# Disintegration in Flight of Deuterons under the Influence of Nuclear Fields

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## 1. INTRODUCTION

Many correlation studies are carried out with deuterons as projectiles, so it may be useful to report here the results of an investigation about the neutron–proton correlation generated by disintegration in flight of deuterons scattered by a target nucleus. This reaction is due to the influence of the Coulomb field of the target nucleus on the structure of the incident deuteron. This Coulomb disintegration has also some bearing on optical-model studies with deuterons.[1] Further, the study of this relatively simple reaction is instructive in understanding the problems that arise in the description of correlation experiments.

Discussions about the possible occurrence of the Coulomb disintegration exist,[2,3] but the experimental evidence for the effect is scanty.[4] Besides the Coulomb disintegration as reason for the production of coincident neutrons and protons, also the diffraction disintegration[5] is discussed as a possible source for this phenomenon. However, this process is a pure high-energy effect, that will have little or no influence on the results to be discussed below, which were obtained at 26- and 23-MeV deuteron energy.

This paper describes three experiments carried out to determine the occurrence and the mechanism of the deuteron disintegration in flight,[6] namely:

(a) the measurement of the spectra and the angular distribution of the protons produced in the disintegration process;

(b) the measurement of the angular correlation between the outgoing neutrons and protons;

(c) the measurement of the energy correlation between the outgoing neutrons and protons.

The first experiment indicates the existence of a direct disintegration of the deuteron, the second experiment proves the occurrence of a disintegration in flight, while the third experiment shows that no important energy transfer to the nucleus occurs during the scattering process.

At this stage not many conclusions about the mechanism of the process can be drawn on the basis of agreement or disagreement with predictions of calculations, because the existing calculations ignore many factors, which should enter into an accurate description of the process.

## 2. THE (*d*, *p*) EXPERIMENT

It is possible to predict the general properties of protons coming from disintegration in flight from the picture of a deuteron disintegrating in the Coulomb field of the nucleus:

(a) the energy spectrum should be a broad peak at somewhat more than half the deuteron energy;

(b) the angular distribution should have a maximum at an angle determined by the deflection of the deuteron before, and of the proton after, the disintegration. The experiment is carried out on thin gold and copper targets with incident-deuteron energies of 26 and 23 MeV. The proton spectra lying between 6 and 22 MeV were recorded in an angular range from 10° to 90° laboratory angle with the deuteron beam. The protons were detected with a solid-state counter telescope.

In the proton-energy spectra from gold, no distinction could be made between the protons from nuclear reactions (compound-nucleus evaporation) and the protons from direct disintegrations. Nevertheless, the angular distributions of the integrated proton spectra show, that a contribution of this kind must be present, because the angular distribution shows a maximum at forward angles. Figure 1 presents one of these results. The curve marked calculated is discussed below.

For copper the situation is different, because the Coulomb barrier is lower. This implies, that the maximum in the evaporation spectrum is so low, that it can be seen separated from the breakup proton contribution. Figure 2 shows two proton spectra obtained from a copper target. It is clear, that at small angles a peak near 15-MeV proton energy is present, which vanishes towards larger angles.

The curve marked "calculated" in Fig. 1 originates from a calculation based on a theory of Nishida.[5] This theory describes the action of the Coulomb field of the nucleus on the moving deuteron with the aid of the concept of virtual quanta. The calculation is classical in the sense that the deuteron is treated localized in the field and the resulting proton angles are calculated in a very simple manner. Nevertheless, the agreement between the results of the calculation and the measured proton angular distributions is quite remarkable. Not only the form of the curve, but also the magnitude of the

[1] C. F. Clement, Phys. Rev. **128,** 2724 (1962).
[2] S. M. Dancoff, Phys. Rev. **72,** 1017 (1947).
[3] R. Gold and C. Wong, Phys. Rev. **132,** 2586 (1963).
[4] E. W. Hamburger, B. L. Cohen, and R. E. Price, Phys. Rev. **121,** 1143 (1961).
[5] R. J. Glauber, Phys. Rev. **99,** 1515 (1955); A. G. Sitenko and V. K. Tartakowskii, Nucl. Phys. **13,** 420 (1959).
[6] These experiments have been carried out in close cooperation with Dr. L. A. Ch. Koerts and H. R. E. Tjin A. Djie.

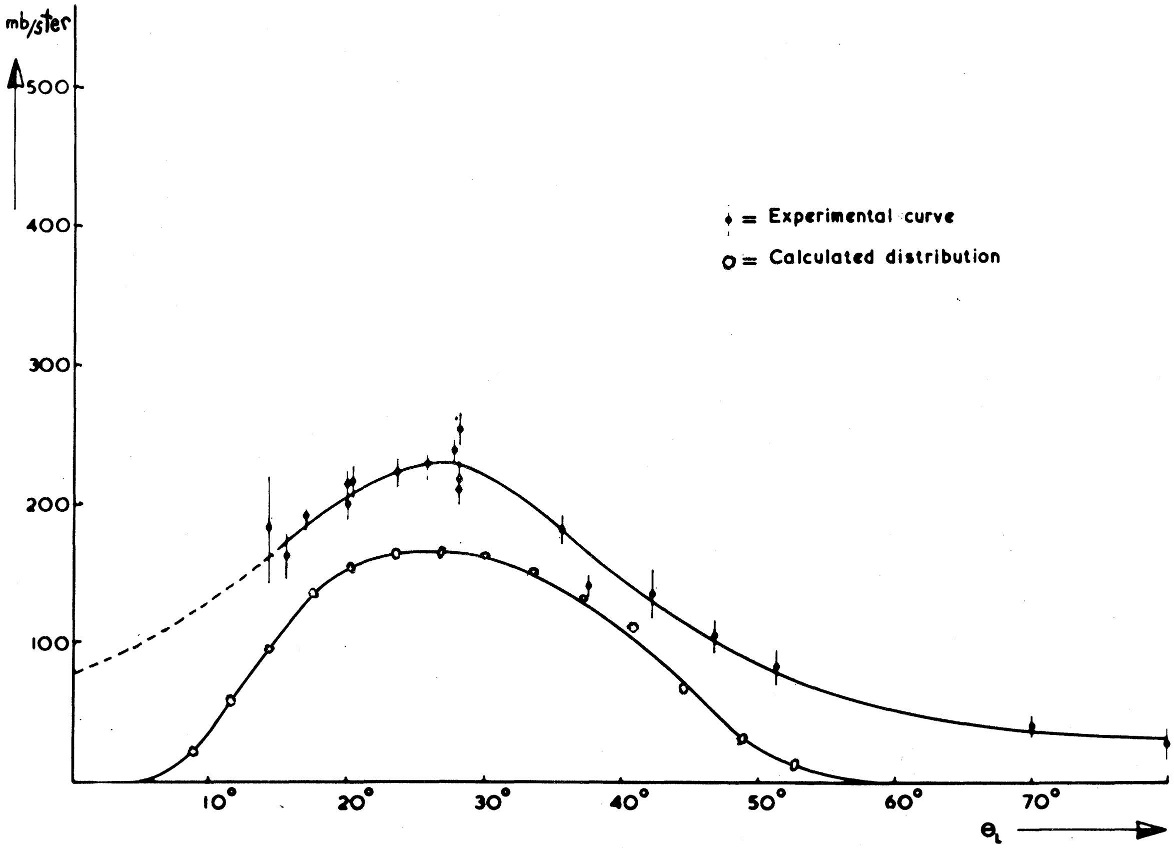


FIG. 1. Angular distribution of the protons with energies between 8 and 22 MeV obtained from a gold target. The incident energy is 26 MeV. The curve marked "calculated" is discussed in the text.

differential cross sections comes out about right. Equally good fits are obtained for the results of a similar experiment done at 15 MeV by Hamburger, Cohen, and Price.[4]

### 3. ANGULAR-CORRELATION MEASUREMENT

An angular-correlation experiment between the outgoing neutrons and protons can provide detailed information about the mechanism of the disintegration process. Here a description is given of some aspects of the results of the measurement of the coincidences between neutrons and protons, when gold and copper targets are bombarded with 26-MeV deuterons. A preliminary account of these measurements has been published.[7] Here a more complete set of correlation curves is presented together with some new results regarding the coincident proton spectra.

Figure 3 shows a set of correlation curves. The correlation cross section is represented as a function of neutron angle with the proton angle as a parameter. Every curve is built up from about 15 measurements at different neutron-counter settings. A sharp peak occurs at slightly negative neutron-counter angles. The concentration of the correlation is demonstrated by a comparison between the experimentally obtained peak cross sections (hundreds of mb) and the differential cross section one obtains for a process with the same total cross section (around 180 mb for gold, 26-MeV incident energy) and an isotropic angular correlation. This differential cross section will be 1 mb/sr$^2$.

The correlation peak is constrained to the plane defined by the deuteron beam and the proton counter direction. This proves that the disintegration takes place outside the nucleus.

An important aspect for the description of the disintegration process is the variation of the form of the coincident-proton spectra with the angles of detection. Figure 4 shows this angular dependence of the proton spectra for some measurements on the copper target. The figure shows the variation of the proton spectrum with neutron angle at a fixed proton angle, 20° in this case. The main energy of the protons diminishes, when the neutron counter moves to the positive angle region (the region where the proton counter is placed). This effect is not found in the gold measurements. This indicates that probably different descriptions are necessary for these two cases. A possible explanation is the value of

[7] F. Udo and L. A. Ch. Koerts, Phys. Letters 3, 181 (1963).

the Coulomb scattering parameter $n(=Ze^2/hv)$: for gold $n=3.67$ and for copper $n=1.40$ for 26-MeV deuterons. The small value of $n$ for copper indicates that one approaches the region where the "high-energy description" of the process is justified, while the gold case is a pure low-energy case.

## 4. THE ENERGY CORRELATION EXPERIMENT

Independent information about the correlated particles can be obtained from a coincidence experiment, where also the energy of the outgoing neutron is meas-

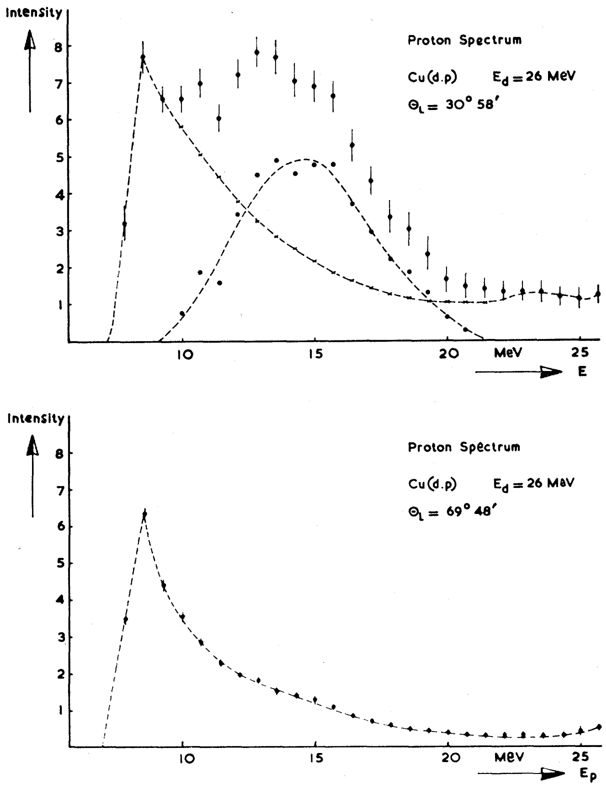


FIG. 2. Two proton-energy spectra obtained from a copper target at 26-MeV deuteron bombarding energy. The upper curve is decomposed into the contribution from the evaporation of protons from a compound-nucleus system and a direct break up process. At 70° the breakup contribution is vanished.

ured. This is easily accomplished by an extension of the former experiment in the sense, that also the flight-time differences between the neutron and the proton are measured.

The first result from such an experiment has been published already in a letter,[8] namely the energy correlation spectrum between the coincident protons and neutrons for gold at 26-MeV incident deuteron energy. Here a similar result is presented for copper at 26-MeV deuteron energy. Figure 5 shows an energy correlation spectrum for the counter angle settings: proton counter

[8] F. Udo and L. A. Ch. Koerts, Phys. Letters **6**, 343 (1963).

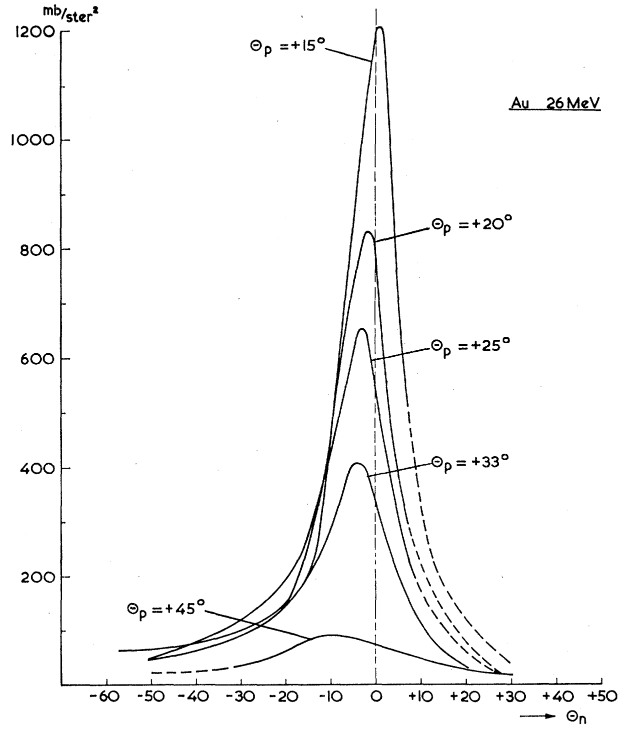


FIG. 3. The angular distribution of the neutron–proton correlation as a function of the neutron angle with the proton angle as a parameter. The curves are measured from a gold target bombarded with 26-MeV deuterons.

$+25°$, neutron counter $-7°$. The grey colored parts on the field are background pulses from accidental coincidences. For instance, the peaks at all times and at 22-MeV proton energy are due to elastically scattered deuterons.

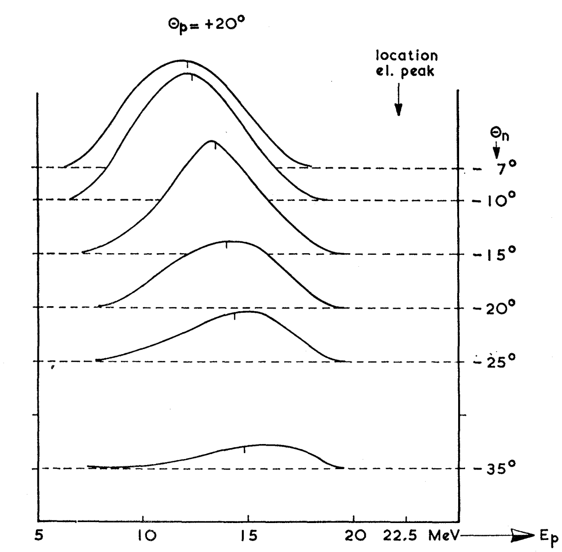


FIG. 4. Spectra of coincident protons as a function of neutron angle for copper at 26-MeV deuteron energy.

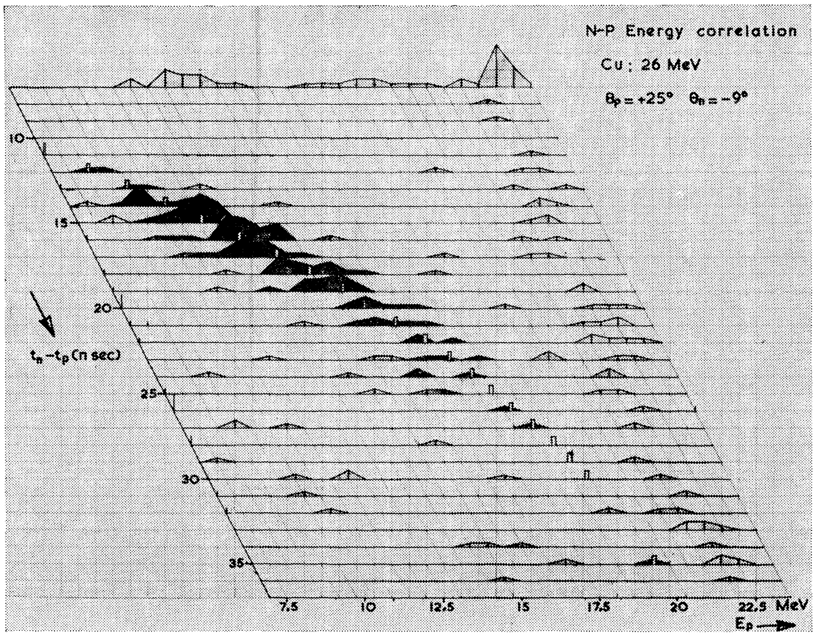


FIG. 5. The energy correlation spectrum between neutrons and protons for copper, 26 MeV. The neutron-energy axis is expressed in nsec flight-time difference. The transformation to neutron energy contains the proton energy.

The white rectangles indicate the energy relation between neutrons and protons in the case no energy is transferred to the nucleus. Then, the relation

$$E_p + E_n = E_d - E_r - 2.23 \text{ MeV} \quad (1)$$

is valid. Here $E_p$, $E_n$, $E_d$, and $E_r$ denote, respectively, the proton energy, the neutron energy, the incident-deuteron energy, and the recoil energy of the target nucleus. This recoil energy can be neglected. Just as in the case published in Ref.8 also for copper the measured energy relation follows Eq. (1) within the error limits

## 5. DISCUSSION

The evidence from the experiments described above is fairly conclusive regarding the deuteron disintegration in flight. Nevertheless, it remains difficult to extract definite conclusions from the data, because the disintegration process has not yet been described in sufficient detail. The existing calculations[2,3] only attempt to calculate a total cross section for the effect under various very simplifying assumptions. It appears, that a calculation similar to a distorted-wave Born approximation is necessary to describe the results obtained in this experiment.

One of the reasons is that at the incident energy used in this experiment the kinematical factors are in between those for high-energy and those for low-energy descriptions. Therefore, for instance, Coulomb wave functions are necessary to describe the motion of the charged particles, but also the presence of the nuclear potential plays a decisive role in the description of the in- and out-going waves. On the other hand, experimentally, the deuteron energy of 26 MeV is most suited for the measurement, because at lower energies the electric disintegration effect diminishes and the correlation spreads out over a much larger angular region, while on the other hand at higher energies the correlation will be found only at very small angles. Furthermore, at higher energies also the diffraction disintegration process comes in as a source for coincident neutrons and protons. This will give an additional complication in a description of the process.

## ACKNOWLEDGMENTS

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### Discussion

HENLEY: I believe the second process you referred to is the diffraction breakup. I don't understand how you can distinguish between these two processes. It depends on the distance from the nucleus at which this diffraction breakup would occur, and I don't see how you can distinguish between the diffraction process and the Coulomb breakup merely from the measured width.

UDO: When you assume electric-dipole interactions you get a selection in the available phase-space. This tends to limit the width of the spectra. I evaluated for the Dancoff approach the outgoing spectra, and indeed they are smaller in width than the spectra following from the Glauber process. I think that only a DWBA calculation that contains both effects can give a realistic description of the process.

ZUPANČIČ: I don't know Glauber's calculation, but it looks, from what you said, like a sudden approximation. In other words, it is only valid when you have very fast deuterons. But you have very low energies. The diffraction disintegration should be calculated by another method, not Glauber's.

UDO: Let me say that 26 MeV is just the intermediate state between a sudden approximation and adiabatic approximation. Very bad, it is true. Furthermore, in the case of Glauber's approximation, I tried to include some finite times and to include internal motion and absorption probabilities of one particle when it originally missed the nucleus. Even then, because of the internal momentum, one of the two can be absorbed. This gives amazing reduction factors for the cross sections; a factor of 10, for instance. This is only one reduction factor. Another reduction factor comes from the process itself when you include a realistic fall-off of the nuclear potential. When you have a sudden cutoff you have a value of say 200 millibarns for the process. With a smooth cutoff and time effects included the calculated cross section is down to about 10 millibarns. So there is a second argument against the occurrence of the diffraction process.

PHILLIPS: What is the magnitude of the absolute cross section here, and how does that cross section compare to ordinary nuclear cross sections? The reason I ask that is that if the ordinary cross section is comparable in your peak, then clearly one must also include the possibility of nuclear reaction in a more subtle way.

UDO: The peak cross section we have measured was 1 barn per steradian, far above any nuclear $n$–$p$ correlation cross section.

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# Study of the $Ca^{40}(\alpha, 2\alpha)$ Reactions*

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The correlations in energy and angle of the alpha particles produced by the reaction $Ca^{40}(\alpha, 2\alpha)Ar^{36}$ have been measured for incident alpha energies of 28.7 and 30.5 MeV. Data were taken with a two-dimensional pulse-height analyzer for an angular range from 20° to 135° with solid-state detectors (angular aperture ±2°) confined to the reaction plane. It was found that the first excited state (1.97 MeV) in $Ar^{36}$ is much more strongly populated than the ground state. Pronounced structure was observed in practically all correlation spectra taken. At the higher incident energy and at detector angles of 35°–35° and 55°–55° with respect to the beam, the alpha particles were found to be emitted preferentially with equal energies. When the incident energy was lowered, one alpha-particle energy remained constant. This implies a two-step process via an excited state in $Ca^{40}$ near 18.8 MeV. Measurements with unequal detector angles were carried out to determine alpha correlations with respect to the recoil axis. The experimental results will be discussed with reference to both direct and sequential reaction mechanisms.

Our study was originally undertaken with the idea of looking for something similar to the quasi-elastic reactions seen at higher energies in the ($p$, $2p$) reactions. Although there may not be justification for such an idea, this was our first outlook.

The experimental arrangement for most of the experiment was as follows: Roughly 20 nA of 30.5-MeV alpha particles from the MIT cyclotron were brought to a focus on an approximately $\frac{1}{2}$-mil-thick self-supporting, natural calcium target. The beam spot size at the target was 1 mm² and the angular divergence of the beam was less than 1°. Defining slits were circular in aperture, subtending approximately $\pm 2\frac{1}{2}°$ from the target, or about $5\times10^{-3}$ sr. The scattered charged particles were detected by two Nuclear Diode 500-$\mu$ surface barrier detectors. The energy resolution arising from beam energy spread, kinematic broadening, and detector noise was less than about 200 keV, which was considerably less than the energy per channel for the analyzer, ~500 keV.

The signals from the detectors are fed through a pair of Tennelec preamplifiers, through attenuators, through Sturrup linear amplifiers, and then to a Nuclear Data 4096 multichannel analyzer. The same signals which are fed into the analyzer are also put into Sturrup discriminators[1] whose coincidence output was used for the coincidence input on the 4096 analyzer.

Data for one pair of angles was collected for typically 3 h, then transferred to paper tape, and then to type-

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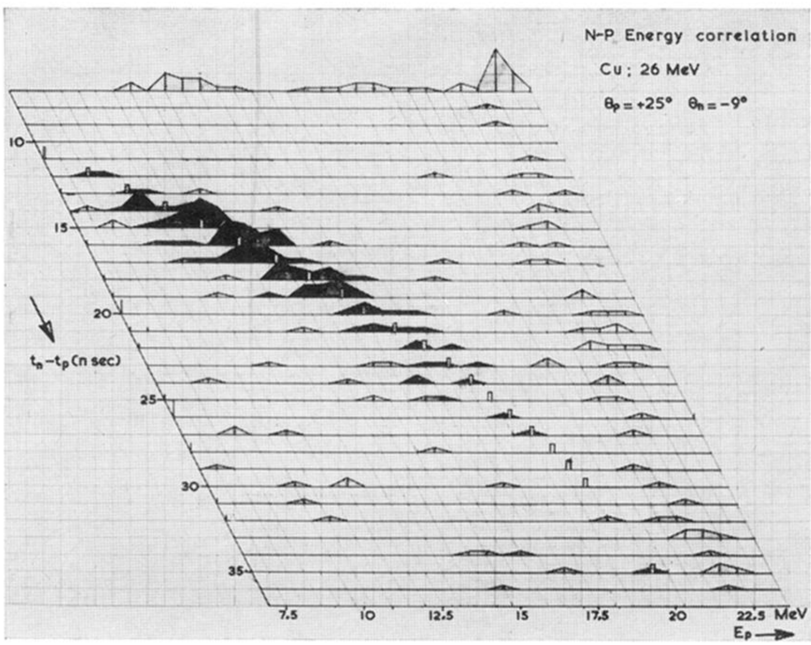
[1] Robert L. Chase, Rev. Sci. Instr. **31**, 945 (1960).

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