Gamma-Radiation from Light Nuclei under Proton Bombardment

W. A. FOWLER AND C. C. LAURITSEN
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
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ADDITIONAL studies of the gamma-radiation emitted in the bombardment of light nuclei by protons by several observers during the past year make it advisable to revise data previously summarized on this subject.[1] The revised data are given in Table I and the various changes are discussed in what follows.

The recent determination[2] of 873.5 kev with a probable error of 0.1 percent for the energy at which the first strong resonance in $F^{19}(p\alpha', \gamma)$ occurs, establishes a new and more reliable scale of bombarding energies in nuclear disintegrations with charged particles. The scale previously used was based on the resonance in $Li^7(p\gamma)$ at 440 kev as standard. We have made several comparisons of these two resonances during the past year. Typical results are shown in Fig. 1. A thin ZnF target evaporated on silver was bombarded with monatomic ions while a thick evaporated lithium target was bombarded by diatomic as well as monatomic ions. Both the maximum intensity and width of the two $F^{19}(p\alpha',\gamma)$ resonances (natural width, 5.2 kev and 8.0 kev) indicated a target thickness of 4.2 kev and one-half this value has been subtracted from the point of maximum intensity to obtain the resonance position.

The Li curve has been corrected for non-resonant radiation[1] and also for surface layers of carbon and oxygen of energy equivalent thickness ~1 kev. The thickness of these layers is measured by the number of elastically scattered protons observed in a magnetic spectrometer[3] simultaneously with the gamma-ray yield measurement. These layers appear on lithium targets deposited in vacuum (5×10^{-6} mm Hg) even with an auxiliary diffusion pump and liquid air trap directly connected to the target chamber. The layers increase during bombardment to energy equivalent thicknesses of several kilovolts and the apparent resonance position shifts to higher energies. We have changed to fresh targets repeatedly throughout the measurements and have corrected for the layers observed on the average for short bombardments. The resonance energy is found to be 441.4 ± 0.5 kev which is slightly lower than the value 442.4 ± 1.5 reported by Hudspeth and Swann.[4]

Carbon and oxygen layers have also been observed on Be foil targets and corrections have been made in the resonance energies. We have not investigated the deposition of layers on ZnF targets by the scattering method but the shift in resonance position under the amount of bombardment necessary to obtain the strong $F^{19}(p\alpha',\gamma)$ radiation is observed to be small. No correction has been made in this case or in the case of graphite targets used in the determination of the carbon cross sections. Small relativistic corrections have been included in all cases. The $Be^9(p\gamma)$ cross sections have been corrected for the stopping power measurements on beryllium recently reported.[5]

Additional information on radiation energies as well as on resonance positions has also become available.[6,7] Using a pair spectrograph Walker and McDaniel[6] at Cornell have resolved the $Li^7(p\gamma)$ spectrum into a sharp line at 17.6 Mev and a line about 2 Mev broad at 14.8 Mev. The relative intensity of the 14.8 Mev line is 0.5 at resonance. This permits a more detailed calculation of the efficiency of detection of the radiation and we have accordingly corrected the resonance cross section. Geiger-counter and electroscope results for the yield agree closely and the average has been used in the calculations.

The gamma-radiation from $F^{19}(p\alpha',\gamma)$ has been resolved into two components at 6.13 ± 0.06 and 6.98 ± 0.07 Mev by Walker and McDaniel[6] and the results confirmed by Rasmussen *et al.*,[7] who give 6.135 ± 0.04 and 7.00 ± 0.07 Mev. Recent work on the short range alpha-particle spectrum[8] indicates that there are probably two high energy gamma-rays at 6.9 and 7.1 Mev. The gamma-ray intensity measurements, although apparently not indicative of all details of the spectrum are sufficient to make reliable calculations of the total cross sections at several resonances. Separate data have been given for four resonances in this reaction and for the thick target yield at 960 kev. The resonance widths are those quoted by Bennett *et al.*[9] The cross sections are somewhat higher than those given by Bonner and Evans[10] who determine the gamma-ray yield by comparison with the alpha particle yield at the 340 kev resonance. Further work on the alpha-particle spectra and yields is now under way in this laboratory.

Two recent precision measurements[11,12] on the energy of the radiation from the first excited state in Li^7 yield a weighted mean

TABLE I. Summary of Yield and Energy Measurements.
(Revision of Table I, Rev. Mod. Phys. **20**, 248 (1948).)

Source	Resonance energy (kev)	Energy of radiation (Mev)	Thick target yield* disintegrations/proton	Partial width $\omega\gamma$(ev)	Width Γ(kev)	σ_R (cm²)
$F^{19}(p\alpha', \gamma)$	340.0 ± 2	6.1 (96%) 7.0‡ (4%)	1.74×10^{-8}	31	3.2	8.4×10^{-26}
$Li^7(p\gamma)$	441.4 ± 0.5	14.8 (33%) 17.6 (67%)	1.90×10^{-8}**	9.4	12	6.0×10^{-27}
$C^{12}(p\gamma)$	456.0 ± 2‡‡	2.3	7.3×10^{-10}	0.63	35	1.2×10^{-28}
$C^{13}(p\gamma)$	554.0 ± 2‡‡	2.3, 5.8, 8.1	1.8×10^{-10}	15	40	2.0×10^{-27}
$F^{19}(p\alpha', \gamma)$	873.5 ± 1	6.1 (72%) 7.0‡ (28%)	3.6×10^{-7}	825	5.2	5.3×10^{-25}
	935.3 ± 1	6.1 (77%) 7.0‡ (23%)	2.0×10^{-7}	470	8.0	1.8×10^{-25}
	All ≤960	6.1 (72%) 7.0‡ (28%)	6.9×10^{-7}	——	——	——
$Be^9(p\gamma)$	998.0 ± 4	7.4	1.78×10^{-8}	11	94	4.0×10^{-28}
	1087.0 ± 2	6.7, 0.72	1.01×10^{-9}	0.7	4	5.3×10^{-28}
$Li^7(pp', \gamma)$	1030.0 ± 5	0.478	1.2×10^{-4}††	2400	168	4.7×10^{-26}††
$F^{19}(p\alpha', \gamma)$	1092.0 ± 2		2.4×10^{-9}	7	<1.2	$>2\times10^{-26}$

* Target materials: crystalline CaF_2, evaporated Li(92.6% Li^7), Be metal, Acheson graphite (98.9% C^{12}).
** At 850 kev the yield is 2.6×10^{-8} disintegrations/proton. The tabulated yield is that part of the yield due to the resonance at 441.4 kev.
† Plus two annihilation quanta from N^{13} which emits positrons at maximum energy 1.206 ± 0.004 Mev.
†† Thick target yield at 1350 kev. The cross section has been corrected for non-resonant background.
‡ See discussion in text.
‡‡ The carbon resonances were compared directly with the lithium resonance at 441.4 and not with the fluorine resonance at 873.5 as in all other cases.

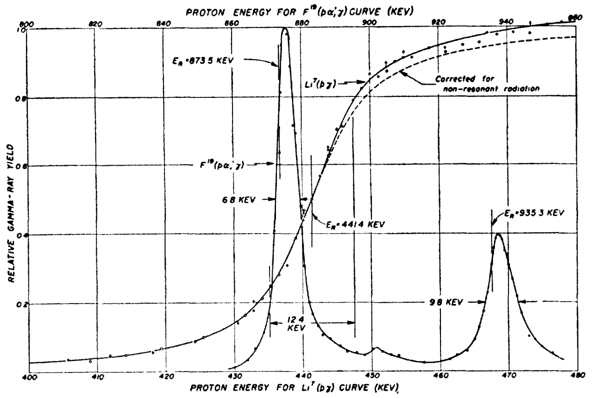

FIG. 1. Excitation curves for the reactions $F^{19}(p\alpha',\gamma)$ and $Li^7(p\gamma)$. In the fluorine reaction a target of 4.2 kev equivalent thickness for protons was used while in the lithium reaction a thick target was used.

value of 477.4±1.0 kev. From measurements on the energy of the protons inelastically scattered by Li^7 to be discussed in more detail in a forthcoming publication we find a value of 479.0±1.0 kev.[13] We have also measured the yield of the radiation following the inelastic scattering. The excitation curve from this reaction has been corrected for penetration factors for the incident and scattered protons and indicates a broad level in Be^8 at 1030±5 kev, superimposed on a continuous non-resonant background. The number of inelastically scattered protons has been measured at 1240 kev and the cross sections per 4π-steradians are 6.5×10^{-26} cm² at 81.1° and 3.6×10^{-26} cm² at 137.8°. The gamma-ray measurements which average over all angles give 5.7×10^{-26} cm² at this energy.

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Thermal Conductivity of Glasses at Low Temperatures

R. BERMAN
Clarendon Laboratory, Oxford, England
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IT was first shown by Debye[1] that for solid non-metals the heat conductivity, K, can be expressed in terms of a mean free path of the heat waves, Λ, by the equation $K=\text{const.}\times c_v q\Lambda$, where c_v is the heat capacity per unit volume and q is the average velocity of the waves. By applying this equation to the results of previous experiments on glasses, using the value of $\frac{1}{4}$ for the constant, the values of Λ in the neighborhood of room temperature were found to be of the order of the interatomic distances. Since q varies little with temperature, the thermal conductivity should vary as the specific heat. The few previous experiments in the hydrogen and helium regions,[2] however, had shown that at lower temperatures the heat conductivity did not fall as rapidly as the specific heat. From this it was deduced that the mean free path of the heat waves increased as the wave-length of the dominant waves became larger than the interatomic distance.

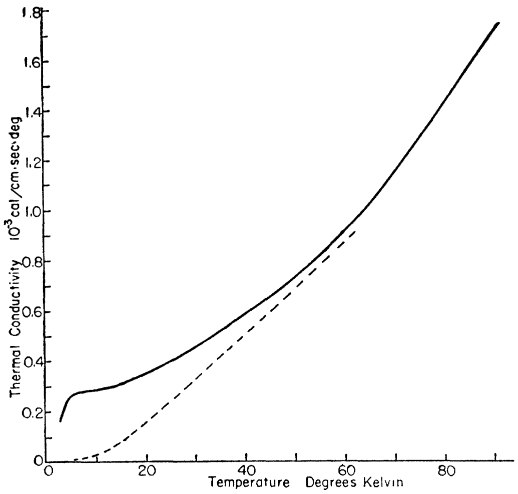

FIG. 1. Thermal conductivity of quartz glass as a function of absolute temperature. Dotted curve shows the specific heat in arbitrary units.

The present experiments were made in order to obtain continuous curves, for each specimen, of the variation of heat conductivity with temperature in the region between 2° and 90°K, from which the variation of mean free path with temperature could be calculated. Since the interpretation of the thermal conductivity of glasses has recently been discussed by Kittel,[3] it seems worth while to give a preliminary report on the results obtained for glass in the present experiments. Two kinds of glass were measured—quartz glass and Phoenix glass (a Pyrex type glass). The values for the two glasses differed by only a few percent over the whole range, and since the specific heat of Phoenix glass has not yet been measured, only the results for quartz glass are shown in Fig. 1. The deviation from proportionality to the specific heat can be seen from the dotted curve, which shows the specific heat[4] plotted in arbitrary units.

The temperature variation of the mean free path is shown in Fig. 2. At the lowest temperature at which measurements were made, 2.5°K, the mean free path is about 6×10^{-5} cm and is roughly proportional to the inverse square of the absolute temperature. If this temperature dependence continued down to lower temperatures, the mean free path would only be comparable with the dimensions of the specimen at about 0.025°K.

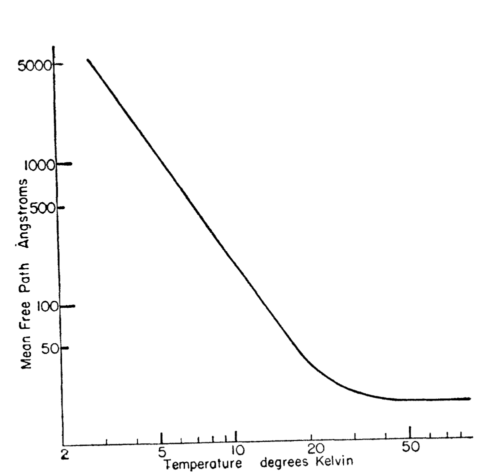

FIG. 2. Mean free path of heat waves in quartz glass as a function of absolute temperature.