Gamma-Ray Emission from Compound Nucleus Reactions of Helium and Carbon Ions*

JAMES F. MOLLENAUER†
Lawrence Radiation Laboratory, University of California, Berkeley, California and Chemistry Department, Brookhaven National Laboratory, Upton, New York

(Received February 8, 1962)

The assumption that gamma emission does not occur in compound nucleus reactions until the excitation energy falls below the particle emission threshold was tested by direct observation of the gamma rays. Bombardments of Ba, Ho, Co, and Ta targets were carried out with helium ions; Te and V were bombarded with C^{12} ions. For the carbon ion reactions, in which the average angular momentum induced by the projectile ranged from $17\hbar$ to $38\hbar$, the total energy release in gamma rays exceeded the neutron binding energy, in contradiction to the assumption. This was not so for any alpha-particle reaction. A comparison of the gamma yields for the same compound nucleus, as produced by alpha particles and carbon ions at the same excitation energy, indicates that the enhancement is an angular momentum effect, independent of excitation energy.

The magnitude of the gamma yield enhancement is in agreement with observed displacements of heavy ion excitation functions to higher bombarding energy.

The gamma yield was measured at 45° and 90° to the beam direction. Both the helium ion bombardments at 45 MeV and carbon ions incident on V^{51} at comparable energy produced large anisotropies in the gamma-ray emission, with maxima in the direction required by quadrupole transitions. The photon emission was more nearly isotropic for alpha bombardments at 28 MeV and for C^{12} on Te at 115 MeV. The average photon energy ranged from 1.0 to 1.6 MeV.

These observations are consistent with gamma emission in collective transitions and are inconsistent with a statistical model of the deexcitation process, which predicts dipole emission, small anisotropy, and an average gamma energy twice that observed. The lack of quadrupole anisotropy for the Te target may result from a high-spin limit to the collective motion. The energy spectra suggest that the collective transitions may be vibrational, with rotational transitions occurring mainly in nuclei deformed in the ground state. Except for compound nuclei of $A\sim 60$, good agreement was obtained between the observed anisotropy and a model based on a gamma cascade through levels of specified rather than randomly chosen spin.

I. INTRODUCTION

In the study of compound nucleus reactions, it has generally been assumed that if an excited nucleus can emit a nucleon, it will. Above the neutron emission threshold, the probability of de-excitation by the emission of gamma rays has usually been considered negligible. The object of this experiment was to examine this assumption experimentally by the direct observation of gamma-ray yields in several reactions differing in the angular momentum induced by the bombarding particle.

An indication that a considerable amount of energy is released as gamma rays from high angular momentum compound nuclei is found in the measurement of excitation functions. In cases where the induced angular momentum is small (i.e., with helium ions or lighter projectiles) observed excitation functions may be fit by calculations neglecting gamma emission.[1] However, in bombardments with heavy ions, where the induced angular momenta average 40 $\hbar$ or more, the excitation functions have been observed shifted upward in energy by as much as 23 MeV.[2,3] Even at low angular momenta, the recent calculations of Grover fit the observed excitation functions better when gamma emission is included above the neutron threshold.[4] The angular distribution of recoil nuclei in the carbon ion bombardment of tellurium has been measured by Morton.[5] He attempted to fit the results to the Jackson evaporation model.[1] In order to do so with a reasonable temperature parameter it was necessary to assume that extra energy was carried off by photons, amounting to 10 MeV at an excitation of 80 MeV.

One may expect high angular momentum to cause an increase in the gamma emission on the following qualitative grounds: Because their binding energy is considerably greater than their average kinetic energy, the emitted neutrons carry off most of the excitation but relatively little of the original angular momentum. As the excitation energy is thus reduced, the number of final states available with sufficiently high spin must become quite small.[6] Consequently, the neutron emission must be slowed considerably while the energy is still above the threshold. If it is slowed enough, photon emission may begin to compete favorably. The gamma rays have no binding energy and, compared to neutrons, may go to final states of higher energy where the level density is higher.

Alternatively, one may visualize a heavy ion initiating collective motion in the target nucleus as it is "swallowed whole" to form a compound nucleus. Compared to excitated states of the same energy without collective motion, such states might be more likely to de-excite by photon emission.

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

† National Science Foundation Predoctoral Fellow 1958–1960; present address: Chemistry Department, Brookhaven National Laboratory, Upton, N. Y.

[1] J. P. Jackson, Can. J. Phys. **34**, 767 (1956).
[2] G. Choppin, Research in Nuclear Chemistry Progress Report, June 1, 1959 to May 31, 1960, Florida State University, Tallahassee (unpublished).
[3] A. S. Karamyan, Y. B. Gerlit, and B. F. Myasoedov, Soviet Phys.—JETP **9**, 431 (1959).
[4] J. R. Grover, Phys. Rev. **123**, 267 (1961).
[5] J. R. Morton, University of California Lawrence Radiation Laboratory Report UCRL-9595, 1961 (unpublished).
[6] T. Ericson, Suppl. Phil. Mag. **9**, 425 (1960).

The existence of a photon yield enhancement from reactions showing an excitation function displacement was verified by comparison of the gamma ray yields under varying angular momentum conditions. Targets were chosen in pairs providing the same compound nucleus when bombarded with heavy ions and alpha particles, respectively; Te and Ba (natural material) going to Ce, and V^{51} and Co^{59} yielding Cu^{63}. In the latter case the Coulomb barrier for the heavy ions was low enough that the same excitation energy could be produced in both targets of the pair, thus separating energy and angular momentum effects. Holmium-165 and Ta^{181} were also bombarded as examples of deformed nuclei. For most targets the gamma spectra were observed at angles of 45° and 90° to the beam, in order to determine the anisotropy of the radiation.

Evidence in the form of the observed anisotropies and energy distributions of the emitted radiation may be used to differentiate between statistical and collective mechanisms. The angular correlations of the gamma radiation are commonly used in studying the properties of discrete low-lying levels. When a statistical number of initial states is populated, such correlations may also provide an average measure of the multipolarity of the de-excitation transitions. The anisotropy of the radiation is sufficient to distinguish quadrupole and dipole transitions: quadrupole radiation is more intense at 45° to the beam direction than at 90°; the reverse is true of the radiation from dipole transitions. The magnitude of the calculated anisotropy depends on the model chosen, and will be discussed in Sec. IV.

The gamma transitions, according to a Fermi gas model for the excited nucleus, should have an average energy of 2 to 3 MeV and dipole multipolarity.[7] This prediction agrees with observations of the photons accompanying thermal neutron capture.[8] On the other hand, quadrupole transitions are expected between collective states.[9] In this case one should expect the radiation characteristic of rotational or vibrational transitions, provided second-order effects introduced by the high spin are not too great. The effect of rotations of the compound nucleus in enhancing the gamma emission has been discussed by Pik-Pichak.[10]

It should be emphasized that discussions of the processes involved in the gamma de-excitation must be rather speculative at present. The data available are sufficient to determine the anisotropy but not the complete angular distribution of the emitted photons. Both the correction of the observed spectra for the crystal response and the calculation of the anisotropy in effect involve taking differences, and thus the statistics with respect to the details of the spectra are not good. Large-scale effects are apparent, however, and it appears possible to draw a number of consistent, if not definitive, conclusions about the gamma emission process. Whether gamma emission may precede a part of the neutron emission still remains an unanswered question. In further work, neutron-gamma angular correlations may be of value in providing the answer.

II. EXPERIMENTAL PROCEDURES

A. Equipment

The experiment was performed at the Lawrence Radiation Laboratory using the Crocker 60-in. cyclotron for the alpha bombardments and the Heavy Ion Linear Accelerator (Hilac) for the carbon ion bombardments.

The chief experimental difficulty in the observation of gamma rays produced in the target lay in the high radiation background at the accelerators. This background was essentially eliminated by the use of a fast-slow coincidence system to record only those gamma-ray counts in coincidence with the removal of a charged particle from the beam. A somewhat similar system had been used by Gooding in the measurement of total reaction cross sections.[11]

The beam passed through two thin plastic scintillators, through the target, and into a plastic scintillator thick enough to stop it. The coincidence circuit selected events in which a charged particle appeared in the first two scintillators, but not in the third. In addition, a fast coincidence with a gamma ray in the 3-in. NaI(Tl) crystal was required. When these conditions were met, a trigger signal to the slow circuit admitted the gamma-ray pulse to the Penco 100-channel analyzer. The arrangement of the target and scintillators is indicated schematically in Fig. 1.[12] A lead collimator was placed in front of the crystal to reduce the large backscatter

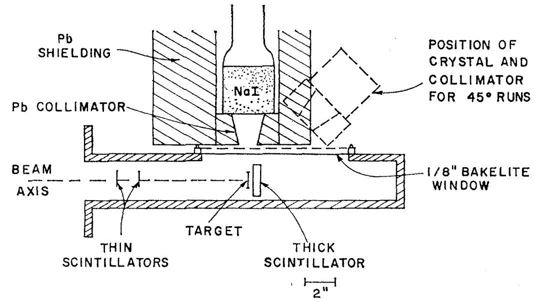

FIG. 1. Arrangement of target, coincidence-anticoincidence scintillators and gamma detector.

[7] V. M. Strutinsky, L. V. Groshev, and M. K. Akimova, Nuclear Phys. **16**, 657 (1960).

[8] L. V. Groshev, V. N. Lutsenko, A. M. Demidov, and V. I. Pelekhov, *Atlas of Gamma-Ray Spectra from Radiative Capture of Thermal Neutrons*, translation from Russian by J. B. Sykes (Pergamon Press, New York, 1959).

[9] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winter, Revs. Modern Phys. **28**, 432 (1956).

[10] G. A. Pik-Pichak, Soviet Phys.—JETP **11**, 557 (1959).

[11] T. J. Gooding, thesis, University of Minnesota, 1958 (unpublished).

[12] For additional details, see also J. F. Mollenauer, University of California Lawrence Radiation Laboratory Report UCRL-9724, 1961 (unpublished).

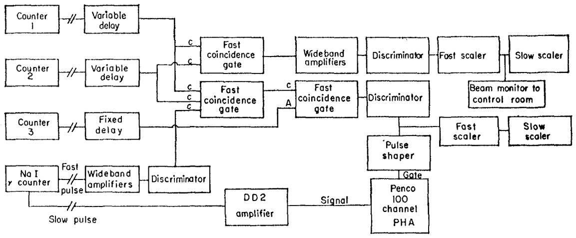

FIG. 2. Block diagram of the electronic circuit. The plastic scintillators are numbered in the order in which the beam passes through them.

peak caused by the proximity of the shield to the crystal.

Natural target materials were used since relatively thick targets were required to provide a sufficient gamma count rate. All were rolled metal, except for Te, which was evaporated on a 6-μ Mylar backing. Their thicknesses in mg/cm^2 were: Ba, 42.6±1.0; Co^{59}, 46.6±0.4; Ta^{181}, 109±4; V^{51}, 14.3±0.2; Ho^{165}, 40.57±0.06 for alpha bombardments and 14.06±0.02 for C^{12} bombardment; Te, 7.05±0.07 and 6.99±0.07 for the two targets used.

A block diagram of the electronic circuit is shown in Fig. 2. Pulses from the two thin scintillators were fed to two coincidence circuits in parallel. One served as beam monitor; in the other, the fast signal from the NaI crystal was also required to be in coincidence. The output was sent to a similar unit where the pulses from the stopping counter were placed in anticoincidence. After amplification and shaping, the resulting signal gated the pulse height analyzer.

Repetition rates of 1.3×10^5 particles per second at the cyclotron and 5×10^5 per second (peak) at the Hilac were found feasible. However, at the Hilac the 3% duty cycle resulted in a considerably lower average beam rate. Fourteen-stage type 6810A photomultipliers were used with the plastic scintillators, providing output pulses of 8V or better. Shunting of the voltage divider string by the internal current at these high repetition rates was prevented by supplying the voltage to each of the last six dynodes separately through cathode followers.

B. Validity of the Experimental Procedures

Confidence in an experimental technique is substantially strengthened by the reproduction of known measurement. However, gamma spectra from few charged particle reactions have been observed, most of the available reaction gamma spectra coming from neutron-capture studies.[13] No measurement suitable as a check has been done with alpha particles, and the use of protons was not feasible because the cyclotron accelerates them as H_2^+ ions. If one proton of the H_2^+ pair reacted with a target nucleus, the other would enter the anticoincidence scintillator and nullify the gamma ray observation. If a scattered beam had been used to avoid this problem, the gamma background would have been prohibitive. For heavy ions, several spectra have appeared in the literature, but the experimental conditions under which they were obtained do not provide confidence in the quantitative results.[14]

Consequently, the spectrum of gamma rays from the fission of Cf^{252} was used as a check. Coincidence was required between a gamma ray in the NaI crystal and a fission fragment in the stopping scintillator. This arrangement provided the closest available approximation to the data-taking circuit. After analysis of the spectrum to compensate for the nonlinearity of the detector response (this procedure will be described in Sec. II D), the results were compared with those of Smith, Fields, and Friedman.[15] The published value of the average gamma energy was 0.80 MeV, while in this check 0.78 MeV was obtained; both spectra peaked at about 0.3 MeV. Statistically significant differences were found only in the vicinity of 4 MeV, where the yield of reaction gamma rays was quite small in any case.

The validity of comparisons made with data from two different accelerators was checked by using helium ions at the Hilac. As the beam energy of 40 MeV was not identical with that of the cyclotron, the cobalt target was chosen because its gamma yield varied least with beam energy. Comparison of this spectrum with one from 48 MeV alpha particles at the cyclotron in Fig. 3

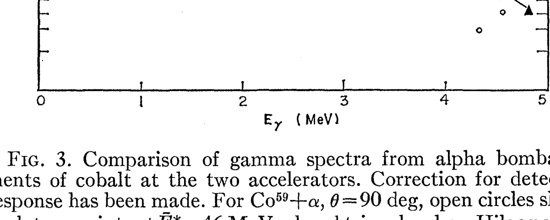

FIG. 3. Comparison of gamma spectra from alpha bombardments of cobalt at the two accelerators. Correction for detector response has been made. For $Co^{59}+\alpha$, $\theta=90$ deg, open circles show cyclotron points at $\bar{E}^*=46$ MeV; closed triangles show Hilac points at $\bar{E}^*=39$ MeV.

[13] E. Pollard and D. E. Alburger, Phys. Rev. **72**, 1196 (1947); W. F. Hornyak and T. Coor, *ibid.* **99**, 675 (1953); J. Seed and A. P. French, *ibid.* **88**, 1007 (1952); J. F. Streib, W. A. Fowler, and C. C. Lauritsen, *ibid*, **59**, 253 (1941); R. B. Day and R. L. Walker, *ibid.* **85**, 582 (1952); R. S. Foote and H. W. Koch, Rev. Sci. Instr. **25**, 746 (1954); H. E. Kubitschek and S. M. Dancoff, Phys. Rev. **76**, 531 (1949).

[14] V. A. Karnaukhov and Yu. C. Oganesyan, Soviet Phys.—JETP **11**, 964 (1960); Yu. B. Lobanov and Yu. C. Oganesyan, Joint Institute for Nuclear Research, Dubna, Report R-734, 1961 (unpublished).

[15] A. B. Smith, P. R. Fields, and A. M. Friedman, Phys. Rev. **104**, 699 (1956).

indicates a negligible difference; therefore, data from the two accelerators can be compared with confidence.

The reproducibility of the spectra was checked in several ways. The data were recorded for two gamma energy ranges, 0.04 to 1.04 MeV and 0.2 to 5.2 MeV. Agreement was required between the two where they overlapped. The number of triggers to the analyzer for a given number of beam particles was never found to differ between runs by more than 6%. Duplicate spectra made before and after the installation of the lead gamma collimator were in agreement. Most of the spectra were recorded several times with the collimator present.

The runs with the Te target at the Hilac were repeated under a variety of experimental conditions. For one run, data were taken using only one counter preceding the target. On another occasion, a stopping scintillator just thick enough to stop the carbon ions was used to discriminate better against charged reaction products. On a third, the brass target holder was rotated 35° to prevent attenuation of low energy photons by the frame. In all cases, the results agreed within statistical errors.

There was no observed variation of the gamma yield with beam intensity. The runs without the gamma collimator were often done with 30% higher beam intensity, yet the spectra were in agreement with the later ones. To warn of beam fluctuations, the monitor signal was displayed on a strip chart recorder and on an oscilloscope. The oscilloscope indicated short term bunching of the beam by the presence of more than one trace. Short term bunching produced a danger of overloading the coincidence and scaling circuits and also increased the probability of two particles appearing in the same rf cycle. At either accelerator the beam emerged over a small fraction of the cycle, such that there was no chance of resolving more than one particle per cycle. (The rf frequencies were 12 Mc/sec at the cyclotron and 70 Mc/sec at the Hilac.) In practice, once the accelerators had warmed up and were properly tuned, fluctuations and bunching did not recur. Data were not taken until the beam had become steady.

The discriminator levels used were such that the stopping counter was not sensitive to neutrons evaporated from the target. Test pulses caused by 12-MeV protons were not sufficiently large to cause anticoincidence, indicating that neither knock-on protons from the neutrons nor evaporated protons were mistaken for beam particles. Protons with an energy above 12 MeV might conceivably have registered but should have been in small yield even from direct events.

The yield of gamma rays in coincidence with direct alpha particles from the breakup of C^{12} projectiles was shown to be negligible by comparison of spectra obtained with different thicknesses of stopping scintillator. One was about 1 cm thick and provided anticoincidence pulses for alpha particles over 15 MeV, while the other was just thick enough (0.6 mm) to stop the C^{12} beam and did not count alphas of any energy. The spectra obtained for C^{12} on Te in the two cases were identical within statistics. Reactions accompanied by heavier direct particles, such as Be^8 or C^{11}, should have been rejected by anticoincidence pulses in either case. This result also indicates that photons in coincidence with evaporated alpha particles, which would be expected to cause differences between the two spectra, were in small yield.

Photons coincident with inelastic scattering were virtually eliminated by the large solid angle subtended by the stopping scintillator. Only the small fraction of scattered particles which was deflected by more than ~75° missed the stopping counter and permitted the coincidence gates to open.

C. Extraneous Gamma Rays

Despite the use of the anticoincidence with the third counter, there remained several sources of extraneous gamma rays. One source was reactions in the beam stopping counter, another was accidental coincidences, and a third was the response of the NaI counter to evaporated neutrons. Of these, the first source was eliminated and the second reduced by alternating runs with the target in and out and taking the difference.

Neutrons produced in the target, however, formed a background which was present only when the target was in the beam and which could not be subtracted directly. The flux of neutrons through the NaI crystal could not be calculated reliably because of the indeterminate effect of the shield in scattering them into the crystal. Low-energy neutrons and those scattered through an indirect path to the crystal were discriminated against by the fast time coincidence, operated at a resolving time of 30 nsec on the gamma channel. Thus, pulses from inelastic scattering of neutrons below 1 MeV in energy occurred out of coincidence.

As an upper limit for the neutron-produced gamma counts, one may ignore the time discrimination and use the cross sections given by Howerton[16] for the inelastic scattering of 2.5-MeV neutrons in Na and I. The inelastic cross sections are large enough to be significant although the radiative capture cross sections are small. A calculation indicated that 25% of the incident neutrons should interact with the crystal. A better correction for neutron effects can be obtained by examining the raw data for the peaks known to be caused by neutrons incident on a NaI crystal. Several authors have published such spectra.[17] These spectra show peaks at 210, 410, and 632 keV, with a low intensity continuum at higher gamma energies. Examination of the

[16] R. J. Howerton, University of California Radiation Laboratory Report UCRL-5226, 1958 (unpublished).

[17] R. B. Day, Phys. Rev. **102**, 767 (1956); J. J. Van Loef and D. A. Lind, *ibid.* **101**, 103 (1956); V. I. Strizhak, J. Exptl. Theoret. Phys. (USSR) **31**, 907 (1956); R. Kiehn and C. Goodman, Phys. Rev. **93**, 177 (1954); M. Rothmann and C. E. Mandeville, *ibid.* **93**, 796 (1954); M. A. Grace, H. R. Lemmer, and H. Halban, Proc. Phys. Soc. (London) **A65**, 456 (1952).

data showed no such peaks, though they could have been masked slightly by the backscatter peak in the vicinity of 200 keV and by statistical fluctuations elsewhere. Certainly the total contribution of neutron events to the gamma spectra was less than 10%.

D. Correction for Gamma Detector Response

The continuous nature of the observed gamma spectra made it impossible to resolve photopeaks by inspection. The nonunique response of the NaI crystal requires a rather extensive analysis in order to correct for the contribution of Compton and other nonlinear processes to a continuous spectrum. In analyzing such spectra, matrix methods are necessary.

The procedure used in analyzing the spectra is described in detail elsewhere,[18] but it may be outlined as follows: The detector was calibrated with standard gamma sources located in the target holder. Parameters dependent on gamma energy and pulse height were fit empirically to the various components of the calibration spectra, such as the photopeak and Compton distribution. Using the parameters, a matrix was derived to represent the response of the detector at equal increments of gamma energy and pulse height. The observed crystal response to the 2.75-MeV gamma ray of Na^{24} is compared with the appropriate row of the calculated matrix in Fig. 4.

Theoretically, multiplication of the inverse of this matrix by a vector representing the observed pulse-height distribution should reproduce the incident gamma energy spectrum. In practice, large fluctuations were observed in the calculated incident spectrum due to statistical and systematic uncertainties in both the matrix and the observed spectrum. Accordingly, a successive approximation method developed by Scofield was used and found to work quite satisfactorily.[19] The generation of the response matrix and its application in correcting the observed spectra were performed on an IBM 704 computer. The computer program also corrected the experimental spectra for small shifts in amplifier gain when necessary.

Application of the program to a spectrum of five sources of known intensity between 0.60 and 2.75 MeV yielded results uniformly between 5 and 10% high, an accuracy which was considered satisfactory. This could undoubtedly be improved by a more careful fitting of parameters to the calibration spectra.

III. EXPERIMENTAL RESULTS

A. Calculation of Cross Sections and Angular Momenta

The total capture cross sections for both the alpha and the carbon ion bombardments were calculated with

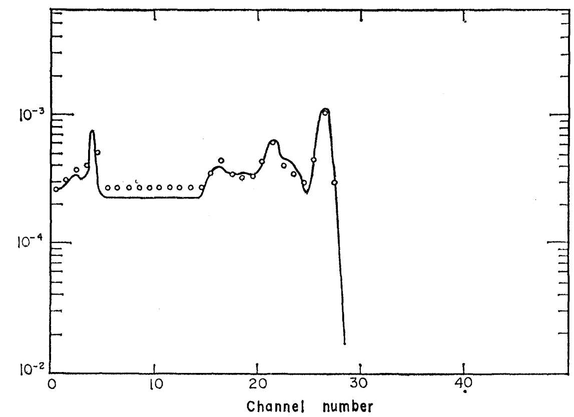

FIG. 4. Comparison of the experimental spectrum of the 2.75-MeV gamma ray of Na^{24} with the appropriate row of the 50-channel response matrix. The spectrum of the 1.38-MeV gamma ray in Na^{24} has been subtracted from the experimental spectrum shown. The open circles are calculated values with $\bar{E}=2.75$ MeV, and the solid curve is the observed spectrum.

Thomas' diffuse-edge program for the IBM 650 computer.[20] Very good agreement with optical model calculations of Huizenga and Igo was found using a radius of 1.61 F for the alpha particle.[21] The cross section σ and average angular momentum $\bar{l}$, as given in Table I, were found for the average energy of the beam in the target for all cases except C^{12} on V^{51} at reduced energy. For the thicker vanadium target, weighted averages were taken over ten energy intervals.

It was necessary to assume that the calculated total cross section approximated the compound nucleus cross section. This assumption is questionable for the heavy ions at high energies. For example, Britt and Quinton found nearly 1 b for the direct alpha production cross section for 125-MeV carbon ions on gold.[22] However, the direct cross section falls rapidly with energy; for oxygen on bismuth it fell by 50% when the beam energy was reduced to 105 MeV. In the present experiment, direct reactions should have been negligible in the alpha and the lower energy carbon ion bombardments.

The diversion of a part of the cross section into direct processes in the full energy carbon cases has several results: most important, since the anticoincidence system rejected gamma rays in coincidence with heavy charged particles in the third counter, the number of gammas recorded corresponds to a smaller number of reactions than calculated. Also, the greater probability of direct processes in high angular momentum collisions reduces the average angular momentum of the compound nuclei which are formed. Any direct particles which miss the stopping counter have deposited less than full excitation energy in the target. All these effects tend to minimize the correlation between angular momentum and gamma-ray yield. Using the calculated

[18] J. F. Mollenauer, Lawrence Radiation Laboratory Report UCRL-9748, 1961 (unpublished).
[19] N. E. Scofield, U. S. Naval Radiological Defense Laboratory Report USNRDL-TR 447, 1960 (unpublished).
[20] T. D. Thomas, Phys. Rev. **116**, 703 (1959).
[21] J. R. Huizenga and G. J. Igo, Argonne National Laboratory Report ANL-6373, 1961 (unpublished).
[22] H. C. Britt and A. R. Quinton, Phys. Rev. **124**, 877 (1961).

TABLE I. Photon yields per reaction n_γ, based on calculated cross sections.

Target	Beam	Laboratory energy range in target (MeV)	Average excitation energy $\bar{E}^*$ (MeV)	σ_{calc} (barns)	l_{calc}	n_γ uncorr	n_γ corr	$\bar{E}_\gamma$ (MeV)	Total gamma energy (MeV)
Ba	α	45−41.7	42	1.84	13.8	6.2	5.4	1.2	6.5
	α	28.4−24.9	26	1.27	9.0	5.6	4.9	1.3	6.4
Ho	α	45−42	42	1.81	13.9	7.1	6.2	1.1	6.8
	α	28.4−25.5	26	1.11	8.1	6.7[a]	5.8[a]	1.1	6.4[a]
	C^{12}	115−103.5	90	1.76	36	14.8	14.1	1.2	17.0
Ta	α	45−37	38	1.72	13.2	5.4	4.7	1.0	4.7
Co	α	45−41	46	1.61	12.3	4.0	3.4	1.5	5.2
	α	28.4−24.4	30	1.45	9.4	4.1	3.5	1.4	5.0
	α	37−33	39	1.57	11.0	2.9[a,b]	2.5[a]	1.6	4.0[a]
Te	C^{12}	111−107	99	2.00	38	11.8	11.1	1.1	12.2
V	C^{12}	115−102	101	1.72	31	8.5	7.9	1.5	11.8
	C^{12}	58−26	49	0.91	16.5	6.8	6.3	1.5	9.4

[a] No data were taken at 45 deg; the value given is that for 90 deg, assuming isotropic distribution.
[b] Assuming the angular distribution of the 46-MeV run, $n_\gamma = 3.7$ (uncorrected).

parameters, the observed angular momentum dependence of photon production must be a lower limit. This limit should be a close one at lower bombarding energies where direct reactions are less common, but at full Hilac energy the difference between the actual and calculated numbers of compound nucleus reactions may be quite significant.

The best available estimate of the total compound nucleus cross section comes from Choppin's preliminary data on individual reactions for Te^{128}.[23] Upper limits for the (C^{12},$p4n$), (C^{12},$\alpha 3n+p5n$), (C^{12},$\alpha n+p3n$), (C^{12},$6n$), and (C^{12},$8n$) cross sections were combined with consistent estimates for unobserved reactions such as (C^{12},$7n$) to yield a total at 110 MeV (lab) barely equal to 1 b. Though crude, this estimate shows that the calculated cross section used (2.00 b) is too high.

By the same token, the calculated spin of the compound state is too high, if we assume that the direct reactions occur preferentially in high-angular-momentum surface interactions. The average induced angular momentum in compound nucleus reactions may well be closer to 20 or 25 units than to 35 or 40.

The angular momentum carried off by evaporated neutrons has been calculated by Pik-Pichak.[10] At a temperature of 4 MeV, it is $\frac{1}{3}\hbar$ per neutron, while at 1 MeV it is $\frac{2}{3}\hbar$. The level density decrease with increasing spin is not so sharp at the higher temperature; hence the transition is less constrained to go to a lower spin state.

B. Total Gamma Yields

The average gamma-ray yields per reaction as computed from these spectra are found in Table I. The total gamma energies listed are based on a corrected number of photons per reaction n_γ. The correction made for neutron effects in the crystal and for the slightly high result found in testing the unfolding program is 15% for the alpha bombardments and 10% in the carbon ion reactions where the ratio of photons to neutrons should be higher. A coincidence summing correction to the number of gammas was also made. With an average absolute efficiency of E, the correction added to n_γ is $En_\gamma(n_\gamma-1)$ assuming isotropic emission. The value of E was about 1% at 90 deg and 0.5% at 45 deg. These corrections are rather arbitrary, but they should serve to correct the data in the right direction.

The spectra of the emitted gamma rays are provided in Figs. 5–10, as corrected for crystal response and geometry. Details will be discussed subsequently.

If the angular distribution of the radiation contains no higher order terms than $\cos^2\theta$, the average yield is equal to that measured at $\theta=55°$, while if there are significant $\cos^4\theta$ terms, the angle is closer to 50°. The measurement made at 45° should provide a good approximation to the average yield. For photons, the center-of-mass and laboratory angles are essentially identical.

It is immediately evident that the heavy-ion bombardments yield a total photon energy in excess of the neutron binding energy in every case observed. This result is contrary to the usual assumption that in the decay of the compound nucleus, neutron evaporation predominates whenever energetically permitted.

C. Agreement with Other Experiments

These results agree well with the observed displacements in excitation functions, indicating that most of these shifts can be attributed to enhanced gamma emission. For V^{51}, the shift found for the (C^{12},$2n$) reaction is 7 or 8 MeV.[3] If some of this shift is due to the proximity of the Coulomb barrier, it is consistent with the observed 9 MeV of gamma rays, about 4 MeV more than would be expected without angular momentum effects. The calculated cross section should be fairly accurate at this low bombarding energy, where direct reactions are not important. The yield of 11.8 MeV of

[23] G. Choppin, Florida State University (private communication).

photons at 101 MeV is reasonbly consistent with Pik-Pichak's prediction of an 8-MeV excess at 80 MeV.[10]

However, the observed yield of 12.2 MeV for Te is not sufficient to account for Choppin's observed shifts. At comparable bombarding energies, the displacement was 23 MeV with respect to Jackson-model calculations using a temperature of 2 MeV. But if one uses the previous estimate that the compound nucleus cross section is half that calculated, the gamma yield becomes 24 MeV, in good agreement with the excitation function displacement.

This corrected yield is consistent with Morton's results obtained by the very different method of recoil angular distributions.[5] While his calculations were carried out for temperatures of 1.5 and 2.5 MeV, 2 MeV is more consistent with Broeck's neutron evaporation spectra.[24] Interpolating in temperature and extrapolating in energy from 87.5 to 100 MeV, one finds the excess-gamma-energy parameter E_γ to be 16 MeV, implying a total yield of about 21 MeV.

The gamma yields found in this experiment are also consistent with the qualitative results of Karnaukhov and Oganesyan for 78-MeV C^{12} ions on tin.[14] By observing the change in pileup in the gamma spectrum as the geometry was varied, these authors estimated that the number of photons emitted was greater than ten.

An exception to the observation of shifts has been seen by Alexander[25] in the reaction $Pr^{141}(C^{12},4n)Tb^{149}$. Morton was able to fit recoil data for this reaction with $E_\gamma=0$. It was not possible to observe the total gamma yield for this reaction as the peak cross section is only 4% of the calculated total, most of the compound nuclei proceeding to even-Z products in which an excitation function shift has been observed. The high spin compound nuclei may well go to the 4-min isomer

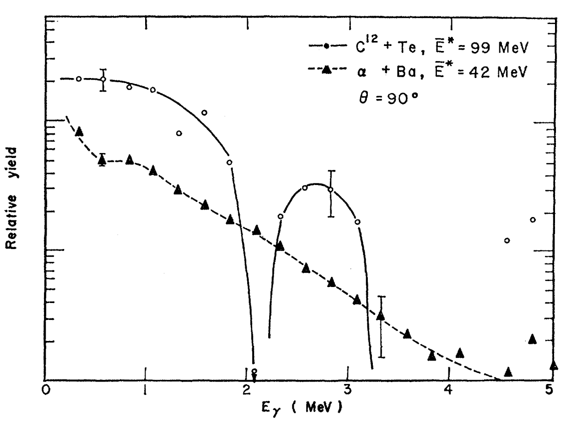

FIG. 5. Gamma spectra from reactions yielding a Ce compound nucleus. The curve with open circles shows Te+Ce^{12}, $\bar{E}^*=99$ MeV, $\theta=90$ deg; with closed triangles, Ba+α, $\bar{E}^*=42$ MeV, $\theta=90$ deg.

[24] H. W. Broeck, Phys. Rev. **124**, 233 (1961).

[25] J. Alexander, Lawrence Radiation Laboratory (unpublished data).

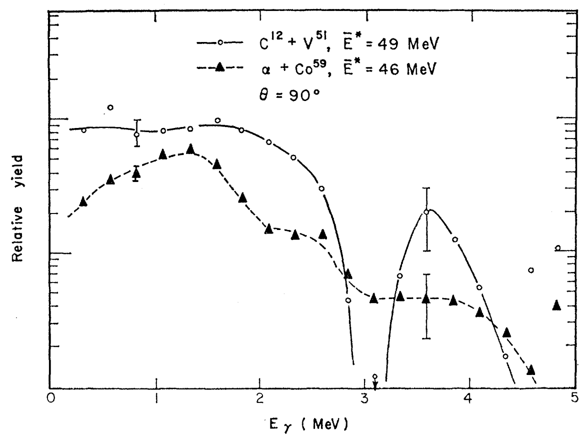

FIG. 6. Gamma spectra from reactions involving a Cu^{63} compound nucleus. The curve with open circles shows V^{51} at $\bar{E}^*=49$ MeV, $\theta=90$ deg; with closed triangles, Co^{59} at $\bar{E}^*=46$ MeV, $\theta=90$ deg.

of Tb^{149}, found recently by MacFarlane, for which there is an excitation function shift of about 20 MeV.[26]

D. Angular Momentum Dependence of the Yield

The reactions of C^{12} and He^4 ions going to Ce show a large difference of gamma yield, but the Coulomb barrier prevents obtaining equal excitation energies in the two cases. However, the pair of reactions producing the Cu^{63} compound nucleus does demonstrate that a change only in angular momentum is sufficient to enhance the gamma-ray yield. The gamma yield in the heavy ion bombardment is more than twice as great with an average spin increase of 50%, or mean square increase of 90%, assuming three units carried off by neutrons before gamma emission. As illustrated in Figs. 5 and 6, the increase appears at all gamma energies up to 3 MeV. The apparent peak near 5 MeV in various spectra is an end effect; it did not appear in spectra covering a larger energy range.

The considerable energy spread in the vanadium target should not be a cause of the greater photon production yield. At twice the excitation energy ($\bar{E}^*=101$ MeV) the yield is increased only 20%. Though the greater cross section for direct reactions at the higher energy makes this increase a lower limit, the chance is slight that the enhancement comes from reactions at the upper end of the energy distribution in the target.

However, the assumption that the compound nucleus "forgets" its mode of formation may be questionable for a heavy projectile. It seems reasonable that an impinging heavy ion consisting of many nucleons should be more effective in inducing collective motions than a proton or an alpha particle. In this sense a second factor may differ in the two ways of making the Cu^{63} compound nucleus. As will be discussed in Sec. IV, there is

[26] R. MacFarlane, Phys. Rev. **126**, 274 (1962).

TABLE II. Comparison of gamma yields at 90° and 45° (data in parentheses may be less reliable than the rest).

Target	Beam	$\bar{E}^*$ (MeV)	$\bar{l}_{calc}$	J_c	$W(90°)$ (sr^{-1})	$W(45°)$ (sr^{-1})	Anisotropy a
Ba	α	42	13.8	10	0.30	0.43	1.43±0.14
	α	26	9.0		(0.38)	0.39	1.03±0.10
Ho	α	42	13.9	10	0.34	0.49	1.44±0.14
	α	26	8.1		(0.47)	···	···
	C^{12}	90	36		···	1.12	···
Ta	α	38	13.2	12	0.24	0.37	1.54±0.15
Co	α	46	12.3	7	0.21	0.27	1.29±0.13
	α	31	9.4		(0.28)	0.28	1.0 ±0.1
	α	39	11.0		0.27	···	···
Te	C^{12}	99	38	10	1.09	0.88	0.81±0.12
V	C^{12}	101	31	7	···	0.63	···
	C^{12}	49	16.5		0.42	0.49	1.17±0.18

evidence for collective gamma transitions, but to about the same extent in both cases; hence, differences in this respect should be a minor factor in the enhancement.

E. Determination of the Multipolarity

A distinction between dipole and quadrupole transitions may be made experimentally in terms of the anisotropy of the radiation. We may neglect higher multipole transitions as major contributors to the de-excitation process in view of their long lifetimes. The observations of the yields made at 90° and 45° suffice to define the anisotropy. Dipole radiation is more intense at 90°, while a higher yield of quadrupole radiation is found at 45°.

The ratio of gamma yields at the two angles is independent of the absolute cross section, but it does depend on the reproducibility of the relative solid angles of the two detector positions. In the 45° runs the crystal was located farther from the target. Checks showed the ratio of solid angles reproducible in the experimental runs within 2%. As determined from the photopeaks of four sources ranging from 0.122 to 2.75 MeV, the ratio at the two positions was 2.25±0.02. The average yields per reaction (using the calculated compound nucleus cross sections in all cases) are summarized in Table II.

Regardless of the de-excitation model chosen, the yield ratio $a=W(45)/W(90)$ is greater than unity for quadrupole transitions and less than unity for dipole transitions. One may note that in the higher energy alpha bombardments and the C^{12} bombardment of V^{51} (at approximately the same energy) the ratio a is large, indicative of quadrupole emission. On the other hand, the radiation from the Te target does not exhibit quadrupole anisotropy although it has received the most angular momentum and might be expected to show the greatest preference for high multipoles. In those 28 MeV alpha bombardments for which a was measured, the emission appears isotropic when averaged over all gamma-ray energies.

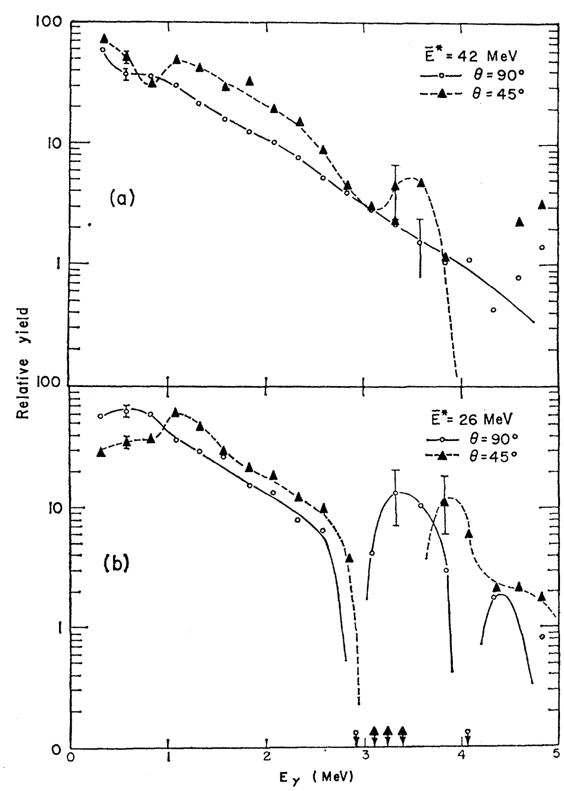

FIG. 7. Spectra from alpha bombardment of Ba at $\bar{E}^*=42$ and 26 MeV.

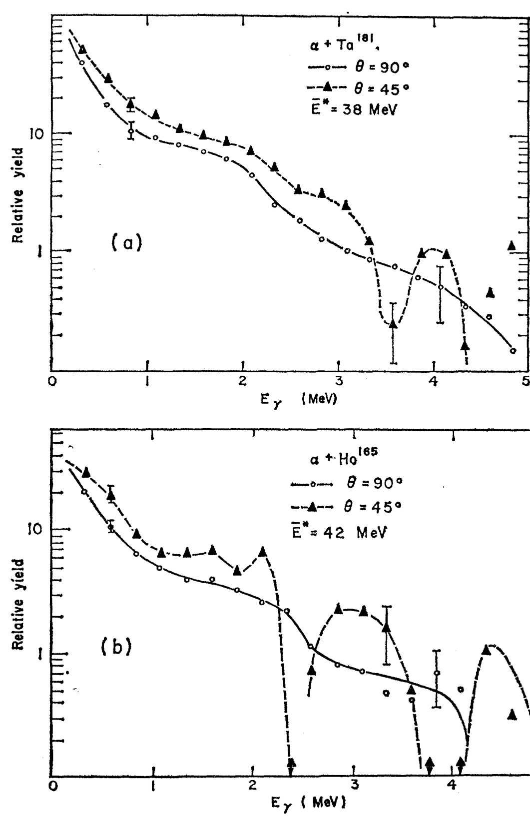

FIG. 8. Spectra from alpha bombardment of (a) Ta^{181} and (b) Ho^{165} at $\bar{E}^*=38$ and 42 MeV, respectively.

The spectra for the two angles are compared in Figs. 7–10. Those from reactions with the same target at two bombarding energies are normalized to the same calculated number of reactions.

The magnification of the statistical fluctuations by the correcting process makes it difficult to estimate errors at all accurately. Based on the reproducibility of the spectra, the errors in individual channels may be very roughly $\pm 10\%$ for the alpha bombardments and $\pm 20\%$ for the carbon ions, at low gamma energy. Around 4 MeV the errors may be $\pm 50\%$ or more in amplitude and ± 250 keV in energy. On the over-all yield the statistics are of course much better. Including all factors except the calculation of the cross section, the yields should be accurate within 15%. The error in the ratios at the two positions should be somewhat smaller, perhaps 10 to 15%. In Table II, the errors in a are figured on a basis of 10% for the alpha runs and 15% for C^{12} bombardments. Considering these limits of error and referring to Fig. 10(a), the data for the bombardment of Te are not inconsistent with isotropic emission or a small anisotropy in the dipole direction.

The dominance of quadrupole transitions is consistent as well with an overall angular momentum balance. One may estimate the angular momentum at the start of the gamma cascade by reducing the initial spin given in Table I by several units representing evaporated particles.[10] Conservation of angular momentum then requires that the average multipolarity of the radiation be at least equal to the starting spin divided by the number of photons emitted. Apparent correlations between number of photons and excitation energy do not alter this relation. The minimum multipolarity obtained in this way is roughly two in most cases. Exceptions occur for the 28-Mev alpha bombardments, where the average photon emission was isotropic and for the higher energy bombardment of V^{51}. Using the calculated cross section for C^{12} on Te the estimate is not so consistent with the observed value of the anisotropy parameter, $a \leqslant 1$. But using the rough experimental cross section of 1 b and assuming that the direct reactions prefer the highest spin states, the revised esti-

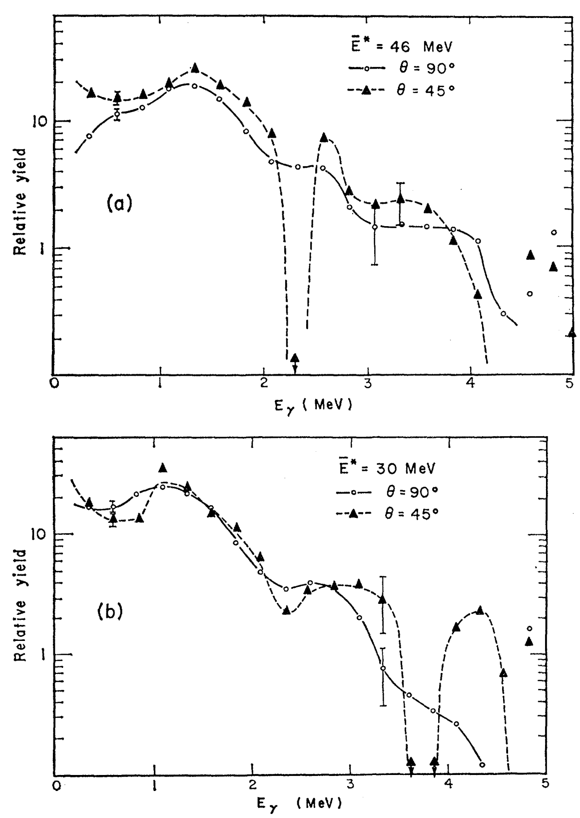

FIG. 9. Spectra from alpha bombardment of Co^{59} at $\bar{E}^*=46$ and 30 MeV.

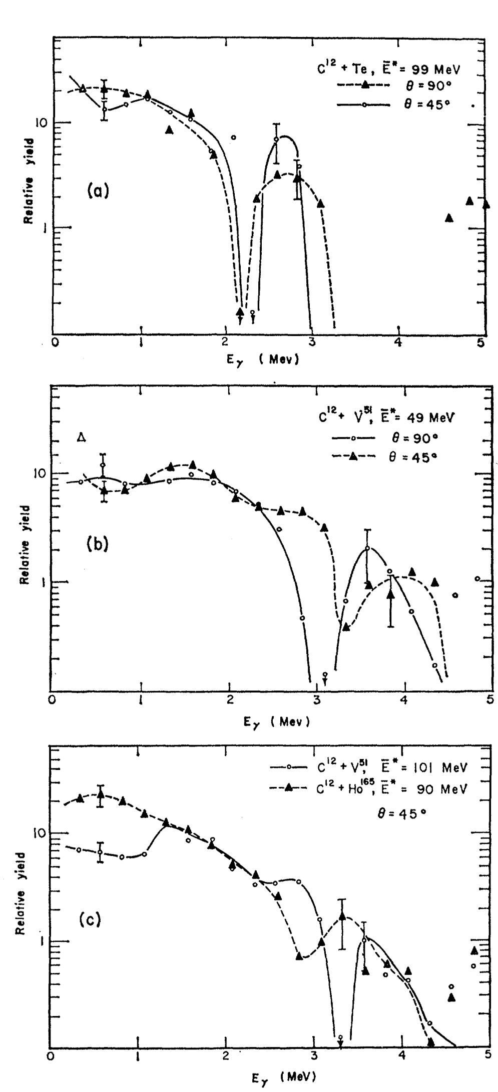

FIG. 10. Gamma spectra observed with C^{12} beam. Spectra at two angles are compared for (a) Te and (b) V^{51}; in (c) yields for V^{51} and Ho^{165} are compared at higher beam energy.

mate is consistent with a large proportion of dipole transitions. A possible explanation for the reduced quadrupole emission in this case will be offered in Sec. IV B. Likewise, the agreement of the angular momentum balance with the observed quadrupole anisotropy for C^{12} on V^{51} at 101 MeV is improved by assuming that part of the cross section goes into direct reactions. Hence, a ratio of initial spin to photon multiplicity of 2, rather than 3, is quite plausible and consistent with the observed anisotropy.

IV. INTERPRETATION OF THE DATA

A. Inadequacy of the Independent Particle Model

The observation of anisotropies characteristic of quadrupole emission suggests that the mechanism of de-excitation in the charged particle bombardments differs from that in thermal neutron capture reactions. This hypothesis is supported by a comparison of the data with the quantitative predictions of the independent particle (statistical) model. In applying this model, the high angular momentum at the beginning of the gamma cascade must be taken into account by the use of a spin-dependent level density in the calculations. The spin dependence is usually derived assuming random coupling of an infinite number of individual nucleon spin vectors.[27] The level density $\rho(J)$ is then given by

$$\rho(J)=\rho(0)(2J+1)\exp[-(J+\tfrac{1}{2})^2/2cT]. \qquad (1)$$

Here, J is the nuclear spin, T is the temperature, and c is related to the moment of inertia $\mathfrak{g}$ by $c\hbar^2=\mathfrak{g}$. This approximation is expected to be accurate for $J\lesssim cT$; for higher J the level density for a finite number of nucleous should cut off more steeply than the exponential.[28]

The energy spectrum and average number of gamma rays from de-excitation has been calculated by Nosov and Strutinsky in the approximation that the fraction of the excitation energy carried by each photon is small.[29] In this experiment the approximation should

TABLE III. Calculated values of the gamma-ray yield based on Eq. (4).

Target	Beam	U_0 (MeV)	J_0	N_γ (calc)	N_γ (exp)
Te	C^{12}	20	25	8.6	~18
V	C^{12}	16	20	6.7	~15 (est)
V	C^{12}	9	13	3.0	6.3
Ba	α	6.4	11	3.1	5.4
Co	α	6	10	2.2	3.4

[27] J. M. B. Lang and K. J. LeCouteur, Proc. Phys. Soc. (London) **A67**, 586 (1954).
[28] T. Ericson, *Proceedings of the International Conference on Nuclear Structure*, Kingston (University of Toronto Press, Toronto, 1960).
[29] V. G. Nosov and V. M. Strutinsky, quoted in reference 7.

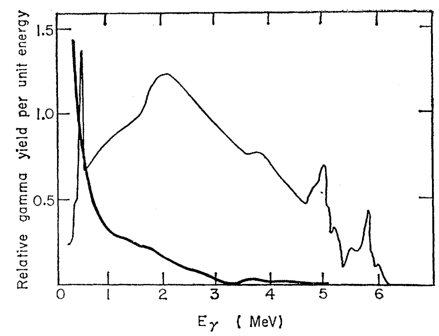

FIG. 11. Comparison of gamma spectra for this experiment with spectra from thermal-neutron capture. Typical deformed-nucleus spectra are plotted, in this case of rhenium. The light curve (from reference 8) represents thermal neutrons on rhenium; the heavy curve, α on Ta at $\bar{E}^*=38$ MeV.

be valid at least in the heavy ion bombardments. The probability of emission of a photon of energy E by a nucleus at an excitation U is given by

$$W_L(U,E)dE=E^{2L+1}\rho(U-E)dE/N_L(U), \qquad (2)$$

where $\rho(U-E)$ is the density of final states, L is the multipolarity of the radiation, and $N_L(U)$ is a normalizing factor:

$$N_L(U)=\int_0^U E^{2L+1}\rho(U-E)dE. \qquad (3)$$

Nosov and Strutinsky did not use a spin-dependent level density, but one may modify the derivation by using Eq. (1). If the total level density is related to the excitation by the expression $\rho(U)\propto\exp[(2aU)^{\frac{1}{2}}]$, and $U=aT^2$, the average number of gamma rays $\bar{\nu}$ is given by

$$\bar{\nu}\approx\{a^{\frac{1}{2}}U_0^{\frac{1}{2}}/(L+1)\}[1+(J_0^2/12cU_0)] \qquad (4)$$

where J_0 and U_0 are the spin and excitation at the beginning of the cascade. Additional assumptions have been made that each transition proceeds to the lowest permissible J value and that $J=J_0U/U_0$ during the course of the cascade. The factor in square brackets is unity in the non-spin-dependent formulation.

The average number of gammas as calculated in this way is compared in Table III with the experimental yields. In the first two cases compound nucleus cross sections smaller than those calculated were used. A multipolarity L of 1 was used to maximize the calculated value, yet the results were a factor of two less than the experimental yields in all cases. The high-spin correction in Eq. (4) amounts to approximately 2% for $J_0=10$ and 10% for $J_0=25$.

Just as the calculated number of photons is too low, the average energy predicted is too high. Calculations by Strutinsky and his co-workers[7] show for dipole emission a broad spectrum peaking between 2 and 3 MeV for thermal neutron capture gamma rays, in agreement with observations. As an example, Fig. 11

compares a thermal neutron spectrum and with one obtained in the present experiment.

The angular distribution of the gamma radiation has been calculated for the statistical model by Strutinsky.[30] He assumed an equal transition probability to all final states of permissible J at each step of the cascade and used the spin-dependent level density of Eq. (1). The distribution in terms of the angle θ with respect to the beam is then given by

$$W(\theta)=1+k_L(\hbar^2J/\mathscr{I}T)^2\sin^2\theta, \quad (5)$$

where the coefficients k_L for the different multipole orders are $k_1=+1/8$, $k_2=-3/8$, $k_2=-81/64$. For the heavier targets, this treatment fails to predict the magnitude of the anisotropy observed, as Table IV indicates. The temperature was determined by the relation $T=(10U/A)^{\frac{1}{2}}$ and a rigid body moment of inertia was used, as required by the Fermi gas model. A smaller moment of inertia, fitting the rotational spectra in the region of Ho and Ta, would still not give agreement. It is assumed here that the transitions are pure quadrupole; any admixture of dipole would make the agreement worse.

B. The Role of Collective Effects

1. Evidence for Vibrational Transitions

The failure of the independent particle model to account for the multipolarity, multiplicity, and anisotropy of the observed photons constitutes good evidence that collective modes of de-excitation must be involved. An examination of the gamma spectra provides information on the nature of the collective modes involved.

The ratio of the yields at 90° and 45° is not the same at all gamma energies. For every spherical target except tellurium a distinct change in the relative amounts of quadrupole and dipole transitions occurs about 1 MeV. Even for the 28.4-MeV alpha bombardments of Ba (Fig. 2), where the yield is isotropic when averaged over all energies, there is a distinct preference for dipole emission below 1 MeV and for quadrupole emission at higher energies.

Both the increase in quadrupole emission above 1 MeV and the average gamma energies of 1.1 to 1.5 MeV are inconsistent with an origin in rotational transitions. For deformed nuclei, the experimentally observed transition energies are 60 $(J-\frac{1}{2})$ keV in the vicinity of holmium, neglecting second order effects which lower the energy at high J. For spherical nuclei, the probability of rotational transitions vanishes.

TABLE IV. Comparison of the experimental values of the anisotropy parameter $a=W(45°)/W(90°)$ with those given by Eq. (5).

Target	J_0^2	$T=(10U/A)^{\frac{1}{2}}$	a_{calc}	a_{exp}
Ba	44	0.47 MeV	1.014	1.43±0.14
Ho	53	0.42	1.010	1.44±0.14
Ta	44	0.33	1.011	1.54±0.15
Co	44	0.71	1.081	1.29±0.13
V	80	0.74	1.149	1.17±0.18

TABLE V. Energies of gamma peaks compared with energies of anomalous inelastic peaks.

Compound nucleus	See Fig. No.	Gamma peak energy (this work)	Anomalous peak energy (scattering studies)	See reference No.
Cu	5,6,8,9	3.3	3.2	31, 32
Te			2.1, 3.0	32, 33
Ba			3.0	34
La			2.5	34
Ce	7	2.7		
Ta	9	3.3	3.0	35
			no peak at 3.0	32
Re	4	4.0	none	34

However, the data are consistent with transitions between vibrational levels. Gamma-vibrational modes may carry up to two units of angular momentum per phonon. In the harmonic oscillator approximation, the levels are evenly spaced and all transitions in a given nucleus have the same energy. The observed energies of vibrational transitions correspond quite closely to the maxima in the 45° gamma spectra. In the region of Cu these energies are about 1.4 MeV, near Ce about 1 MeV, and in the range 1.2 to 1.5 MeV near Ho and Ta.[9]

The observation of quadrupole photons with energies up to about 2.5 MeV may result from the breakdown of the harmonic-oscillator approximation. If the number of phonons is large, all transitions may not be equal in energy. Moreover, the selection rule requiring single-phonon transitions may break down, permitting higher energy transitions.

For the two deformed target nuclei Ho^{165} and Ta^{181}, there is no division between energy ranges of greater and lesser quadrupole emission (Fig. 8). Quadrupole transitions predominate over all gamma energies. In these nuclei, rotational transitions can serve as a source of quadrupole emission at the lower energies.

Whereas the simplest vibrations are the even-parity quadrupole modes, there is some evidence in the gamma spectra for radiation from odd-parity octupole states. The peak appearing between 3 and 4 MeV in most of the spectra agrees closely in energy with the "anomalous peak" of inelastic scattering.[31–35] This peak is attributed to a (3−) state.[31] Generally, the anisotropy of the radiation in this peak is more pronounced than in other parts of the spectrum. As indicated in Table V, the correspondence in energy is within the resolution of this

[30] V. M. Strutinsky, Soviet Phys.—JETP **10**, 613 (1960).

[31] M. Crut, D. R. Sweetman, and N. S. Wall, Nuclear Phys. **17**, 655 (1960).
[32] B. L. Cohen and R. E. Price, Phys. Rev. **123**, 283 (1961).
[33] B. L. Cohen, Phys. Rev. **105**, 1549 (1957).
[34] B. L. Cohen and A. G. Rubin, Phys. Rev. **111**, 1568 (1959).
[35] J. L. Yntema and B. Zeidman, Phys. Rev. **114**, 815 (1959).

experiment except in the case of Re (Ta+α), in which the gamma peak is rather small.

The origin of this peak is not at all clear. It could come from either the de-excitation of the compound nucleus through odd-parity levels or from inelastic excitation of the target. However, arguments may be readily advanced against either interpretation. For inelastic scattering, the beam particle must be scattered by an angle greater than about 75° to miss the stopping scintillator. To reproduce the peak of Fig. 10(a) would require an inelastic cross section greater than one barn for scattering through angles greater than 75°. This figure is much larger than the cross section integrated over all directions. Further, in alpha-gamma coincidence data for 40 MeV alpha particles on Ta, Au, and Pb, only monotonically decreasing gamma spectra are seen for residual excitations up to 20 MeV; yields of 4-MeV gammas are quite low.[36] Also, the peak at 2.7 MeV for C^{12} on Te, for example, does not correspond to the observed anomalous peak energies of 2.1 and 3.0 MeV for scattering on Te.[31,32]

On the other hand, one would expect the (3−) state to decay preferentially to the first (2+) state in an even-even nucleus, rather than to the ground state. The observed ground state branches for $A\sim 100$ are of the order of 10–30%.[31] The shoulders observed on the spectra below the peaks may contain the gamma going to the (2+) level, but they appear a bit small to contain peaks several times larger than the ground state transitions. One may also expect broadening in the peak due to coupling with the odd particle in odd-A product nuclei and to the existence of several possible product nuclei. In many cases the peaks are nearly 1 MeV wide and might conceivably accommodate such broadening. However, the present statistics are not sufficient to determine accurately either the width or energy of the peaks and therefore their origin must remain an open question.

2. *An Alignment Model*

The evidence for collective transitions as a source of the observed photons suggests treating the de-excitation process as a cascade through levels of specified spin. Such a model represents the opposite limit to Strutinsky's statistical model, which assumes random selection of final states at each step. Neglecting the initial target spin, we may assume that the incident beam particle induces an initial angular momentum J_i aligned in a plane perpendicular to the beam axis ($M_J=0$). The cascade of gamma rays is then assumed to proceed to $J=0$ entirely via the lowest spin states consistent with the multipolarity. Quantization about the beam axis leaves the azimuthal angle undefined. In effect it averages over all azimuthal angles of the induced spin in the bombardment.

[36] P. Donovan, Bell Telephone Laboratories (private communication).

TABLE VI. Comparison of experimental values of the parameter a with predictions of the alignment model.

Target	Beam	J_{assumed}	a_{calc}	a_{exp}
Ba	α	$12\to 10\to 8\cdots 0$	+1.57	+1.43±0.14
Ho	α	$12\to 10\to 8\cdots 0$	+1.57	+1.44±0.14
Ta	α	$12\to 10\to 8\cdots 0$	+1.57	+1.54±0.15
Co	α	$10\to 8\to 6\cdots 0$	+1.58	+1.29±0.13
V	C^{12}	$14\to 12\to 10\cdots 0$	+1.56	+1.17±0.18

The angular distribution for quadrupole emission is then given by the expression derived in the study of aligned nuclei[37]:

$$W(\theta)=1+B_2F_2P_2(\cos\theta)+B_4F_4P_4(\cos\theta). \qquad (6)$$

For dipole emission, the last term is zero. Here $P_k(\cos\theta)$ is the Legendre polynomial of order k, and F_k and B_k are constants whose value depends on the multipolarity of the radiation and the spins of the states involved. In this model, the magnetic substates are populated in such a way that the angular distribution remains constant at each step of the cascade, and thus only the angular distribution of the first gamma ray need be calculated.

Table VI compares the experimental values of $a=W(45)/W(90)$ with those calculated from Eq. (6). Pure quadrupole radiation is assumed. Except for the lighter Cu compound system the agreement is very good. The experimental values are lower than those calculated; deviation in this direction is consistent with the assumption of the alignment model as a limiting case.

For the Cu compound nucleus, the agreement is not as good as that found in Table IV for the statistical model. Yet there is a large angular momentum dependence of the gamma yield in this system. Another mechanism in addition to the collective motion may contribute to the enhancement in this case.

In contrast to the heavier nuclei, in the Cu system the average angular momentum induced by carbon ions equals cT, the value at which the level density should be falling below the exponential dependence of Eq. (1). In this case, cT is about 13 $\hbar$, while it is 50 $\hbar$ for Te and 82 $\hbar$ for Ta under the conditions of the experiment. Thus, the effect of the spin dependence of the level density may be much greater than was assumed in the statistical calculations, sufficient to favor quadrupole emission and to produce the observed enhancement of the multiplicity. In the heavier targets, Eq. (1) and the statistical calculations based on it should still be valid.

3. *Possibility of Dipole Emission at High J*

Despite the higher angular momentum induced in the C^{12} bombardment of Te, the anisotropy characteristic of quadrupole emission is missing. While there was no

[37] R. J. Blin-Stoyle and M. A. Grace, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42, p. 555.

check on the 45° data in the form of a duplicate run, there was no evidence of malfunction in the equipment. The conclusion still appears valid that the preference for collective quadrupole transitions is greatly reduced.

The best explanation for this effect seems to be in the prediction, made by Mottelson and Valatin[38] and by Pik-Pichak,[39] that at sufficiently high angular momenta nuclear correlations should disappear. According to Mottelson and Valatin, this should occur when the Coriolis forces are of the magnitude of the energy gap. Interpolation in the results of both papers gives the critical value of the angular momentum J_c as $\sim$7 for $A=60$, $\sim$10 for $A=135$, and $\sim$12 for $A=175$. In the production of Ce with carbon ions the average angular momentum exceeds J_c by a large margin but is about equal to it when the projectile is an alpha particle. Under these conditions, collective motions may not be initiated by the incident particle and the gamma emission may be compelled to proceed in dipole transitions.

However, the C^{12} bombardment of V^{51} induces a spin in excess of J_c and yet quadrupole emission still predominates. This might follow from inaccuracy in the estimation of J_c at low A. It might also be due to the closeness of the average induced spin to cT, as mentioned previously, leading to quadrupole emission through level density considerations alone.

E. Summary

While it is impossible to ascribe the observed gamma radiation to an individual nuclide, it is possible to draw some over-all conclusions on the role of gamma emission in the de-excitation process. We may summarize these conclusions as follows:

1. The assumption that gamma emission does not compete with particle emission above the particle threshold is not valid when the induced angular momentum is only moderately large. In every carbon ion bombardment studied, the average total amount of excitation energy carried off by photons was greater than the neutron binding energy.

2. The observed displacements of excitation functions to higher energy may be explained by the diversion of excitation energy into gamma emission rather than particle emission. The total gamma energy was in good agreement with the observed magnitudes of these displacements.

3. At the same excitation energy, the number of photons from the Cu compound nucleus was greater in the presence of a higher angular momentum, thus demonstrating that the enhancement is an angular momentum effect, not dependent on excitation energy.

4. The greater part of the angular momentum induced by the incident He or C^{12} ion is released in quadrupole gamma transitions. This conclusion follows from the multiplicity and anisotropy of the photons; it is consistent with arguments based on the shape of the spectra and the estimated initial angular momentum. A possible exception may occur for very high angular momenta.

5. Since single-particle transitions cannot account for the quadrupole emission, at least for the heavier targets, it must be attributed to collective effects. The energy spectra suggest that the transitions are vibrational with some rotational transitions occurring in deformed nuclei.

There is also a possibility that octupole as well as quadrupole vibrations may be involved. As with the reduction of the quadrupole anisotropy at high spin, the extent of this effect is uncertain. In further work, better statistics and observations at a number of angles would make interpretation more accurate.

ACKNOWLEDGMENTS

It is the author's pleasure to express his gratitude to Dr. B. G. Harvey for proposing this experiment and for his guidance and assistance in its execution. The author is indebted to Professor J. O. Rasmussen for his encouragement and for his many valuable suggestions in the interpretation of the data. The assistance of M. Nakamura with the electronic circuitry was invaluable. Thanks are due to Dr. J. R. Morton, Dr. J. Huizenga, Dr. J. Alexander, and Dr. G. Choppin for fruitful discussions and for the use of unpublished data, and to the crews of the Hilac and cyclotron for the difficult feat of providing steady low-level beams.

[38] B. R. Mottelson and J. G. Valatin, Phys. Rev. Letters **5**, 511 (1960).
[39] G. A. Pik-Pichak, Soviet Phys.—JETP **7**, 238 (1958).