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Author:
Chamberlain, Owen; Segre, Emilio

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Owen Chamberlain and Emilio Segre

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Radiation Laboratory, Department of Physics
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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 1, 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 beam integration method was the same as that described in reference 1.

The curves shown in Figures 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^{o} and 30^{o} 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^{o}. 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 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

$(39 \pm 4) \times 10^{-27}$ cm^2/sterad. - Li atom (lab. system) at 30^{o} (lab.).

The simplest analysis of the results shown in Figures 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 Li nucleus. After the collision, the 2 protons escape without suffering any other collision; otherwise they would not be detected by the counter arrangement used. The protons in the Li 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.

Let us call P and p the momenta of the impinging proton and of the colliding proton in the Li nucleus before the collision, P' and p' are the momenta after the collision. We have then separate conservation of momentum for the two colliding protons.

$$\underline{P} + \underline{p} = \underline{P'} + \underline{p'} \tag{1}$$

The conservation of energy can be expressed by saying that:

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

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). Equations (1) and (2) can be combined, and give:

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

where α is the angle between p and the impinging proton momentum, and m is the mass of proton. A is the atomic mass of the residual nucleus; in this case $A \doteq \infty$. For $E_P \doteq 345$ Mev, $E_p \doteq 20$ Mev, $B \doteq 15$ Mev and $\frac{p'P'}{m} \cong 330$ Mev, 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 Li nucleus and represents a plausible average value of p.

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

$$\psi = \theta + \Phi - \frac{\pi}{2}$$

(ψ = 0 is the value that would obtain non-relativistically for p and B equal zero.) Eq. (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 $N_\alpha\, d\alpha = \frac{1}{2\pi}\, d\alpha$; they give rise to a distribution in ψ,

$$N\psi = (1/\pi)(\cos\psi)(0.25 + 0.23\sin\psi - \sin^2\psi)^{-1/2}$$

for the case $\Phi = 45^\circ$. 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 $\Phi = 45^\circ$ as well as for the case $\Phi = 30^\circ$. 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 $\psi = -2.6^\circ$ 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 $\int N\psi(p)pdp$ we obtain a function of ψ which is not too different from a triangle having a maximum at $\psi = -2.6^\circ$ and a base of 62° extending from $\psi = -39^\circ$ to 23° (for the case $\Phi = 45^\circ$).

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 $\psi = -8^\circ$ and not at $\psi = -2.6^\circ$, -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 with the nucleus of 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 $\Phi = 30^{\circ}$, the free p-p cross section (laboratory system) is 13.2×10^{-27} cm^2 sterad.$^{-1}$. Three times this cross section is 39.6×10^{-27} cm^2 sterad.$^{-1}$. This compares remarkably well with the cross section $(39 \pm 4) \times 10^{-27}$ cm^2 sterad.$^{-1}$ obtained from lithium. It should be mentioned, however, that the vertical spread, observed when counter B is moved out of the plane of P and 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.

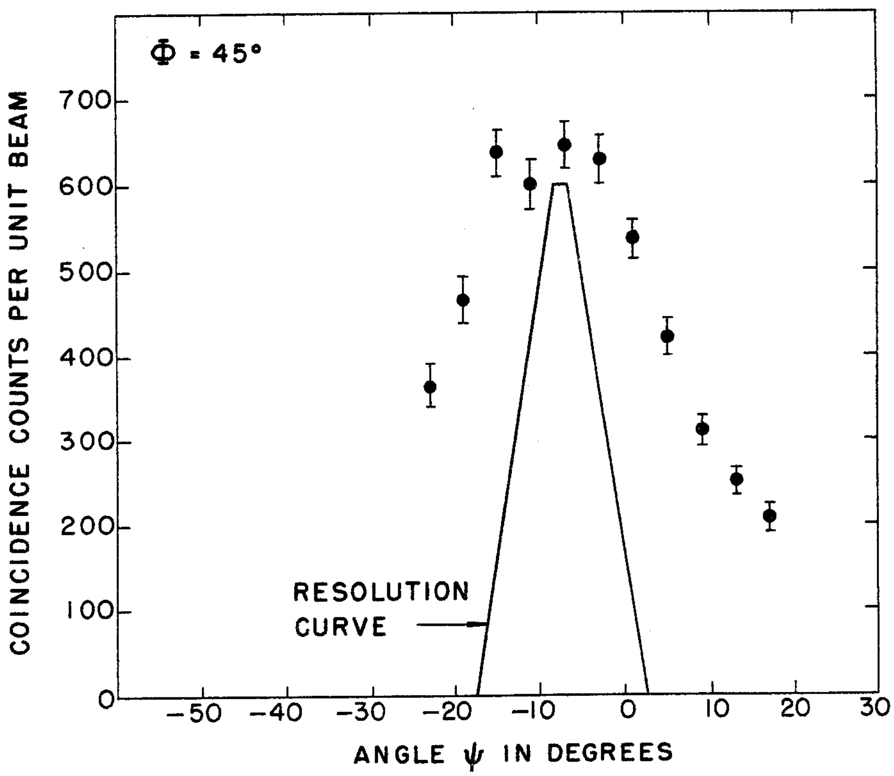
This work was preformed under the auspices of the Atomic Energy Commission.

Information Division
3/26/52 bw

References

1 Cladis, Hess, and Moyer, Phys. Rev., in press.

2 Chamberlain, Segre, and Wiegand, Phys. Rev. 83, 923 (1951).


Φ = 45°
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500
400
300
200
100
0
COINCIDENCE COUNTS PER UNIT BEAM
RESOLUTION
CURVE
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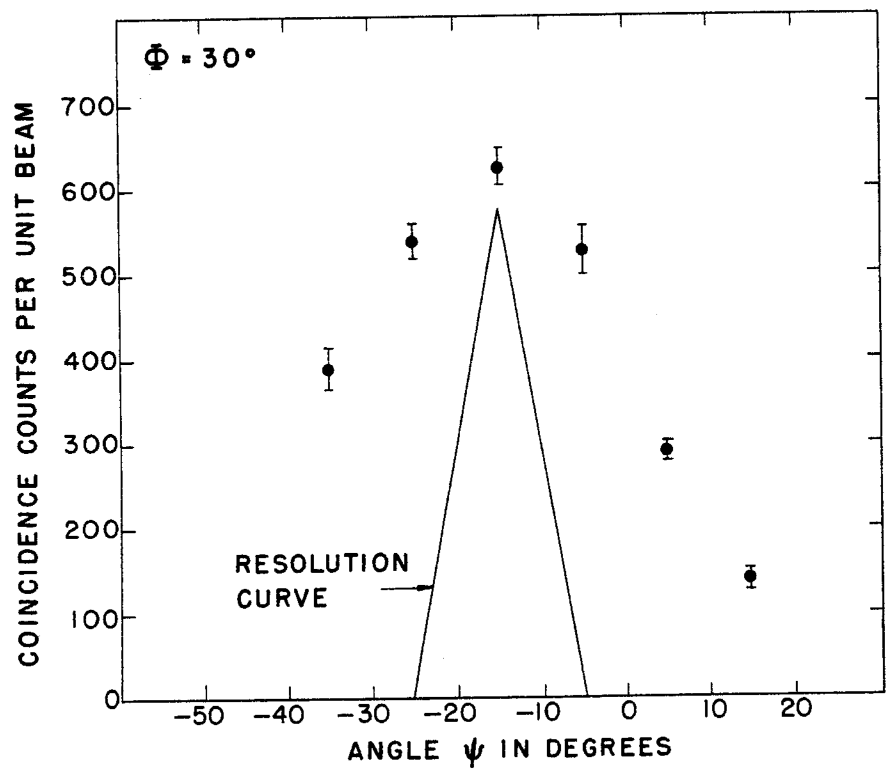
−40
−30
−20
−10
0
10
20
30
ANGLE ψ IN DEGREES

MU 3324

Fig. 1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ANGLE ψ IN DEGREES

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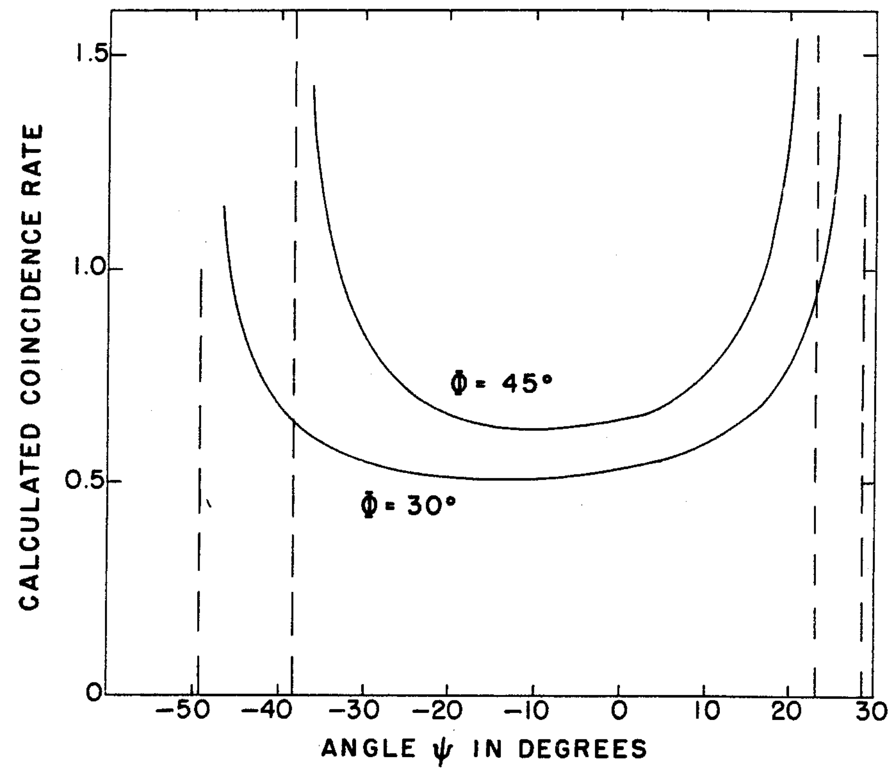
Fig. 2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Φ = 30°
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30
ANGLE ψ IN DEGREES

MU3325

Fig. 3