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Study of Neutral Pion Production in Proton-Proton Collisions*

C. York, R. March, W. Kernan, and J. Fischer
The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois
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A large lead glass Čerenkov counter has been used to measure the energy spectrum of gamma rays resulting from neutral pions produced in proton-proton collisions. A liquid hydrogen target was bombarded with protons of 447 Mev, 415 Mev, and 397 Mev. Gamma rays emitted at 90° to the incident proton beam were detected by a counter telescope comprised of an anticoincidence counter, a $\frac{1}{8}$-in. lead converter, two coincidence counters, and the lead glass counter. Pulses from the lead glass counter were fed through a gating circuit into a one-hundred channel pulse-height analyzer. The three pulse-height spectra obtained have been compared with those predicted from the phenomenological theory, to estimate the contributions of the various possible final angular momentum states. It is found that the spectra are consistent with isotropic emission of the π^0's in the center-of-mass system. The differential cross sections for π^0 production are 12.6 ± 2.0, 9.0 ± 1.9, and 7.4 ± 1.7 microbarns/sterad at 445, 415, and 397 Mev, respectively.

I. INTRODUCTION

MEASUREMENTS[1] of the cross section for neutral pion production in the reaction

$$p+p\rightarrow \pi^0+p+p, \qquad (1)$$

have employed counter telescopes designed to detect one of the two gamma rays produced by the π^0 decay. Because the neutral pion decays with a very short mean life ($\tau_{\pi^0}<10^{-15}$ sec), the gamma rays produced in this way originate very near the point at which the proton encounter takes place. These gamma rays will suffer both an aberration of direction and a Doppler shift of frequency due to the combined motion of the π^0 in the center-of-mass system of the collision and the motion of the center of mass itself. In order to interpret the counting rates obtained in the earlier work, it was necessary to calculate the gamma-ray energy distribution observed at a given angle of observation and bombarding energy, and fold into it the detection efficiency of the counter telescope. Because at least three final angular momentum states are allowed in reaction (1), the gamma-ray spectrum for each was computed by means of the phenomenological theory[2] and integrated to give the total count rate expected from each state. Each of these computed rates was then multiplied by an arbitrary constant and a linear relation constructed which was equated to the observed rate. A sufficient number of experimental observations had to be made to determine the set of arbitrary constants and hence the relative contributions of the various angular momentum states to the cross section.

In the present work, an attempt has been made to observe the energy spectrum of the gamma rays from neutral pions by using a large lead glass Čerenkov counter[3] as a detector. In this way, all corrections to the data requiring the gamma-ray spectrum can be made directly, without recourse to the theory. If, on the other hand, the gamma-ray spectra are calculated with the aid of the phenomenological theory, a direct comparison between these spectra and the measured spectra can be made.

II. APPARATUS

A. The Proton Beam

The arrangement of the external proton beam of the University of Chicago synchrocyclotron is shown in Fig. 1. After regenerative extraction[4] from the cyclotron, the beam traverses a quadrupole strong-focusing magnet. Near the real focus of this magnet, the vacuum pipe is capped off with a thin Mylar film and an air space of about ten inches is provided before re-entry into a separate vacuum pipe to the experimental area. The air space permitted rapid changes of beam energy to be made by the insertion of polyethylene moderators during the course of the experiment. After the air space, another strong-focus magnet and a bending magnet are provided, as shown. The former is used to focus the beam on the target while the latter is used to deflect the beam. Deflection of the beam removes neutron contamination. When absorber is introduced into the beam, appropriate adjustment of the currents in the second

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[1] Hales, Hildebrand, Knable, and Moyer, Phys. Rev. **85**, 373 (1952); Marshall, Marshall, Nedzel, and Warshaw, Phys. Rev. **88**, 632 (1952); J. Mather and E. Martinelli, Phys. Rev. **92**, 780 (1953); Iu. D. Prokoshkin, *Proceedings of the CERN Symposium on High-Energy Accelerators and Pion Physics, Geneva, 1956* (European Organization of Nuclear Research, Geneva, 1956), Vol. 2, p. 385; Baiukov, Kozodaev, and Tyapkin, *Proceedings of the CERN Symposium on High-Energy Accelerators and Pion Physics, Geneva, 1956* (European Organization of Nuclear Research, Geneva, 1956), Vol. 2, p. 398; W. O. Lock, *Proceedings of the CERN Symposium on High-Energy Accelerators and Pion Physics, Geneva, 1956* (European Organization of Nuclear Research, Geneva, 1956), Vol. 2, p. 383; Iu. D. Baiukov and A. A. Tyapkin, J. Exptl. Theoret. Phys. U.S.S.R. **32**, 953 (1957) [translation: Soviet Phys. JETP **5**, 779 (1957)]. B. J. Moyer and R. K. Squire, Phys. Rev. **100**, 1798(A) (1955); and **107**, 283 (1957); Stallwood, Sutton, Fields, Fox, and Kane, Phys. Rev. **109**, 1716 (1958).

[2] The phenomenological theory of K. Brueckner and K. Watson is summarized in M. Gell-Mann and K. Watson, *Annual Review of Nuclear Science* (Annual Reviews Inc., Stanford, 1954), Vol. 4, p. 219; and A. H. Rosenfeld, Phys. Rev. **96**, 139 (1954).

[3] Fischer, March, and Marshall, Phys. Rev. **109**, 533 (1958).

[4] A. V. Crewe and U. E. Kruse, Rev. Sci. Instr. **27**, 5 (1956).

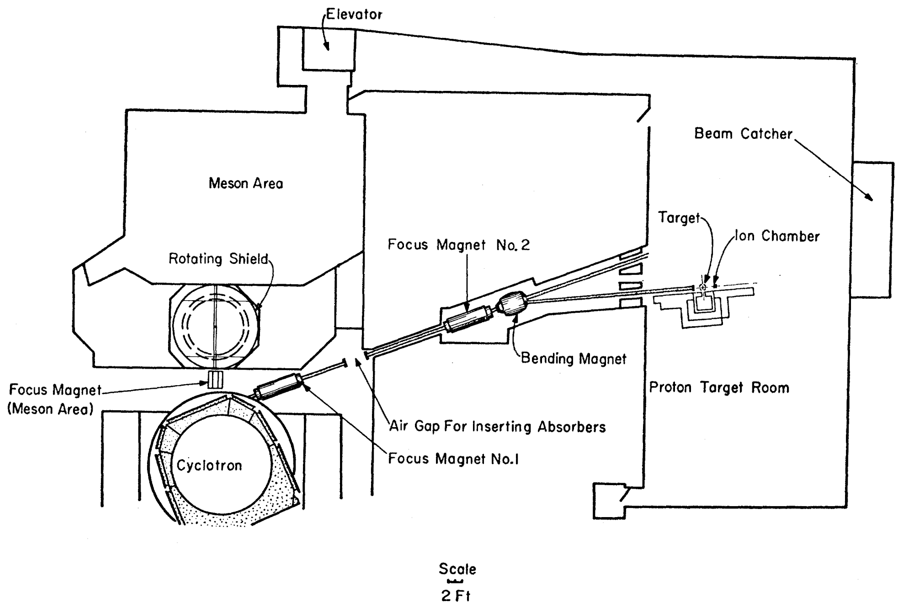

FIG. 1. Plan view of the external proton beam facility of the University of Chicago synchrocyclotron.

strong-focus and bending magnets must be made. During the course of this experiment, the power supplies for these magnets were regulated to better than $\frac{1}{4}$% and the variation in beam position on the target was less than $\pm\frac{1}{4}$ in. Photographs of the beam spot on the target were taken before and after each run, and no detectable drift of the beam's position was observed.

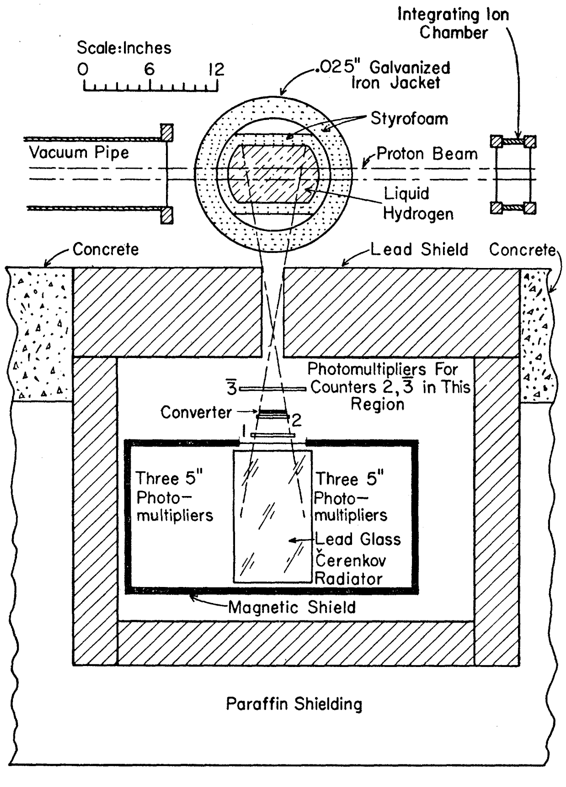

FIG. 2. Detailed plan view of the apparatus.

Three different proton energies were used in the present experiment. The maximum energy was obtained by operating the beam without any absorber at the focus of the first strong-focus magnet, while the two lower energies were obtained by the insertion of appropriate polyethylene absorbers into the beam. Each of the three energies was determined by measuring a Bragg curve in copper and using standard range curves[5] to convert to energy. Appropriate corrections for scattering have been applied and the incident proton energies determined to be 447±4 Mev, 415±4 Mev, and 397±4 Mev.

B. The γ-Ray Detector

In Fig. 2, the counter array and target geometry are indicated. The proton beam emerges from the vacuum pipe several inches from the styrofoam Dewar containing liquid hydrogen. The counter array is mounted in a shield, as shown, and views the target through a two-inch square aperture in the eight-inch wall of lead bricks. The scintillation counter telescope provides a "gate" pulse when counters 1 and 2 are triggered in coincidence without a simultaneous pulse from the anticoincidence counter, $\bar{3}$. Such counts are attributed to gamma rays traversing the system and producing showers in the $\frac{1}{8}$-in. lead converter placed between counters $\bar{3}$ and 2. The "gate" pulse opens a gate of one-half microsecond duration which permits the pulse from the lead glass Čerenkov counter to be fed into a 100-channel pulse-height analyzer.[6] A block diagram of the electronics is given in Fig. 3. The threefold

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[5] M. Rich and R. Madey, University of California Radiation Laboratory Report UCRL-2301, March, 1954 (unpublished). R. Mather and E. Segrè, Phys. Rev. 84, 191 (1951).
[6] Penco Model PA-3.

coincidence rate of counters 1, 2, and 3 was used as a monitor on the operation of the counter telescope, although this function has been omitted from Fig. 3 for simplicity.

Because this arrangement is quite different from that used by Fischer *et al.*,[3] a separate experiment was performed with electrons accompanying the 70-Mev negative pion beam from the cyclotron in order to determine the pulse height in the glass counter as a function of incident electron energy. Figures 4(a) and 4(b) show the results of this study using four different electron energies. The resolution curves were fitted to Gaussians to determine the central channel position and the width of the distribution at each energy. The location of the central channel proved to vary linearly with momentum, and was fitted to a straight line as seen in Fig. 4(a). Since the width of the distributions varied slowly with momentum, it was assumed constant with energy in the following analysis. These Gaussian distributions are compared to the experimentally measured pulse-height spectra in Fig. 4(b). The linear relation between pulse height and energy is used to convert the observed pulse-height spectra into energy spectra.

Throughout the experiment, periodic checks were made of the linearity and constancy of amplification in the lead glass counter system. The linearity of the amplifiers was checked with the aid of a precision pulse generator, and the pulse-height spectrum due to cosmic rays gave a check on the behavior of the glass counter during the course of the experiment. It was found that, in spite of the magnetic shield surrounding the glass counter, the magnetic field of the cyclotron exerted a considerable influence on the effective gain of the counter during the calibration run. As a result, an appropriate correction was applied before applying the calibration to the pulse-height spectra taken with the external proton beam. The primary source of uncertainty in assigning the proper number of gamma rays to a given energy interval arises from the uncertainty in this correction rather than from the statistical fluctuation on the number of counts in a given energy interval.

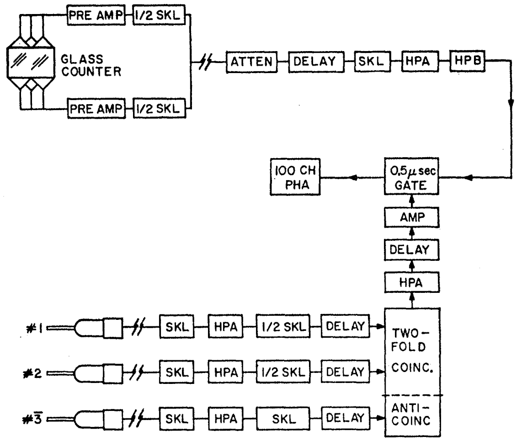

FIG. 3. Block diagram of the electronic detection system.

C. The Beam Monitor

An argon-filled ion chamber was used to monitor the proton beam intensity during the course of the experiment. This chamber had been calibrated by the technique of measuring the number of protons scattered from the beam with scintillation counter telescopes at successively higher beam rates.[7] The resulting value of the mean ionization potential of argon is in good agreement with the published values and is considered to

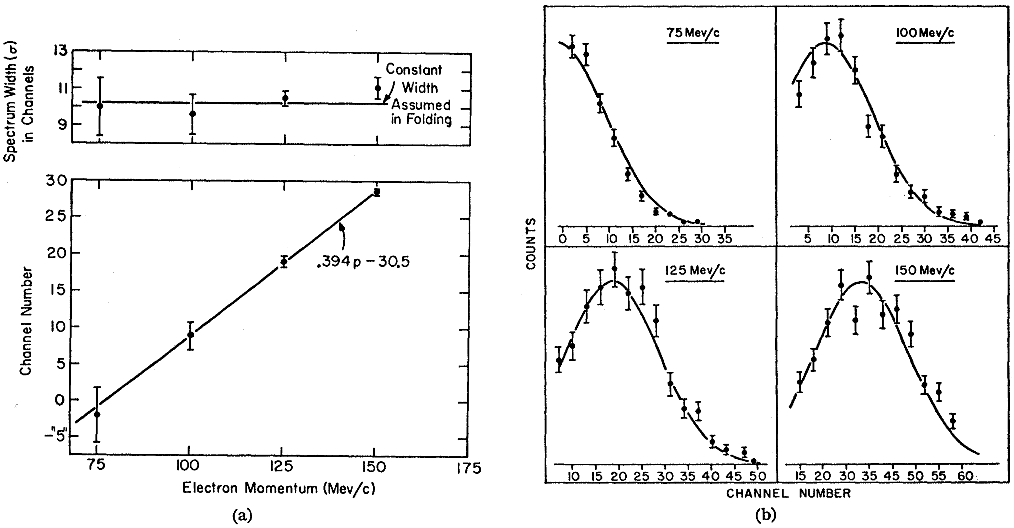

FIG. 4. (a) Calibration curves of pulse height *vs* electron momentum (below) and resolution *vs* electron momentum (above). (b) The data together with the best-fitting Gaussian curves used to determine the pulse height to energy calibration.

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[7] The authors are indebted to Professor U. E. Kruse's group for providing this calibration.

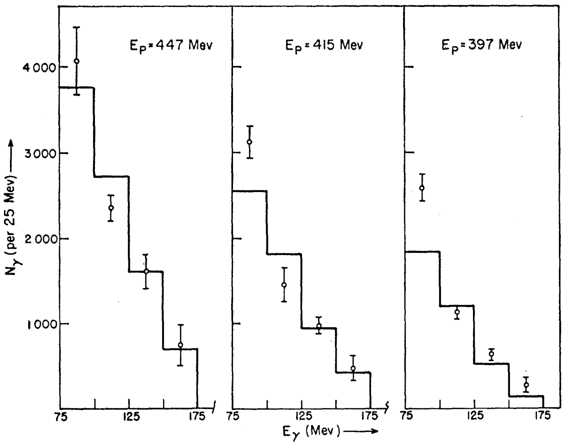

FIG. 5. A plot of the experimentally measured number of gamma rays per 25-Mev interval. The histogram indicates the best fit of the spectra computed from the phenomenological theory to the data.

contribute an error of about 3% to the final cross-section estimates.

III. EXPERIMENTAL PROCEDURE

After performing the beam energy measurements and checking the reproducibility of the magnet settings, the counter telescope electronics were adjusted using a carbon target in the proton beam. Care was taken to measure the rate of gate pulses as a function of beam intensity to avoid losses due to saturation of the trigger circuit actuating the gate. All data were taken with beam intensities of about half that at which the onset of this saturation was observed to take place.

In the hydrogen data, two types of background are important. The first is due to counts from the empty target Dewar itself. The second results from random coincidence effects associated with fluctuations in the beam intensity during the beam pulse. The average beam pulse is about 10 μsec in duration and consists of short bursts, emitted with the cyclotron "dee" frequency of about 20 Mc/sec. These short bursts are not of uniform intensity but can vary during the beam pulse by as much as a factor of two. Hence, the beam current, as measured by the ion chamber monitor, is only an average and not an indication of the instantaneous beam rate. Fortunately, the fluctuations in burst intensity vary slowly from one burst to the next, and the large over-all variations can be of several microseconds in duration. With the comparatively long gate time of 0.5 μsec, used to pass pulses from the lead glass counter into the pulse-height analyzer, the possibility of random pulses accompanying the true counts had to be investigated. Furthermore, if variations of the beam intensity with periods of several microseconds occur, then the probability of getting a true count together with a randomly occurring background pulse is greatly enhanced during such a period. In order to measure this effect, appropriate time delays were provided so that the gate could be opened 0.6 μsec *before* the truly coincident glass counter pulses arrived, in coincidence with the glass counter pulses, and 0.6 μsec *after* the glass counter pulses. In this way the background was sampled within times which are at least comparable to, and somewhat smaller than, the duration of the observed intensity fluctuations.[8]

One particular source of background was the possibility that positive pions produced during the early part of an intense series of beam bursts could be "stored" by coming to rest in the lead glass and then undergoing $\mu^+ \rightarrow e^+$ decay in times of the order of 2 μsec later. The gate might then be opened by either an accidental or true coincidence later in the intense burst and pass an appreciable number of these ~50-Mev decay positrons. To avoid this it will be noted from the results of the calibration run that the counter threshold is set at 75 Mev. A further check on the negligible nature of such an effect was to compare the rates and spectral shapes of the background spectra taken with the gate opened before and after the time-coincident glass counter pulse. These two were in fact the same within the statistics so that no net contribution of such a storage effect was observable.

TABLE I. The net counts due to gamma rays of $k>75$ Mev per 4×10^9 protons incident upon the target.

	Hydrogen		Empty Dewar	
E_p (Mev)	In time coinc.	Out of time coinc.	In time coinc.	Out of time coinc.
447	137±2	29 ±1	21.0±1.0	7.0±0.4
415	90±2	19 ±1	16.0±0.6	7.0±1.0
397	67±1	10.0±0.6	13.0±0.5	5.0±0.5

IV. EXPERIMENTAL RESULTS

Table I summarizes the observed count rates used to determine the gamma-ray spectrum from liquid hydrogen. It is to be noted that the two sources of background are comparable to each other in magnitude, but considerably less than the effect being studied. In order to determine the number of gamma rays with energy greater than 75 Mev, the net number of counts is determined from the two sources of background. However, to determine a net pulse-height distribution, requires that the background spectra be unfolded from the total spectrum. This can be done in a straightforward way. After unfolding, account must be taken of the energy variation of the efficiency of the lead converter. Finally,

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[8] The fine structure of the beam was studied by Professor J. Marshall and Mr. J. Fischer with the aid of a thin Lucite Čerenkov detector placed directly in the proton beam. The output of the photomultiplier tube of the detector was observed with a fast oscilloscope and the traces photographed at several different sweep speeds. The description of the beam behavior given here is based on a study of a large number of these photographs.

the number of gamma rays per 25-Mev interval can be plotted as shown in Fig. 5. As mentioned above, the uncertainty in the number of counts per 25 Mev is due primarily to the uncertainty in correcting the energy to pulse-height calibration for the effects of the cyclotron's magnetic field rather than statistics.

The histogram in Fig. 5 results from a least-squares fit of the measured spectra to the predictions of the phenomenological theory. In computing these theoretical spectra, the energy distributions of the gamma rays are computed for each final angular momentum state. Then the detector's resolution is folded into each. It is assumed that no final angular momentum states with $l>1$ can enter, and hence there are only four spectra to use in the fit. These correspond to the *Ss*, *Ps*, *Pp* (isotropic), and *Pp* ($\cos^2\theta$) final angular momentum states of the two nucleons (capital letter) and neutral pion (small letter).[1] In carrying out the fit of the data, the weighting constants are determined as indicated in Table II. The first attempt at a fit gives $\alpha_{Pp(\text{iso})}<0$, and since these angular momentum states cannot interfere to give a negative contribution to the cross section, $\alpha_{Pp(\text{iso})}$ is set equal to zero in the second attempt at fitting the data. As seen in Table II, $\alpha_{Pp(\cos^2)}$ is <0 in this second case. Finally a satisfactory result is obtained with positive weighting coefficients for the *Ss* and *Ps* states in a ratio of about 5:1.

TABLE II. The weighting constants of each final angular momentum state obtained by least-squares fit.

	α_{Ss}	α_{Ps}	α_{Pp}(iso)	$\alpha_{Pp}(\cos^2)$
First trial	1.89±0.30	2.37±0.65	−1.91±0.96	0.04±0.41
Second trial	1.52±0.23	1.23±0.31	0	−0.68±0.19
Third trial	1.50±0.24	0.32±0.18	0	0

To estimate the differential cross section for neutral pion production, these results are used together with the theoretical spectra to determine what fraction of the gamma rays have energy greater than 75 Mev. From the measured number, the differential pion cross sections are determined as shown in the first part of Table III.

V. DISCUSSION

In the second part of Table III, a comparison of the differential cross sections for neutral pion production at 90° is made. The only data selected for comparison are those taken with external proton beams of comparable energy to that used here, bombarding liquid hydrogen targets. Clearly the cross sections measured in this experiment do not decrease with energy as rapidly as indicated by previous work. In this connection, a reservation should be expressed with regard to the 415- and 397-Mev results. These data contain only one-half the statistics of the 447-Mev data and there is some question regarding the background subtraction at these energies. However, it is of interest to note that the general result of having only *Ss* and *Ps* states contribute to the cross section is in agreement with the results obtained at the Carnegie Institute of Technology.[9] Furthermore, it should be noted that the extensive work of both Tyapkin and Prokoshkin[10] is based upon analyses which do not include the effect of the forces between the two protons, in the final state of the reaction, on the energy distribution of the neutral pion. Thus, although these authors have invoked a contribution due to a $\cos^2\theta$ term in the angular distribution of the emitted pions, it is not clear that this is necessary.

TABLE III. The experimental results of this experiment together with the results of other groups.

E_p (Mev)	Chicago results $(d\sigma/d\Omega)_{90°,k>75\text{ Mev}}$ (μb/sterad)	$(d\sigma/d\Omega)_{90°,\pi^0}$ (μb/sterad)
447	15.0±2.3	12.6±2.0
415	10.2±1.0	9.0±1.9
397	7.9±1.7	7.4±1.7
	Other Data	
E_p (Mev)	Observer	$(d\sigma/d\Omega)_{90°,\pi^0}$ (μb/sterad)
437	Carnegie Tech.[a]	6.7± 1.4
409	Soroko[b] (Moscow)	25 ±25

[a] R. A. Stallwood *et al.* (see reference 1).
[b] As quoted by Iu. D. Baiukov *et al.* (see reference 1).

The present results are indicative of the value of using the lead glass counter technique for this type of study and it is the intention of the authors to make a more thorough survey of the neutral pion production process at a later time.

VI. ACKNOWLEDGMENTS

The authors are indebted to the members of the cyclotron staff for their aid in performing this experiment and especially to Mr. Robert Ramsey for his loyal help in maintaining the apparatus. It is a pleasure to thank Mr. Burton S. Garbow of the Argonne National Laboratory for his help in programming the least-squares calculations for the A.N.L. electronic computer, "George."

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[9] See reference 1, Stallwood *et al.*

[10] A. A. Tyapkin, J. Exptl. Theoret. Phys. U.S.S.R. **30**, 1150 (1956) [translation: Soviet Phys. JETP **3**, 979 (1956)]; Iu. D. Prokoshkin, J. Exptl. Theoret. Phys. U.S.S.R. **31**, 732 (1956) [translation: Soviet Phys. JETP **4**, 618 (1957)].