selected because they offer excellent energy resolution for alpha particles, and because with appropriate selection of the silicon resistivity and the reverse-bias applied, their response to β-, γ-, and x-ray backgrounds can be made so low that heavy particles can be detected with almost zero background even in very high background fluxes. This low sensitivity to β, γ, and x rays was necessary

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[1] E. L. Kelly and E. Segrè, Phys. Rev. **75**, 999 (1949).

[2] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

[3] M. Weissbluth, T. M. Putman, and E. Segrè (unpublished). Reported by D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

[4] M. M. Winn, Proc. Phys. Soc. (London) **A67**, 949 (1954).

[5] R. G. Griffioen and R. D. Macfarlane, University of California Radiation Laboratory Report UCRL–10023, 1962 (unpublished).