Proton-Proton Collisions within Lithium Nuclei

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When lithium is bombarded by 350-Mev protons, one frequently observes pairs of protons emitted in coincidence at approximately 90° to each other. These protons are most easily interpreted as the result of the scattering of the primary protons on free protons in the lithium nucleus. Assuming a model of free nucleons in the nucleus, it is possible to calculate the angular correlation and the intensity of this scattering process. The present experimental results are quite consistent with this picture, if one assumes the distribution of momentum corresponding to a Fermi gas in the nucleus.

IN the course of making measurements on proton-proton scattering, it has occurred to us that light nuclei should be sufficiently transparent to high energy protons to allow observation of proton-proton collisions within the nucleus. The ultimate goal of such an investigation would be to explore the frequently used model in which nucleons within nuclear matter act very much as do free nucleons, and to determine the nucleon momentum spectrum within nuclei. Concurrently with our work, an experiment with similar purposes has been conducted by Cladis, Hess, and Moyer.[1]

One salient characteristic feature of the scattering of two bodies of equal mass is the fact that they escape at 90° in the laboratory system and it was decided to observe this aspect of the collision.

In order to study this phenomenon more closely, we have used a lithium target in the apparatus used previously for proton-proton scattering.[2] Our experimental arrangement is virtually identical to that shown in Fig. 1 of reference 2, with counters A and B in a horizontal plane containing the beam. We use only the laboratory coordinate system, in which counter A is at angle Φ from the beam, and counter B is at angle Θ from the beam on the opposite side.

In typical observations, detector A was kept at a fixed angle while the coincidence counting rate was measured as a function of the angle Θ of counter B. In all cases the coincidence rates were carefully extrapolated to zero beam intensity to eliminate accidental coincidence counts. Typical solid angles subtended by the counters at the target were about 0.05 steradian. The lithium target had a thickness of 0.46 g cm^{-2}. The integration method was the same as that described in reference 2.

The curves shown in Figs. 1 and 2 represent the rate of coincidences as a function of the angle of one of the counters, the other counter being held fixed at 45° and 30° in the respective cases. In both cases the two counters and the beam were in a common plane at all times. The abscissa used in the figures is the deviation of the angle between the two counters from 90°. The resolution curves shown in the figures are those calculated from the sizes of the stilbene counters. These shapes have been checked in detail using free p-p scattering.

Similar curves have been obtained by moving counter B vertically, out of the plane defined by the beam and

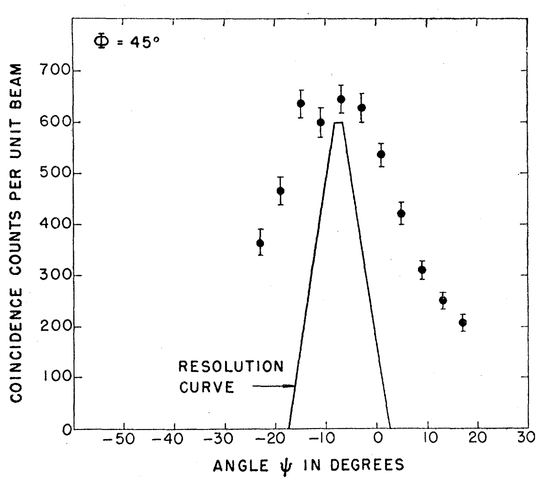

FIG. 1. Coincidence counting rate *vs* the deviation from 90° of the angle between the two counters, when one counter is held fixed at 45°.

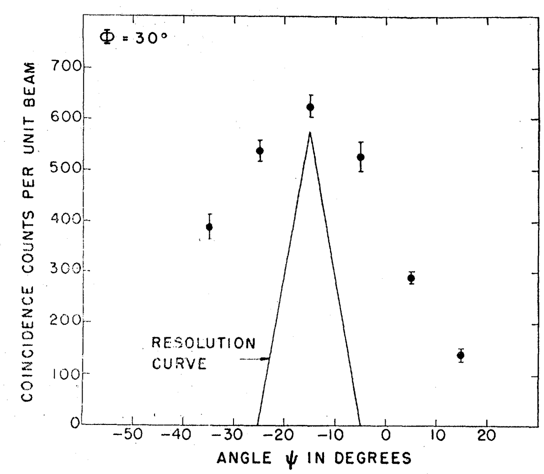

FIG. 2. Coincidence counting rate *vs* the deviation from 90° of the angle between the two counters, when one counter is held fixed at 30°.

[1] Cladis, Hess, and Moyer, Phys. Rev. (to be published).
[2] Chamberlain, Segrè, and Wiegand, Phys. Rev. **83**, 923 (1951).

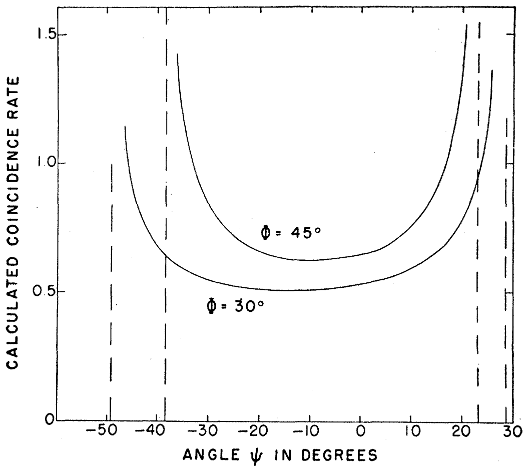

FIG. 3. Calculated coincidence counting rate *vs* ψ for the hypothetical nucleus in which all protons have 20-Mev kinetic energy. The counter at angle Φ is assumed held fixed at the angle indicated.

counter A. These have been used to perform an integration of the coincidence counting rate over all positions of counter B, to obtain the differential cross section for this effect in the direction of counter A. The result is $(39\pm4)\times10^{-27}$ cm²/steradian per lithium atom at 30° (cross section and angle in the laboratory system).

The simplest analysis of the results shown in Figs. 1 and 2 can be made on the assumption that we deal with p-p scattering of the impinging proton by an individual proton in the lithium nucleus. After the collision, the two protons escape without suffering any other collision; otherwise they would not be detected by the counter arrangement used. The protons in the lithium nucleus, however, are not at rest and in applying the conservation of energy and momentum to the system we shall take into account, by some admittedly crude assumptions, the internal motion of the protons and their binding energy. The momentum distribution in the lithium nucleus is assumed to be that of a Fermi gas with a maximum kinetic energy of about 20 Mev.

Let us call $\mathbf{P}$ and $\mathbf{p}$ the momenta of the impinging proton and of the colliding proton in the lithium nucleus before the collisions, $\mathbf{P}'$ and $\mathbf{p}'$ are the momenta after the collision. We have then separate conservation of momentum for the two colliding protons (lab. system).

$$\mathbf{P}+\mathbf{p}=\mathbf{P}'+\mathbf{p}'. \tag{1}$$

The conservation of energy can be expressed by saying that

$$E_P=E_{P'}+E_{p'}+B+E_{\mathrm{He}^6}, \tag{2}$$

where B is the binding energy of the proton in Li^7 (10 Mev) plus the excitation energy left in the He^6 atom after the collision, which we estimate for the sake of argument to be 5 Mev. The E's are kinetic energies in the laboratory system.

In the simplest case in which all the four momenta are coplanar (corresponding experimentally to Figs. 1 and 2), Eqs. (1) and (2) can be combined, and give

$$2p'P'\cos(\Theta+\Phi)=(1+A^{-1})p^2+2Pp\cos\alpha+2mB, \tag{3}$$

where α is the angle between $\mathbf{p}$ and the impinging proton momentum, and m is the mass of the proton. A is the atomic mass number of the residual nucleus; in this case $A=6$. For $E_P=345$ Mev, $E_p=20$ Mev, $B=15$ Mev and $p'P'/m\simeq330$ Mev and $\Phi=45°$, Eq. (3) gives

$$\cos(\Theta+\Phi)=0.115+0.51\cos\alpha. \tag{4}$$

E_p has been chosen on the basis of the free particle model for the lithium nucleus and represents a plausible average value of p.

We call ψ the departure of $\Theta+\Phi$ from 90°.

$$\psi=\Theta+\Phi-\tfrac{1}{2}\pi.$$

($\psi=0$ is the value that would obtain nonrelativistically for p and B equal zero.) Equation (4) gives

$$-\sin\psi=0.115+0.51\cos\alpha.$$

The number of protons having α in a given interval $d\alpha$ is given by $N_\alpha d\alpha=(1/2\pi)d\alpha$; they give rise to a distribution in ψ:

$$N_\psi=(1/\pi)(\cos\psi)(0.25-0.23\sin\psi-\sin^2\psi)^{-\frac{1}{2}},$$

for the case $\Phi=45°$. In developing this formula we take into account that p-p scattering is spherically symmetric and that the influence of relative velocity on the probability of collision is negligible. This distribution in ψ is plotted in Fig. 3, for $p^2/2m=20$ Mev for the given case $\Phi=45°$ as well as for the case $\Phi=30°$. If we vary p, the distribution changes, becoming narrower as p is decreased (and shifting slightly toward larger values of ψ), approaching a delta-function around $\psi=-2.6°$ for $p=0$ if $B=15$ Mev. The number of protons with a value of p in an interval dp and moving in the plane of P and P' is proportional to pdp, and if we perform the integral $\int_0^{p_{\max}}N_\psi(p)pdp$ we obtain a function of ψ which is not too different from a triangle having a maximum at $\psi=-2.6°$ and a base of 62° extending from $\psi=-39°$ to 23° (for the case $\Phi=45°$).

Actually this consideration is not relativistic and we can take relativity into account approximately by shifting our calculated curves in such a way that they have a maximum at $\psi=-8°$ and not at $\psi=-2.6°$, $-5.6°$ being the relativistic value of ψ that would obtain in free p-p scattering.

It is noteworthy that the spread in ψ observed agrees with the one corresponding to a maximum kinetic energy of nucleons within the nucleus of approximately 20 Mev. Furthermore, there is approximately the expected shift of the maximum and the expected increased spread as Φ is changed from 45° to 30°.

We can also compare the free p-p differential scattering cross section with the differential cross section obtained by integrating over all directions of the second counter. At $\Phi=30°$, the free p-p cross section (laboratory system) is 13.2×10^{-27} cm^2/sterad. Three times this cross section is 39.6×10^{-27} cm^2/sterad. This compares remarkably well with the cross section $(39\pm4)\times10^{-27}$ cm^2/sterad obtained from lithium. It should be mentioned, however, that the vertical spread, observed when counter B is moved out of the plane of $\mathbf{P}$ and $\mathbf{P}'$, is about 40 percent larger than that to be expected from the present interpretation of the horizontal spread (Figs. 1 and 2). This aspect will be investigated more closely in further work.

These experiments are preliminary in nature but they show qualitative features which seem of interest to us. When improved and extended, they ought to be able to give direct information on the motion of the protons inside of the nucleus and on the transparency of nuclear matter for protons.

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Decay Times, Fluorescent Efficiencies, and Energy Storage Properties for Various Substances with Gamma-Ray or Alpha-Particle Excitation*†

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The results of measurements of the decay time of light flashes induced by gamma-ray quanta, or alpha-particles by means of pulse distribution curves for various crystals, powders, and solutions are presented. The decay of organic substances can be described essentially by a single exponential; in addition, a small more slowly decaying portion is present. The decay of inorganic crystals can be represented by a sum of exponentials with time constants in different ranges. The results support a previous explanation of the lower efficiency of alpha-particles in producing fluorescence when compared to gamma-rays.

Results on various activated inorganic crystals of integrated fluorescent light output under gamma-rays and peak height measurements under gamma-ray and alpha-particle bombardment are also presented. The relative integrated and peak height properties are not well correlated, neither are the responses to gamma-rays and alpha-particles. Such variations are associated with the different emission times of the crystals. It is found that CsBr and CsI activated with Tl are excellent crystals with respect to luminescent properties especially when volume is a factor. The capability of these crystals to store energy to be released later as light by light of longer wavelengths is also indicated. Very good storage and stimulation properties are shown only by NaCl crystals activated with AgCl.

I.

THE duration of scintillation pulses when a fluorescent material is excited by a single gamma-ray, photon, or alpha-particle has been extensively investigated. The results described in this paper are obtained by a method similar to that described previously.[1] The peak voltages of the pulses produced by a photomultiplier tube receiving the light flashes from the fluorescent material were determined as a function of the resistance at the output of the tube. (The experimental arrangement will be described in a future publication.) For this purpose, pulse distribution curves were measured under equivalent geometrical conditions for different output resistors, and for each the characteristic cut-off voltage was determined. These cut-off voltages provide information on how the light given off in the flash is emitted as a function of time. If the light flash decays exponentially, the time constant of the decay can be determined readily from the ratio of peak voltages for two different resistors.[1] Measurements were made on various single crystals, solutions, and powders using gamma-ray and alpha-particle radiation. The results of the relative pulse-height measurements are reported in Table I.

The analysis of these measurements show that for the organic substances the light flash decays almost exponentially. The time constants calculated under this assumption are given in Table II for various organic scintillators. They are average values obtained from the measurements with different resistors from 100K ohms downwards to 500 ohms and are listed only in those cases where the results could be closely approximated by a single exponential. They agree fairly well with time constants measured by different methods.[2] A closer

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