TABLE IV. Observed cross sections at $E_p = 5.245$ Mev.

Particle group	σ mb/steradian	Angle of observation degrees
Ground state	23 ± 10	174.2 ± 1.9
Broad group	1.2	172.3 ± 1.9
2.43-Mev state	3.6 ± 1.1	170.7 ± 1.9

determining the natural width of the state, a more sensitive method was devised. For this experiment a very thin beryllium target was evaporated onto a carbon foil. The proton group for the 2.43 state was then observed with a bombarding energy of 5.25 Mev, and the ground state group observed at a bombarding energy of 3.00 Mev, computed to give the protons the same energy loss in the physical thickness of the target. The results of this experiment are shown in Fig. 3. Both groups show a thickness at half maximum of 3.2 kev.

All controllable quantities were adjusted to produce equal effects on the two proton groups. Three factors then remain which could affect the observed widths; these are: the natural width of the state, changes in the spectrometer width, and changes in the energy spread of the incident beam at the two different energies. Since it is believed that each of these factors should produce a greater observed width for the group from the 2.43-Mev state, it is concluded that this state has no observable natural width. An upper limit of 1 kev may be set for the natural width to take into account any factors which may not have been considered.

Since the 2.43-Mev state of Be^9 is about 766 kev unbound to neutron emission, an appreciable width would be expected for this state, if low angular momentum neutron emission were possible. The fact that a narrow width is observed for the proton group implies that a high centrifugal barrier exists for the neutrons. Calculations indicate that a lower limit of $J = 5/2$ may be set for the state on this basis.

An estimate may be made of the cross sections for the proton groups of Fig. 1. The values and the angle at which they were observed are listed in Table IV. These values should be accurate to approximately ±30%, except in the case of the broad group, where the cross section is somewhat indeterminate from our data.

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(p,γ) Cross Sections

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Several (p,γ) cross sections were measured by activation with protons from 8 to 22 Mev. The dependences on incident energy and target mass are very slight, whereas a compound nucleus model would predict variations by many orders of magnitude. It seems probable, therefore, that the observed reactions are due to high-energy gamma transitions taking place prior to compound nucleus formation. The magnitudes involved indicate that these transitions have single-particle dipole matrix elements.

EXPERIMENTAL

CROSS sections and excitation functions for several (p,γ) reactions were measured by stacked foil-induced activity techniques with the internal circulating beam of the Oak Ridge 86-inch cyclotron. The absolute cross sections were determined by the ratio method as described previously.[1]

The $C^{12}(p,\gamma)N^{13}$ cross section was measured by observing the 10-min activity in an isotopically enriched[2] sample of carbon-12. A small (~10%) correction was applied for the activity from the (p,n) reaction on C^{13} which was present in 0.05% abundance. The sample contained a considerable amount of copper as impurity, so the cross section was determined relative to the known cross section of the $Cu(p,n)$ reaction.[3] The amount of copper impurity was determined by an activation analysis carried out in the Oak Ridge graphite reactor. The (p,γ) excitation function could not be extended to high energies because a 10-min activity from $Cu^{63}(p,pn)Cu^{62}$ is induced in copper by protons above 15 Mev.

The $Fe^{54}(p,\gamma)Co^{55}$ cross section was determined by comparing the activity of 18-hr Co^{55} with that of 44-min Mn^{51} produced by the (p,α) reaction, in an isotopically enriched[2] sample of $Fe^{54}{}_2O_3$. This measurement was not possible above the threshold of the $Fe^{56}(p,2n)$ reaction (~15 Mev) since that reaction also leads to Co^{55}. The cross section for the $Fe^{54}(p,\alpha)$ reaction was measured by bombarding stacks of natural iron foils and comparing the Mn^{51} activity in the low-energy foils with the Co^{55} activity in the high-energy foils, where the $(p,2n)$ cross section is known.[1]

The cross section and excitation function for the $Ni^{60}(p,\gamma)Cu^{61}$ activity was measured by bombarding

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[1] B. L. Cohen and E. Newman, Phys. Rev. 99, 718 (1955).

[2] Enriched stable isotopes were obtained from the Isotope Research and Production Division of this laboratory.

[3] Blaser, Boehm, Marmier, and Peaslee, Helv. Phys. Acta 24, 3 (1951).

metal foils of isotopically enriched Ni^{60} and comparing the 3.3-hour activity of Cu^{61} with the 36-hour activity of Ni^{57}. The latter is produced by a (p,pn) reaction on Ni^{58}, which was present in 1.5% abundance. Only small corrections were necessary for the Cu^{61} activity induced by (p,n) and $(p,2n)$ reactions on Ni^{61} and Ni^{62} since these were present in only 0.02 and 0.01% abundances respectively.

The cross section for $Zn^{64}(p,\gamma)Ga^{65}$ was determined by measuring excitation functions for the 250-day Zn^{65} activity in stacks of natural zinc foils. At high energies, this is produced by the (p,pn) reaction on Zn^{66}, but below the threshold for that reaction, it is produced principally as the daughter of Ga^{65} from (p,γ) on Zn^{64}. The absolute values were obtained by comparison with the known cross section for $Zn^{66}(p,pn)$ at high energy.[1] It was also necessary to subtract a small background from neutron capture in Zn^{64}. In general, the measured cross sections are accurate to within 20%.

RESULTS

The measured (p,γ) cross sections are listed in Table I. The measurements for bismuth by Kelly[4] are also included. The last column of Table I was obtained by dividing the measured cross sections by the theoretical reaction cross sections for protons (σ_p). It is a measure of the competition between gamma-ray and particle emission.

TABLE I. (p,γ) cross sections.

Reaction	Q (Mev)	Incident proton energy (Mev)	Cross section (mb)	$\frac{\sigma(p,\gamma)}{\sigma_p}$ $(\times 10^3)$
$C^{12}(p,\gamma)N^{13}$	1.9	11	1.8	2.5
		5	2.5	4.4
$Fe^{54}(p,\gamma)Co^{55}$	4.6	11	0.33	0.46
$Ni^{60}(p,\gamma)Cu^{61}$	5.5	22.5	0.9	0.8
		21	0.9	0.8
		16	0.7	0.8
		10	0.9	1.1
$Zn^{64}(p,\gamma)Ga^{65}$	6	11	1.2	1.6
		8	1.3	2.1
$Bi^{209}(p,\gamma)Po^{210}$	5.0	22.5	0.26[a]	0.23
		20	0.43[a]	0.40
		15	0.63[a]	0.95
		10	0.17[a]	1.54

[a] From reference 4.

THEORY AND DISCUSSION

In considering nuclear reactions in this energy region, it is interesting first to investigate whether the results can be explained by compound nucleus theory. In order for a (p,γ) reaction to be observed, the compound nucleus which is formed after capture of the proton must de-excite electromagnetically to a level from which heavy particle emission is not energetically possible; that is, to a level within the particle binding energy, $B(\sim 6$ Mev), of the ground state.

This can happen either by a direct transition to one of these levels accompanied by emission of a high-energy gamma ray, or by a cascade process involving one or more intermediate levels. In the latter process, after each transition the probability is very large $(>99\%)$ that a particle rather than another gamma ray is emitted, so that cascade processes could only be important if emission of quanta with energies about half the incident proton energy were hundreds of times more probable than emission of those with about the full incident proton energy. Measurements of energy distributions of gamma rays from proton bombardment of copper have been carried out by Gugelot with 18-Mev protons[5]; it was found that the probability does not increase nearly that fast with decreasing gamma-ray energy. It therefore can be concluded that the (p,γ) reactions observed here are not the result of cascade processes, but rather of single high-energy gamma-ray transitions to levels within the particle binding energy of the ground state.

It will be assumed here that all transitions are electric dipole. This is probably reasonably correct, and in any case, roughly the same conclusions would be reached regardless of the type of transitions. For simplicity, selection rules will be neglected. Since, in all cases, only ratios of cross sections will be discussed, this is equivalent to assuming that the same fraction of all possible transitions are allowed in each reaction. While this is not generally true, it should almost certainly not lead to large errors.

The problem of radiative capture of heavy particles has been treated by Blatt and Weisskopf.[6] For the case under consideration, their formula (7.23), page 649 for the gamma emission width, Γ_γ, reduces to

$$\Gamma_\gamma \approx 1.5\times 10^{-6}\frac{D(E_p+B)}{D_0}\int_{E_p}^{E_p+B} E^3\frac{dE}{D(E_p+B-E)}, \tag{1}$$

where D denotes level spacing, E_p is the incident proton energy, E is the energy of the emitted gammas, and D_0 is the level spacing at low excitation energies. Applying (approximately) the theorem of the mean, and defining the level density, ω, as $1/D$, (1) becomes

$$\Gamma_\gamma \approx 1.5\times 10^{-6}\frac{N}{D_0}\frac{(E_p+B/2)^3}{\omega(E_p+B)}, \tag{2}$$

where N is the number of states of the compound nucleus with energy less than B.

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[4] E. Kelly, University of California Radiation Laboratory Report UCRL-1044 (unpublished).

[5] P. C. Gugelot, Brookhaven Conference on Statistical Aspects of the Nucleus, Brookhaven National Laboratory Report BNL-331, 1955 (unpublished).

[6] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

The width for emission of a particle, Γ_π (where π is generally a neutron or a proton) is proportional to[7]

$$\Gamma_\pi \propto \frac{\int_0^{\epsilon_\pi} \sigma_\pi E \omega(\epsilon_\pi - E) dE}{\omega(E_p+B)} = \frac{F_\pi}{\omega(E_p+B)}, \tag{3}$$

where σ_π is the cross section for capture of particle π in an inverse process, ϵ_π is the maximum energy avilable for emission of particle π, and F_π is defined by the numerator. The last is identical (within a constant multiplier) with the F_π of Blatt and Weisskopf who present curves of its dependence on energy and mass (reference 6, p. 373).

If we neglect emission of all particles except that which is most probably emitted (which for bismuth is a neutron and in all other cases considered here, a proton), the cross section for a (p,γ) reaction may be written[6]

$$\sigma(p,\gamma) = \sigma_p(\Gamma_\gamma/\Gamma_\pi). \tag{4}$$

Thus the quantity listed in the last column of Table I is, from (2), (3), and (4),

$$\frac{\sigma(p,\gamma)}{\sigma_p} = \frac{\Gamma_\gamma}{\Gamma_\pi} \propto \frac{(E_p+B/2)^3}{F_\pi}. \tag{5}$$

Data on the energy dependence of $\sigma(p,\gamma)/\sigma_p$ are available from Table I for Ni^{60} and Bi^{209}. In comparing Eq. (7) and the curves of reference 6 with the data, it is immediately evident that large discrepancies exist. For example, in Ni^{60}, the ratio between the cross sections at 10 and 22.5 Mev should be about 100 as compared with an observed ratio of 1.3. In Bi^{209}, this ratio should be about 10^5 as compared with an observed ratio of 6.7.

While the theoretical derivation may appear to be on a somewhat uncertain basis, its results are qualitatively clear and reasonable. The essential difference between Γ_γ and Γ_π is that, for the latter, the number of final states increases exponentially with increasing incident energy, whereas for the former, the number of final states is a constant, consisting of the set of states with excitation energy less than B. The fact that the number of final states available for particle emission increases exponentially (rather than according to a power law, for example) would seem to be guaranteed by the fact that the observed energy spectra of emitted particles are Maxwellian with a low and slowly varying temperature. It is therefore difficult to understand how the ratio can be as independent of energy as is indicated in Table I.

Similar difficulties are encountered in investigating the dependence of the cross section on atomic number (Z). From (2), (3), and (4), this is

$$\frac{\sigma(p,\gamma)}{\sigma_p} \propto \frac{1}{D_0} \frac{N}{F_\pi}. \tag{6}$$

The quantity D_0 varies rather slowly with Z, increasing by about a factor of ten from carbon to bismuth. The value of N can be estimated from level spacings found in slow neutron capture. This is about 100 times greater for bismuth (neglecting closed shell effects which do not enter into proton capture in bismuth) than for Fe, Ni, and Zn. However, F_π is smaller for these than for bismuth by a factor of about 10^5. Thus, $\sigma(p,\gamma)/\sigma_p$ should be smaller for bismuth by at least a factor of 1000, whereas the observed cross sections are about equal. While there is considerably more uncertainty in (1) as regards the dependence on Z than on E_p, such a large discrepancy would not be expected.

Since there seems to be great difficulty in explaining the experimental results by a compound nucleus interaction, other possibilities should be considered.

Weisskopf[8] has suggested that direct, single particle transitions may take place to bound states. If such transitions occur with the full single particle matrix element, their probability per unit time, P, is given by[6]

$$P = 2(E/20\ \text{Mev})^3 (A^{\frac{1}{3}}/4)^2 \times 10^{19}/\text{sec}. \tag{7}$$

The time of interaction between the incident particle and the nucleus, τ, is given, approximately, by the nuclear radius divided by the velocity; since the emitted gamma-ray energy is approximately the same as the incident proton energy, this is

$$\tau \approx (20\ \text{Mev}/E)^{\frac{1}{2}} (A^{\frac{1}{3}}/4) \times 10^{-22}\ \text{sec}. \tag{8}$$

The probability for such a transition to occur in a nuclear encounter is τP. Since this is just the quantity $\sigma(p,\gamma)/\sigma_p$, (7) and (8) give

$$\frac{\sigma(p,\gamma)}{\sigma_p} = \left(\frac{E}{20\ \text{Mev}}\right)^{5/2} \frac{A}{32} \times 10^{-3}. \tag{9}$$

The absolute values of $\sigma(p,\gamma)/\sigma_p$ given by (9) are in satisfactory agreement with the observed values from Table I. The theoretical values seem to be too large by a small factor, but this can be explained by the fact that the interaction time, τ, is less than given by (8) because of competition from formation of a compound nucleus.

There is no evidence in the data for the increase of $\sigma(p,\gamma)/\sigma_p$ with energy or target nucleus mass predicted by (9); in fact, there seem to be trends in the opposite direction. However, this can be explained by variation in the matrix elements.

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[7] See, for example, V. F. Weisskopf, Phys. Rev. **52**, 295 (1937). Also, reference 6.

[8] V. F. Weisskopf (private communication).