laboratory, in which we exchanged information about "106" experiments, G. N. Flerov of the Dubna Laboratory reported the observation of spontaneous fission activities with half-lifes of 4–10 msec produced by bombarding $^{207,208}\mathrm{Pb}$ with $^{54}\mathrm{Cr}$.[9] They attribute these activities to lighter isotopes of element 106. In view of the simultaneity of the experiments at the Dubna and Lawrence laboratories, and their very different nature, we shall postpone suggesting a name for element 106 until the situation has been clarified.

It is a pleasure to make the following acknowledgements: to C. A. Corum, J. Meneghetti, and the mechanical technicians at the SuperHILAC for the design and fabrication of the apparatus; to R. G. Leres for his ingenious advanced data acquisition systems; to A. A. Wydler and others for the extensive electronic hardware used; and to the SuperHILAC operations and maintenance staffs for providing many hours of reliable beam operation.

---

†Work supported by the U.S. Atomic Energy Commission.

[1] P. F. Dittner, C. E. Bemis, D. C. Hensley, R. J. Silva, and C. D. Goodman, Phys. Rev. Lett. 26, 1037 (1971).

[2] C. E. Bemis, R. J. Silva, D. C. Hensley, O. L. Keller, J. Tarrant, L. Hunt, P. F. Dittner, R. Hahn, and C. D. Goodman, Phys. Rev. Lett. 31, 647 (1973).

[3] A. Ghiorso, M. Nurmia, J. Harris, K. Eskola, and P. Eskola, Phys. Rev. Lett. 22, 1317 (1969).

[4] A. Ghiorso, M. Nurmia, K. Eskola, J. Harris, and P. Eskola, Phys. Rev. Lett. 24, 1498 (1970).

[5] G. N. Flerov, G. N. Akap'ev, A. G. Demin, V. A. Druin, Yu. V. Lobanov, and B. V. Fefilov, Yad. Fiz. 7, 977 (1968) [Sov. J. Nucl. Phys. 7, 588 (1968)].

[6] P. Eskola, K. Eskola, M. Nurmia, and A. Ghiorso, Phys. Rev. C 2, 1058 (1970).

[7] A. Ghiorso *et al.*, to be published.

[8] J. R. Alonso, in *Gmelin Handbuch der Anorganischen Chemie, Ergänzungswerk* (Springer, Berlin, 1974), Vol. 7b, Part A 1,II, p. 28.

[9] Yu. Ts. Oganessian, Yu. P. Tretyakov, A. S. Iljinov, A. G. Demin, A. A. Pleve, S. P. Tretyakova, V. M. Plotko, M. P. Ivanov, N. A. Danilov, Yu. S. Korotkin, and G. N. Flerov, Joint Institute of Nuclear Research Report No. JINR-D7-8099, 1974 (unpublished).

[10] K. Eskola, Phys. Rev. C 5, 942 (1972).

Gamma Rays Observed from 100-MeV Protons Interacting with $^{56}\mathrm{Fe}$ and $^{58}\mathrm{Ni}$†

C. C. Chang and N. S. Wall
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742

and

Z. Fraenkel
Department of Nuclear Physics, Weizmann Institute of Science, Rehovoth, Israel

(Received 16 September 1974)

Gamma radiation from 100-MeV protons incident on targets of $^{58}\mathrm{Ni}$ and $^{56}\mathrm{Fe}$ has been observed. Residual nuclei were identified by using the known γ rays. Some of the strongest γ rays observed involved residual nuclei *equivalent* to the target nucleus minus one to three α particles. These results can be understood on the basis of a pre-equilibrium stage involving an intranuclear nucleon-nucleon cascade followed by an evaporation process.

Several groups[1-5] have observed γ radiation coming from the interactions of fast pions, as well as stopped pions and kaons, with nuclei for $A \lesssim 65$. It was found especially in the case of fast pions that there was particularly strong production of the γ ray corresponding to the first excited state of the nuclei with two protons and two neutrons (an "α" particle), and in some cases several "α" particles, less than the target nucleus. Earlier, Clegg[6] had observed γ rays from nuclei with $A \lesssim 40$ when bombarded with 150-MeV protons. Various authors have observed the similarity of the results in these two classes of experiments, but there has been little quantitative work done in explaining the relative role of direct α knockout, or pre-equilibrium processes,[7] as distinguished from evaporation processes. Since the main features of intermediate-energy processes in nuclei are understood semiquantitatively, we felt that an investigation of proton-induced γ-ray production could shed light on the questions of the connection particularly between fast-meson and -proton reactions as well as information on the role of evaporative versus nonequilibrium processes.

The experiments we report on here were performed at the University of Maryland Cyclotron Laboratory. A beam of typically no more than 1 nA was directed onto targets of the order of 10^{21} nuclei/cm^2. The γ radiation was observed perpendicular to the beam direction with a Ge(Li) detector which had a photopeak efficiency of 1.67×10^{-4} for 1.332-MeV γ rays when approximately 10 in. away from the target. The detector efficiency was measured by using several calibrated radioactive sources and the efficiency was found to vary exponentially over the range of γ-ray energies we observed. The maximum systematic error for these efficiencies is thought not to exceed 30%. The data were accumulated with the IBM 360/44 on-line computer system at the cyclotron, utilizing a program GELIAN developed by N. R. Yoder and T. W. White (see Yoder[8]). The peak locations, areas, and errors in both location and area were found by using a program based upon the analysis of Mariscotti.[9] Final energy calibrations were based on relatively intense, known γ rays in the measured spectrum to compensate for counting rate shifts. Table I shows that the typical discrepancy between the assigned and known γ rays was of order $|0.5|$ keV and that the average deviation, $\sum(E_{\text{obs}} - E_\gamma)/$(No. of lines), was ≤ 0.5 keV consistent with an overall resolution of order 3–5 keV over the entire energy range. Most runs were of several hours duration. Care was taken to ensure that no beam was intercepted by the beam-line tubes until the beam was stopped in a very well shielded enclosure. Weak known transitions due to the ^{74}Ge in the detector and showing Doppler broadening were also observed, arising from neutrons produced in the target and the beam dump. No detailed attempt was made to study the background continuum on which the various γ-ray peaks were observed.

Figure 1 shows a selected portion of one of the observed γ-ray spectra covering the energy range of maximum interest and Table I shows some of the results for ^{56}Fe and ^{58}Ni targets. In this table the identification is given in terms of the final nucleus. The assignments were made largely from Bowman and McMurdo[10] and Brown *et al.*[10] Table I also indicates which lines were used for internal calibration and where, based on either a large energy discrepancy, anomalous peak shape, or low yield, we are uncertain of the assignment. The cross sections indicated in these tables assume isotropy for the γ-ray angular distribution relative to the beam direction and are expressed in millibarns as are the errors. For the weakest lines the statistical errors are generally less than 25%, and for the intense lines they are less than about 5%, except where indicated by an A. The spectra show many

TABLE I. Gamma rays observed from 100-MeV protons incident on ^{56}Fe and ^{58}Ni. The first column lists the resultant nucleus and possible reactions leading to it with "α" signifying either α emission or other processes with two protons and two neutrons less than the target nucleus. E_{obs} are the γ rays observed in this experiment; E_γ, tabulated γ-ray energies mostly from Ref. 9. ΔE are the differences showing the difference between E_γ and E_{obs} which is an indication of experimental error and therefore the accuracy of γ-ray assignment. The next two columns are the yield as explained in the text assuming isotropy, and its statistical error, in millibarns. The asterisks indicate internal calibration lines and the question marks indicate uncertain assignment; and an A indicates an unreliable estimate for the cross section.

Residual Nucleus	E_{obs} (MeV)	E_γ (KeV)	ΔE (keV)	Cross Section (mb)	$\delta\sigma$ (mb)	Comments
(p,p')^{56}Fe	846.5	846.7	-0.2	12.2	0.2	*
	1238.5	1238.3	0.2	5.40	0.17	*
	1810.0	1810.4	-0.4	4.78	0.34	
(p,p"α")^{52}Cr	743.9	744.1	-0.2	5.41	0.20	
	1333.4	1333.4	0.0	3.07	0.18	
	1434.4	1434.3	0.1	23.1	0.2	* a
(p,p"2α")^{48}Ti	983.4	983.4	-0.1	3.05	0.13	
	1037.4	1037.4	0.0	1.73	0.15	
	1313.2	1311.9	1.3	6.93		A
(p,p"3α")^{44}Ca	749.8	747.9	1.9	1.40	0.10	?
	1021.3	1020.0	1.3	2.65		? A
	1222.8	1222.3	0.5	1.08	0.12	?
(p,pn)^{55}Fe or (p,d)^{55}Fe	93.4	92.0	1.4	3.5	0.14	
	385.7	385.2	0.5	0.53		A
	411.6	411.4	0.2	4.32	0.10	*
	477.5	477.2	0.3	3.27	0.10	
	804.9	803.8	1.1	2.26		? A
	930.8	931.1	-0.3	15.0	0.2	
	1317.1	1316.4	0.7	2.57		A
	1369.1	1369.7	-0.6	3.07	0.18	
	1408.4	1408.3	0.1	13.9	0.2	* b
^{55}Mn	127.4	127.3	0.1	4.50	0.16	
(p,p')^{58}Ni	1454.2	1454.3	-0.1	3.82	0.28	*
	1809.1	1809.7	-0.6	4.06	0.43	
(p,p"α")^{54}Fe	1130.2	1131.0	-0.8	11.0	0.6	
	1408.1	1407.7	0.4	19.0	0.3	b
(p,p"2α")^{50}Cr	783.1	783.3	-0.2	6.43	0.17	
	1097.9	1098.0	-0.1	5.09	0.25	
	1282.9	1282.4	0.5	2.05	0.20	
	1440.0	1440.	0.9	5.08	0.26	
(p,p"3α")^{46}Ti	889.7	889.2	0.5	0.88		A
(p,pn)^{57}Ni or (p,d)^{57}Ni	768.5	0.76MeV		6.00	0.18	?
(p,2p)^{57}Co	124.2	127.1	-2.9	156.	1.	?
	378.3	380.0	-1.7	6.30	0.18	?
	1222.9	1223.5	-0.6	6.43	0.28	
	1377.7	1377.9	-0.2	2.64	0.24	

[a] This level in ^{52}Cr seems to be fed approximately equally by the radioactive decay of ^{56m}Mn and the direct production in (p,p "α").

[b] The difference in these transitions is <0.6 keV and therefore we are unable to assign it uniquely to either ^{54}Fe or ^{55}Fe.

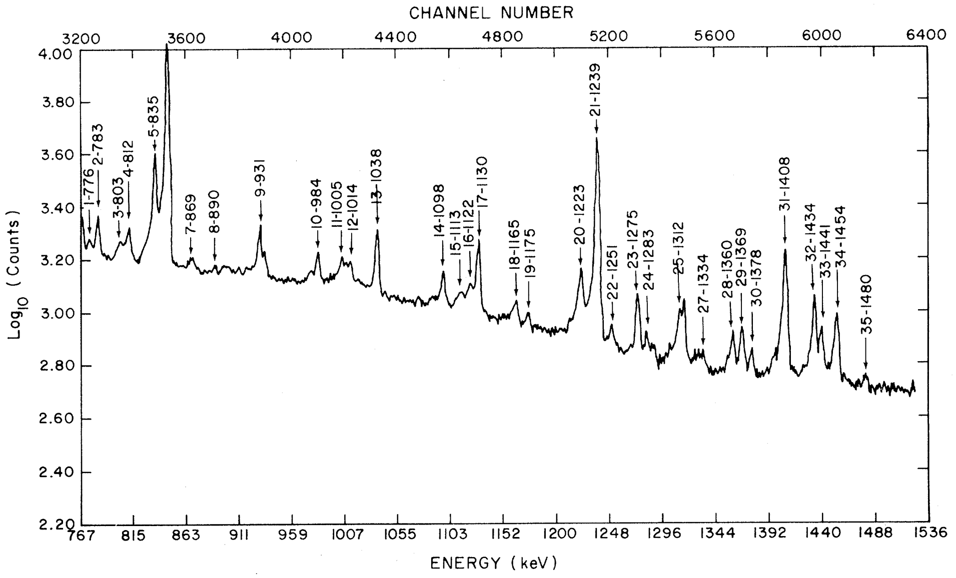

FIG. 1. Partial spectrum of γ rays observed in a Ge(Li) detector from 100-MeV protons incident on a ^{58}Ni target.

more γ rays than those appearing in Table I. We have made assignments for only those transitions which satisfy a criterion of being clearly associated with the energy of a known transition and a further criterion that branching ratios are consistent with published data.[10]

From much work done at medium energies, a consistent picture of the nucleon-nucleus interaction has been developed.[6,11] The essential character of this interaction is that an incident nucleon initially interacts with one nucleon in the nucleus and following this nucleon-nucleon encounter one nucleon usually leaves the nucleus carrying away a significant fraction of the energy. This single, relatively large-energy-loss collision occurs with a probability of ~0.8 for all reactions in the nuclei we are dealing with here.[11] Consistent with this observation, an attempt to explain the present (p, p"α") measurements on the basis of an evaporation calculation, with the absorption of the entire incident energy by the target nucleus, failed in that it predicted too low a cross section.[12] A cross section for the ($p, p\alpha$) + ($p, 3p2n$) reaction on both ^{56}Fe and ^{58}Ni targets of about 5 mb was predicted[13] with the cross section increasing with decreasing energy. These observations suggest that for these nuclei a single or at most relatively few nucleon encounters affords a pre-equilibrium process leading to an average excitation energy of the order of 50 MeV. In fact, this is borne out by a calculation based on the VEGAS program, which is a Monte Carlo program for the calculation of high-energy nucleon-nucleus interactions based on the intranuclear cascade model.[14] This calculation does not assume the existence of α-particle clusters in the nucleus nor does it assume the emission of α particles in the first stages of the reaction ("pre-equilibrium"). The output of this program is a spectrum of excited nuclei, 25% with no nucleon, 63% with one nucleon, and 12% with two or more nucleons emitted in both the ^{56}Fe and ^{58}Ni cases. These nuclei then serve as input to an evaporation calculation. Emission of α particles is included in the evaporation calculation.[15] Table II summarizes some of the results of such calculations and except for the case of 3"α" emission from ^{56}Fe, it can be seen that there is qualitative agreement between experiment and the calculated results for "α," as well as single-nucleon, emission. The 3"α" discrepancy in the ^{56}Fe case may not be real in that the γ-decay data for ^{44}Ca are uncertain. The relative yields in the case of ^{58}Ni are quite reasonable.

Evaporation calculations with no pre-equilibration show that in general at 100 MeV the ratio 2"α"/1"α" is $\geqslant 1$ and may be as high as 30, depending upon the nucleus and level-density parameters used. Furthermore this ratio becomes $\ll 1$ as the compound-nucleus energy decreases. We believe that this further confirms our view of the necessity of a mechanism for decreasing the average excitation of the target nucleus below that which would be achieved by absorbing the inci-

TABLE II. Comparison of theoretical and experimental results. We have made use of the fact that all known γ rays for the 1"α" case go through the first excited state. This results in an underestimate for the experimental value because of the neglect of possible ground-state contributions. Similar assumptions are made for the 2"α" and 3"α" cases (Ref. 12). The asterisk on the ^{56}Fe entry is a reminder that this also includes the indirect path, through ^{52m}Mn, described in the text. The entries in parentheses take this effect into account. For the cases where there is a $(p, 2p)$ or (p, pn) reaction the cross section is estimated by summing the yield of several direct (noncascade) excited-state to ground-state transitions.

	^{58}Ni		^{56}Fe	
	Exp	Calc	Exp	Calc
$\sigma(1\text{“}\alpha\text{”})$	19 mb	93 mb	23* mb (12)	29 mb
$\frac{\sigma(2\text{“}\alpha\text{”})}{\sigma(1\text{“}\alpha\text{”})}$	0.34	0.36	0.13 (0.26)	0.32
$\frac{\sigma(3\text{“}\alpha\text{”})}{\sigma(1\text{“}\alpha\text{”})}$	0.05	0.013	0.05 (0.10)	0.0044
$\frac{\sigma(1n)}{\sigma(1\text{“}\alpha\text{”})}$	...	...	1.44 (2.88)	2.72
$\frac{\sigma(1p)}{\sigma(1\text{“}\alpha\text{”})}$	0.48	0.28	0.2 (0.4)	0.33

dent particle.

A beam-off background run taken immediately after the ^{56}Fe run shows the presence of a γ ray of 1434 keV. This line arises from the decay of the 21.3-min isomer of ^{52}Mn. The yield of this γ ray suggests that the beam-on contribution coming from the equilibrium production and decay of this isomer contributes about $\frac{1}{2}$ to the total yield of this γ ray. In other words this level is directly produced in $(p, p\text{“}\alpha\text{”})$ and $(p, 3p2n)$ reactions with strength comparable with production through the indirect path of the $(p, 2p3n)$ reaction to ^{52m}Mn followed by the decay of this isomer. The calculations described above predict a larger cross section for the total ^{52}Mn production than for ^{52}Cr but do not specifically predict the isomer yield.

Similar calculations made by one of us (Z.F.) for the fast-pion–nucleus interaction results of Refs. 1–3 with the aid of a program extending VEGAS[14] to include pion-nucleus interactions[16] seem to indicate that a large part of the results of Refs. 1–3 [including the cross sections for "$(\pi^-, \pi^- n\alpha)$" $(n = 1-5)$ reactions], though not necessarily all, may similarly be explained with requiring pion–α-particle interactions in the first stages of the reaction.

We would like to thank N. R. Yoder and T. W. White for very significant help in supplying data accumulation and analysis programs. We would further like to acknowledge assistance from and discussions with J. N. Craig, W. F. Hornyak, R. I. Steinberg, and Wm. Walters. We should also like to thank R. Segel, Luise Meyer-Schützmeister, and J. Schiffer for interest in and discussion concerning these experiments.

---

†Work supported in part by the U. S. Atomic Commission.

[1] P. D. Barnes *et al.*, Phys. Rev. Lett. 29, 230 (1972).

[2] H. E. Jackson *et al.*, Phys. Rev. Lett. 31, 1353 (1973).

[3] V. G. Lind *et al.*, Phys. Rev. Lett. 32, 489 (1974).

[4] H. Ulrich *et al.*, Phys. Rev. Lett. 33, 433 (1974).

[5] D. Ashery *et al.*, Phys. Rev. Lett. 32, 943 (1974).

[6] A. B. Clegg, *High Energy Nuclear Reactions* (Oxford Univ. Press, Oxford, England, 1965).

[7] J. J. Griffin, Phys. Rev. Lett. 17, 478 (1966), and Phys. Lett. 24B, 5 (1966). More recently M. Blann and collaborators; B. J. Berne, G. D. Harp, and J. M. Miller; H. Feshbach, A. K. Kerman, and S. E. Koonin; and others have been studying this problem. See *Proceedings of the Europhysics Study Conference on Intermediate Processes in Nuclear Reactions, Plitvice Lakes, Yugoslavia, 1972,* edited by N. Cindro, P. Kulišić, and T. Mayer-Kuckuk (Springer, Berlin, 1973).

[8] N. R. Yoder, University of Maryland Technical Report No. 73-042, 1972 (unpublished).

[9] M. A. Mariscotti, Nucl. Instrum. Methods 50, 309 (1967).

[10] W. W. Bowman and K. W. McMurdo, At. Data Nucl. Data Tables 13, 89 (1974), and in *Nuclear Level Schemes A = 45 through A = 257 from Nuclear Data Sheets,* edited by the Nuclear Data Group (Academic, New York, 1973); B. A. Brown *et al.*, Phys. Rev. C 9, 1033 (1974).

[11] P. G. Roos, Ph.D. thesis, Massachusetts Institute of Technology, 1964 (unpublished); N. S. Wall and P. G. Roos, Phys. Rev. 150, 811 (1966); F. R. Kroll and N. S. Wall, Phys. Rev. C 1, 138 (1970). These results establish the framework for many of the arguments in the present paper.

[12] We appreciate the calculations performed for us by M. Blann as well as the copy of the code he sent us.

[13] In this and other calculations we only estimate the total yields of a particular nucleus. For many nuclei in this region of the periodic table the decays are known to cascade strongly through the first excited state. In these cases our results then only neglect production of the ground state.

[14] K. Chen *et al.*, Phys. Rev. 166, 949 (1968); R. Serber, Phys. Rev. 72, 1114 (1947); M. L. Goldberger, Phys. Rev. 74, 1269 (1948); N. Metropolis *et al.*, Phys. Rev. 110, 185, 204 (1958).

[15] I. Dostrovsky *et al.*, Phys. Rev. 116, 683 (1959).

[16] G. D. Harp *et al.*, Phys. Rev. C 8, 581 (1973).