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**Neutron Energy Distributions from Be, C, and Pb
Bombarded by 245 Mev Protons**

by

B. K. Nelson (a)

G. Guernsey (b)

G. Mott (c)

Department of Physics

University of Rochester, Rochester, New York

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Abstract:

The energy distribution of the neutrons radiated by targets bombarded by protons of energy 244 Mev has been measured. Neutrons in the forward direction from Be, C, and Pb targets were observed, and in a direction 15° from forward from Be and C targets.

The neutrons were allowed to bombard a polyethylene radiator; scattered protons were observed by a scintillation counter coincidence telescope of four anthracene crystals. The effect of the carbon in the polyethylene was determined by taking similar data with a carbon radiator. The last counter in the telescope was used as a proportional counter, proton energies being determined by measuring the height of the scintillation pulse in this crystal. A gated amplifier, turned on by a coincidence among the four crystals of the telescope, assured that only those pulses in the proportional counter corresponding to protons traversing the telescope from the radiator were counted. The entire neutron spectrum from about 120 to 240 Mev was measured at once by measuring the spectrum of pulses in the proportional crystal with a 24-channel pulse height analyzer.

All the spectra observed were found to be peaked, the energies at the peaks being about 215, 195, and 180 Mev for Be, C, and Pb, respectively, in the forward direction, and at about 175 and 165 for Be and C at 15° .

The carbon and lead spectra were more broadly peaked than the beryllium spectra, and the 15° spectra were broader than the 0° spectra, the full widths at half maximum being 27%, 33% and 49% for Be, C, and Pb forward spectra, and 40% and 42% for Be and C at 15° .

Introduction:

This experiment is one of a group of three performed with the same equipment; the others were the measurement of the total neutron cross section in hydrogen and carbon at various energies in the range from 90 to 220 Mev⁽¹⁾, and the measurement of the differential n-p scattering cross section at 180 and 220 Mev⁽²⁾.

The experiments make use of an anthracene scintillation crystal in the measurement of the energy of the protons from n-p scattering; since the intensity of the scintillation is a monotonic function of the energy loss of the proton in the crystal, which in turn is a function of the incident energy of the proton, it is possible, by measuring the height of the scintillation pulse, to determine the energy of the proton. This method of determining the proton energy presents certain advantages over the use of absorbers, namely, the large and somewhat uncertain corrections for losses in the absorbers do not have to be made, and further, it is possible to obtain information concerning a large part of the neutron spectrum at one time.

APPARATUS:

The Neutron Source:

Three targets were mounted on flip coils arranged in a circle so that any one of them could be raised into the same position in the proton beam. They were a 1" Be target, a 0.761" carbon target, and a 0.209" Pb target, located at the 58" radius of the Rochester 120" cyclotron, where the energy of the proton beam, calculated from the magnetic field at that radius, is about 244 Mev. Two of the sets of data reported were obtained with a fourth, $\frac{1}{2}$ " Be target, at a radius of 58 $\frac{1}{4}$ ", where the proton energy is about 245 Mev.

Collimator:

A three foot cube of copper, with a 1"x1" hole through it, was used to collimate the neutron beam and shield the counters from the direct radiation from the cyclotron. This shielding was essential for reduction of the background.

Radiator and Counter Telescope:

Two n-p radiators, one polyethylene and one carbon, were mounted on a wheel in such a way that by selsyn control from the research room either one could be inserted in the neutron beam behind the collimator, or no radiator at all. The polyethylene radiator was $\frac{1}{2}$ " thick, the carbon radiator of such a thickness as to have the same number of carbon nuclei per square centimeter as the other.

Protons scattered from the radiator were detected by a counter telescope consisting of four anthracene crystals with RCA 5619 photomultipliers. The photomultipliers and their associated preamplifiers were provided with magnetic shields consisting of three concentric iron cylinders, for operation in the stray magnetic field of the cyclotron. The first three crystals were mounted on lucite light pipes to remove their shields from the neutron beam. The fourth crystal was mounted directly on the photomultiplier, adjacent to the photocathode, for maximum pulse height resolution.

Alignment:

The equipment was designed so that the collimator could be put in a predetermined position by rolling it into place along tracks which had been aligned with lines scribed in the coil dust cover. The counter telescope and radiator support wheel, in a separate assembly, were then

supported on the tracks behind the collimator, a slight amount of adjustment being allowed to center the radiator in the beam. The telescope assembly was constructed so that the entire telescope could be rotated about a vertical axis through the radiator.

Figure 1(a) is a diagram of the experimental arrangement.

Electronics: (2)

A four-fold coincidence circuit with a resolving time of 4×10^{-8} seconds was used with the telescope. Pulses from this circuit were used to trigger a gated amplifier which was part of a highly stabilized (by negative feedback) chain of amplifiers driven by the fourth, or proportional, crystal. The length of the gate was 0.75 microseconds. The output of this amplifier chain was analyzed by a 24-channel pulse height analyzer⁽⁴⁾.

Cathode followers were used to couple the first three photomultipliers to the 93 ohm cable between cyclotron and research rooms, while for increased stability under line voltage changes, a three-stage feedback amplifier with unity gain was used with the fourth.

A delay of 600 feet of 93 ohm coaxial cable was used in the proportional chain ahead of the gated amplifier, to assure the arrival of the pulse in the middle of the gate.

After the coincidence circuit was adjusted for proper discrimination against triples, counting rate versus voltage data were taken with each photomultiplier separately; the tubes were then operated at voltages on the plateaux of these curves. The high voltage for the photomultipliers was supplied by a regulated power supply. Figure 1(b) shows a block diagram of the electronics.

Calibration:

The equipment was calibrated both with electrically generated pulses simulating the shape of a scintillation pulse, and with monoenergetic protons.

The electronic pulses were generated by discharging a condenser into a 92 ohm cable connected to the input of the photomultiplier pre-amplifier. Additional outputs from the pulser were used to trigger the coincidence circuit during calibration in a manner similar to that obtaining during a run. The voltage to which the condenser was charged was used as an indication of the size of the pulse. By varying this voltage and observing the response of the pulse height selector, the response of the entire amplifier chain to pulses at its input was calibrated.

Monoenergetic protons were obtained by using the collimator and magnetic field as a mass spectrometer, detecting protons scattered from a target properly placed in the internal proton beam. (See Fig. 1) The telescope was aligned with the collimator hole and the radiators removed. The response of the proportional crystal to these protons could then be observed. Additional proton energies for calibration were obtained by putting various thicknesses of copper in the proton beam, as well as by using a second target in the cyclotron, scattered protons from which had a trajectory of different radius to the collimator.

The energy of the protons was determined by measuring their range in copper⁽⁵⁾, and in the case of the higher energy group, by calculation from their known trajectory in the field. These two methods agreed within one percent, giving as the energy at the crystal, 193 ± 1.5 Mev.

Information concerning the resolution of the response of the equipment to monoenergetic protons was also obtained simultaneously with calibrating data.

The finite resolution is due largely to statistical fluctuations of the energy loss of the protons in the crystal. This has been treated theoretically in an unpublished thesis by K. R. Symon, Harvard, 1948; calculations based on this treatment indicate that resolutions between 10 and 15% are to be expected, improving with increasing pulse height. The resolution observed with monoenergetic protons is plotted as a function of pulse height in Figure 2. The resolution is of the right order of magnitude to agree with Symon's thesis, and does improve with increasing pulse height, though not so fast as the theory predicts, namely from 15% at pulse height 16.2 to 10% at pulse height 23.4. The effect of straggling of the protons in the copper absorber can be seen in the increase in the width of the resolution for pulses greater than pulse height 20.

In the calculations of neutron energy spectra from scintillation pulse height spectra, the resolution has been taken as given by the straight line, $\Delta h \sqrt{h}$ constant, in Figure 2.

This line has been drawn somewhat below most of the points corresponding to data obtained with the 192 Mev protons. This was done because there was evidence that part of the width of the response curves was due to the fact that this proton group was not completely monoenergetic. Preliminary data taken with a larger hole in the collimator had indicated a second group of protons, just resolved, of energy about 170 Mev; it appeared that these came from some other source in the cyclotron than the target, as for example, one of the Dees, and they were almost completely removed when the collimator opening was reduced to the 1"x1" size used throughout the experiment. But it appeared that perhaps they were not completely removed. The line is drawn through the point at

pulse height 30, 10% resolution, because this point corresponds to data obtained with the undegraded 77 Mev group of protons from the second proton target, which had exhibited no such low energy contamination.

The anthracene crystal used was the best available at the time of the experiment. The resolution obtained left much to be desired, as it was sometimes almost as great as the width of the spectra to be observed. The theory indicates that a thicker crystal would improve this situation, the resolution being better with the corresponding increased energy loss. The limit in this direction will be set by experimental difficulties in light collection and by nuclear interactions of the protons with the crystal.

Monitor:

The monitor used was a scintillation counter telescope similar to the main telescope. This telescope was set up alongside the collimator, which shielded its counters from direct ionizing radiation from the cyclotron, as indicated in Figure 1. There were four anthracene crystals and a polyethylene radiator. 1P21 photomultipliers were used. The proper operating voltages were determined, as before, by using a voltage on the plateau of a counting rate versus voltage curve for each counter.

EXPERIMENTAL PROCEDURE

The procedure adopted was as follows: First the response of the equipment to calibrating protons was observed. Then the telescope was set to some convenient angle, a neutron target raised, and with the polyethylene radiator in place, a pulse height spectrum taken. The polyethylene was then replaced by the carbon radiator and a second pulse height spectrum taken. This alternation between CH_2 and C

radiators was then repeated until a reasonable compromise was reached between excessively long running time with good counting statistics and a short running time with poor counting statistics. The response to the calibrating protons was then checked again.

Run Calibration:

There was evidence of drift of the response of the photomultiplier during the course of the experiment, hence the calibration check for each run as outlined above.

For the two sets of data obtained with the $\frac{1}{2}$ " Be target at the $56\frac{1}{4}$ " radius, the geometry was the same as that during the original calibration, and the run calibrating protons had the same energy, 193 Mev. For the data obtained with the other three targets, however, the geometry of the setup was different, and the calibrating protons were of different energy. Since they were to be used to check the calibration, their energy could not be determined by direct reference to the calibration curve. The original calibration data were used, however, to determine the energy in a very simple manner. A copper absorber of known thickness was inserted in half of the proton beam, so that at the proportional crystal the proton spectrum consisted of two monoenergetic groups. The ratio of the scintillation pulse heights of these two groups is correctly given by the original calibration curves (of pulse height versus p.h.s. channel number) even under a drift in the response of the photomultiplier, since such a drift will be one in gain. Having this ratio, the amount of absorber used, and the original pulse height -vs- proton energy curve, one can calculate the energy of the protons. It was found to be 112 ± 1 Mev, under varying conditions of thickness of absorber and photomultiplier high

voltage.

One final check on the calibration is available when the neutron spectrum is calculated from the pulse height spectrum. There must be no neutrons of energy greater than $(E_p + Q)$, E_p being the bombarding proton energy and $-Q$ being the threshold of the (p,n) reaction in the target. As it turns out, application of this criterion indicates that there was a systematic error in pulse height determination, of about 6% for those runs calibrated with the 113 Mev protons, and about 2% for those runs calibrated with 193 Mev protons. Apparently there was a 2% error in the high energy portion of the initial calibration curve, and an additional 2% error in the determination of the energy of the "113" Mev protons.

The neutron spectra reported here are as calculated with these corrections applied to the pulse height scale.

Treatment of background:

The background in this equipment can be classed in two categories as due to either fast random coincidences or slow random coincidences. In the first group, the gate is opened by a random quadruple registered in the "fast" four-fold coincidence circuit (as for example a particle traversing the first three counters accompanied by a chance coincidence in the fourth). In the second group, the gate is opened by either a true or random fast fourfold coincidence, and a particle traverses the fourth crystal by chance at such a time that its pulse reaches the gated amplifier during the time its gate is open. Of the two, because of the longer resolving time, the latter should be the more numerous. Measured, by removing the pulse-timing delay from the proportional channel, it was found, with the polyethylene radiator, to be of the order of 10% of the total. Its spectrum, however, ex-

hibited the same shape as that of the total spectrum, indicating that in large part it arose from protons originating in the radiator, and hence, though measured in a random way, really consisted of a part of the true spectrum. It need not, then, be subtracted. Thus, the random background which should be subtracted is small compared with 10% of the total counting rate with the CH_2 radiator; it will be of the same order of magnitude with the carbon radiator, and save for a correction too small to be justified by the counting statistics attained, the random background correction will be made automatically with the carbon background subtraction.

EXPERIMENTAL RESULTS

The pulse height spectra obtained ($\text{CH}_2 - \text{C}$ differences) are presented in figures 3(a) to 3(g). The standard deviations of the data are indicated. The data are plotted as obtained with pulse height corrections made as indicated by the run calibration checks. The smooth curves are those corresponding to the neutron spectra of Figures 4(a) to 4(g).

METHOD OF ANALYSIS OF DATA

The following steps are followed in calculation of a neutron spectrum from an observed pulse height spectrum:

- (a) Correction is made for the finite pulse height resolution of the response to monoenergetic protons (this correction is described below).
- (b) The corrected pulse height spectrum is transformed to a proton energy spectrum, making use of the pulse-vs-energy calibration curve and

its slope: $\frac{dN}{dE} = -\frac{\frac{dN}{dE}}{\frac{\partial h}{\partial E}}$

(c) The proton energy spectrum at the proportional crystal, just obtained, is transformed to a proton energy spectrum at the radiator, correction being made for the energy loss in the first three crystals of the telescope and in the radiator.

(a) Correction is made for the finite angular resolution of the telescope because of the finite spread in proton energies scattered into the telescope by a monoenergetic neutron beam. This correction is similar to that of step (a).

(e) From this proton spectrum, of form $\frac{dN_p}{dE_p}$, is calculated a spectrum of protons per unit neutron energy interval, of form $\frac{dN_p}{dE}$, proton energy as a function of neutron energy being obtained from the relativistic expression

$$E_p = \frac{E}{1 + (\tan^2 \theta) \left(1 + \frac{E_n}{2Mc^2}\right)}$$

(f) Finally, the neutron spectrum is calculated from this by

$$\frac{dN}{dE} = \left(\frac{dN_p}{dE}\right) \left(\frac{1}{k \sigma_{np}(E, \theta)}\right)$$

The cross section, $\sigma_{np}(E, \theta)$ was obtained by interpolation from the Berkeley data⁽⁶⁾ for the differential n-p scattering cross section at 40, 90, and 260 Mev. The constant k is the

product of the number of H nuclei in the radiator times the solid angle of the telescope as seen by each such nucleus.

The correction for finite resolution is the solution of the integral equation

$$F(h) = \int_{-\infty}^{\infty} g(\eta) f(h - \eta) d\eta$$

for $f(h)$, where $F(h)$ is the observed spectrum, and $g(\eta)$ is the resolution curve of the instrument, $g(\eta)\Delta\eta$ being the probability for recording at height h a pulse which should be recorded between height $h - \eta$ and $h - (\eta + \Delta\eta)$. This equation was solved numerically, $g(\eta)$ being obtained from the response of the equipment to monoenergetic protons.

NEUTRON SPECTRA

The spectra obtained are presented in figures 4(a) to 4(c). As remarked before, they are plotted as corresponding to pulse height spectra with pulse height scale 1.06 times that of the pulse height spectra observed (the correction is 1.03 for the two Be spectra with 20° and 40° telescope angle).

In figure 5 is the spectrum of figure 4(a) plotted together with the spectra reported from Harvard⁽⁷⁾, Harwell⁽⁸⁾, and Berkeley⁽⁹⁾, from beryllium bombarded by protons of energies 114, 149, and 360 Mev, respectively.

NEUTRON SPECTRUM TO BE EXPECTED FROM A MONOENERGETIC PROTON BEAM

In the course of an experiment on meson yields of various targets⁽¹⁰⁾, D. Clark has made measurements of the recirculation of the cyclotron beam. His data indicate that with a 1" Be target, one

would expect a recirculation of 1.24, i.e. the beam intensity is 1.24 times that which would obtain without recirculation. With this information, and the known energy loss in the target, one can calculate a reasonable energy spectrum for the proton beam. It is presented in Figure 6(a). The widths of the steps of this histogram are the energy loss in the target (15.7 Mev for 244 Mev protons in 1" of Be), and the heights of the successive steps constitute a geometric progression whose sum is 1.24, the height of the largest step being unity.

By making use of this spectrum and the neutron spectrum observed with this target (Figure 4(a)), one can calculate the neutron spectrum that would arise from a monoenergetic proton spectrum. The calculation is of the same sort as that used in treating the finite pulse and angular resolutions in calculating the neutron spectra. This neutron spectrum is given in Figure 6(a). For ease of calculation it has been somewhat idealized, but its important features are correctly represented.

It is, of course, possible to do this again, using the neutron spectrum observed with the $\frac{1}{2}$ " Be target. However, what has been done in this case is to use the neutron spectrum just calculated as corresponding to monoenergetic protons, and the hypothetical proton spectrum corresponding to a $\frac{1}{2}$ " Be target (recirculation 1.50, energy loss 7.6 Mev), and calculate the neutron energy spectrum one would expect to observe with this target. This can then be compared with the spectrum already reported for this target, Figure 4(b), to get some idea of the validity of the neutron spectrum for monoenergetic protons of Figure 6(a). The various spectra involved in this process are presented in Figure 6(b); the observed spectrum, D, has been expanded vertically

by a factor of 1.07, not a severe renormalization since the monitor geometry was slightly different in the two runs.

It is to be observed that the two spectra are not identical. The difference, particularly at the low energy end, is a bit greater than is to be expected from a consideration of the uncertainty of the shapes of the two reported neutron spectra.

The difficulty probably lies in the simplicity of approach to the energy spectrum of the proton beam. No consideration was taken of the inhomogeneity of the primary proton beam, due, for example, to radial oscillations. The assumption was implicitly made that the target was aligned exactly tangent to the proton orbit, so that all the protons traversed the same target thickness; this assumption is not justified. Also, the two targets were not in the same position in the cyclotron, so that the effect of the radial oscillations might have been different for the two. In view of these considerations, the disagreement is perhaps not so bad. There is, in this disagreement, an indication of the uncertainty of the spectra of Figures 6 reported as corresponding to monoenergetic protons.

UNCERTAINTY IN SHAPE OF SPECTRA

Because of the nature of the calculations it is impossible to present observed points with their statistical spreads on the neutron spectra of Figures 4(a) to 4(g). As an indication of the uncertainty in the knowledge of the shape of these spectra, then, the pulse height spectra corresponding to two idealized neutron spectra have been calculated. These spectra, Figures 7, have about the same width at half maximum as the spectra of Figure 4, but one has its peak at a higher energy and one at a lower energy. The pulse height spectra are

plotted in Figures 8, along with the experimental data, and the smooth curves from which the spectra of Figure 4 were calculated.

Some idea of the precision obtained is given by these curves; the extremes shown are clearly poor fits to the data.

Acknowledgment

It is a pleasure to acknowledge the help that was received from various quarters. Professor A. Roberts was very generous with advice and assistance throughout the course of the experiment, and offered many valuable suggestions during the preparation of this paper. We are indebted to Mr. D. Clark for the use of his coincidence equipment with our monitor telescope, and for the information on recirculation of the cyclotron proton beam used herein. The personnel of the Electronics Shop and of the Engineering Department constructed much of the equipment used. Mr. L. Momo of the Engineering Department was responsible for the detail design of the collimator and telescope mount and support. This research was supported by the Atomic Energy Commission under Contract No. AT 20-(1)-875.

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Fig 1(a) Experimental Arrangement. The dotted lines indicate the position of the equipment during the calibration, the solid lines the position during the run.

Fig 1(b) Block Diagram of Electronics

During the calibration with the test pulser, an additional connection was made between the pulser and the coincidence analyser, so the gated amplifier was turned on in the same way as during a run.

Fig 2 Resolution of Equipment versus Scintillation Pulse Height.
The circles indicate data obtained with 192 Mev protons from one target, degraded by various amounts of copper; the crosses indicate data obtained with 77 Mev protons from a second target, similarly degraded. The straight line is of the form $\frac{1}{\Delta H} = \frac{1}{H_0} + \frac{1}{H_1}$ constant.

Fig 2 Pulse Height Spectra (Polyethylene-Carbon Differences)
The standard deviations of the data are indicated.

(a) Target: 1" Be

Neutron Angle: 0°

Telescope Angle: 15°

(b) Target: $\frac{1}{2}$ " Be

Neutron Angle: 0°

Telescope Angle: 20°

(c) Target: $\frac{1}{8}$ " Be

Neutron Angle: 0°

Telescope Angle: 40°

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- (d) Target: C
Neutron Angle: 0°
Telescope Angle: 15°
- (e) Target: Pb
Neutron Angle: 0°
Telescope Angle: 10°
- (f) Target: 1" Be
Neutron Angle: 15°
Telescope Angle: 16°
- (g) Target: C
Neutron Angle: 15°
Telescope Angle: 16°

Fig 4 Neutron Energy Spectra Corresponding to the Pulse Height Spectra of Fig 3.

- (a) Spectra in the forward direction from 1" Be, .781" C, and .309" Pb targets
- (b) Spectrum in the forward direction from $\frac{1}{2}$ " Be target (corresponds to Figs 3(b) and 3(c))
- (c) Spectra at 15° from 1" Be and 0.781" C targets.

Fig 5 Comparison of Spectrum of this Paper with those Reported by Harvard, Harwell, and Berkeley.

The spectrum labeled Rochester is that of Fig 4(b). The others are from references (7), (8), and (9).

Fig 6 Neutron Spectrum Corresponding to Monoenergetic Proton Beam

- (a) Spectra associated with 1" Be target
 - A: Hypothetical proton spectrum calculated from data on recirculation of cyclotron proton beam.
 - B: Neutron spectrum of Fig 4(a)

C: Neutron spectrum corresponding to monoenergetic proton spectrum, calculated from A and B.

(b) Spectra Associated with $\frac{1}{2}$ " Be Target

A: Hypothetical Proton Spectrum Calculated from Recirculation Data

B: Neutron Spectrum Corresponding to Monoenergetic Protons, from Fig 6(a)

C: Neutron spectrum to be Expected from A and B

D: Observed Neutron Spectrum, from Fig 4(b), to compare with C

Fig 7 Extreme Neutron Spectra for an Indication of the Uncertainty of the shape of the reported spectra.

The pulse height spectra corresponding to these neutron spectra are given, with the observed data, in Figs 8; they do not fit the data well.

(a) Spectra Corresponding to 1" Be Target

(b) Spectra Corresponding to $\frac{1}{2}$ " Be Target

Fig 8 Pulse Height Spectra Corresponding to the Neutron Spectra of Fig 7.

The circles indicate the observed data, and the solid lines the spectra corresponding to the neutron spectra of Fig 7. The small-pulse-height spectrum corresponds to the high-energy spectrum.

(a) Spectra Corresponding to 1" Be Target Data

(b) Spectra Corresponding to $\frac{1}{2}$ " Be Target Data (40° Telescope)

Fig. 1(a)

RESOLUTION OF RESPONSE TO
MONOENERGETIC PROTONS

o data from 195 Mev protons
+ data from 77 Mev protons

Fig. 2

Fig 3(a)

Fig 3(b)

Fig 3(d)

Fig 3(g)

Fig 4(a)

Fig 4(b)

NEUTRON ENERGY SPECTRA
from
BERYLLIUM

SPECTRA ASSOCIATED WITH 1" Be TARGET

- A: Hypothetical Proton Spectrum
 B: Neutron Spectrum Calculated from
 Pulse Height Data
 C: Neutron Spectrum Corresponding
 to Monoenergetic Protons

Fig 6(a)

SPECTRA ASSOCIATED WITH $\frac{1}{2}''$ Be TARGET

- A: Hypothetical Proton Spectrum
 B: Hypothetical Neutron Spectrum
 Corresponding to Monoenergetic
 Protons, Obtained from $1''$ Be
 Target Data
 C: Neutron Spectrum Predicted from A & B
 D: Neutron Spectrum Calculated from
 Pulse Height Data

Fig 6(b)

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EXTREME NEUTRON SPECTRA
FOR COMPARISON WITH
SPECTRUM CALCULATED
FROM 1" Be TARGET DATA

Fig 7(a)

EXTREME NEUTRON SPECTRA
FOR COMPARISON WITH
SPECTRUM CALCULATED
FROM $\frac{1}{2}''$ B₀ TARGET DATA

Fig. 7(b)

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Fig 8(a)

Fig 8(b)