UCRL-9673

UNIVERSITY OF CALIFORNIA

Ernest O. Lawrence Radiation Laboratory

TWO-WEEK LOAN COPY

This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 5545

BERKELEY, CALIFORNIA

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

To be published in Physical Review

UCRL-9673

UNIVERSITY OF CALIFORNIA
Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

ANTIPROTON-PROTON INELASTIC INTERACTIONS AT 1.61 Bev/c AND THEIR USE FOR A TEST OF CHARGE-CONJUGATION INVARIANCE IN STRONG INTERACTIONS

Nguyen-huu Xuong, Gerald R. Lynch, and C. Keith Hinrichs

April 21, 1961

ANTIPROTON-PROTON INELASTIC INTERACTIONS AT 1.61 Bev/c AND THEIR USE FOR A TEST OF CHARGE-CONJUGATION INVARIANCE IN STRONG INTERACTIONS

Nguyen-huu Xuong, Gerald R. Lynch and C. Keith Hinrichs

Lawrence Radiation Laboratory
University of California
Berkeley, California

April 21, 1961

ABSTRACT

The reactions $\bar{p} + p \rightarrow \bar{p} + p + \pi^0$, $\bar{p} + n + \pi^+$ and $p + \bar{n} + \pi^-$ have been investigated for antiprotons of 1.61 Bev/c. The cross sections are measured and found to be 1.6 ± .3 mb, 1.15 ± .3 mb, and 0.96 ± .22 mb respectively. The combined inelastic (nonannihilation) cross section is estimated to be 5.3 mb, and the annihilation cross section 51 ± 3 mb. The angular and energy distributions are presented. In all cases the antinucleons are peaked forward and the nucleons backward in the center-of-mass system.

These events can be used to check charge conjugation in strong interactions.

ANTIPROTON-PROTON INELASTIC INTERACTIONS AT 1.61 Bev/c AND THEIR USE FOR A TEST OF CHARGE-CONJUGATION INVARIANCE IN STRONG INTERACTIONS*

Nguyen-huu Xuong,† Gerald R. Lynch and C. Keith Hinrichs

Lawrence Radiation Laboratory
University of California
Berkeley, California

April 21, 1961

Inelastic Cross Section

The following four reactions constitute the nonannihilation inelastic antiproton-proton interactions which produce one pion:

$$\bar{p} + p \rightarrow \bar{p} + p + \pi^0 \quad (1)$$

$$\bar{p} + p \rightarrow \bar{p} + n + \pi^+ \quad (2)$$

$$\bar{p} + p \rightarrow p + \bar{n} + \pi^- \quad (3)$$

$$\bar{p} + p \rightarrow \bar{n} + n + \pi^0 \quad (4)$$

We have measured the cross section for Reactions (1), (2), and (3) for antiprotons of 1.61±.03 Bev/c. Reaction (4) is difficult to observe alone, but some measurements of the charge-exchange cross section have included this reaction. The details of the beam used in this experiment are given in another paper.[1]

Because many antiprotons annihilate into two charged pions plus several neutral pions ($\bar{p} + p \rightarrow \pi^+ + \pi^- + n\pi^0$), it is extremely difficult to identify unambiguously Reactions (1), (2) and (3) from a random sample of two-prong events. Therefore in order to study Reactions (1) and (2) we have analyzed

*Work done under the asupices of the U.S. Atomic Energy Commission.

†On leave from the Viet-Nam Atomic Energy Office, Saigon, South Viet-Nam.

only those events in which the negative secondary produces a four- or a six-prong event. One of these connected events is shown in Fig. 1. A six-prong secondary event is nearly certain to be an annihilation of an antiproton. Since almost all secondary four-prong events produced by pions can have at most one associated neutral pion, they can be identified by kinematic analysis.

In a total of 21,000 antiproton interactions in the 72-inch hydrogen bubble chamber, there were 495 connected events of this type. A careful scanning-table measurement of these enabled us to identify almost all the elastic scatterings among these events. The Franckenstein measuring projector was used to measure the remaining 55 candidates for the inelastic reactions. Kinematic analysis of these, using program KICK[2] (supplemented by an ionization measurement of the positive track for a few events), yielded

25 events of $\bar{p} + p \rightarrow \bar{p} + p + \pi^0$,

17 events of $\bar{p} + p \rightarrow \bar{p} + n + \pi^+$,

and 1 which fitted either reaction.

The remaining 13 events were either elastic scatterings of antiprotons or pion interactions. In all subsequent statements we will treat the one ambiguous event as if it were one-half Reaction (1) and one-half Reaction (2).

In order to study Reaction (3), we analyzed the 81 two-prong events which were possible associated with three-, five-, or seven-prong stars. Many of these stars were found not to be associated with any visible interaction. Many others were associated with a zero-prong event in the same frame and were produced by antineutrons from the reaction $\bar{p} + p \rightarrow \bar{n} + n$. Careful kinematic analysis showed that only 19 of these events were the reaction $\bar{p} + p \rightarrow p + \bar{n} + \pi^-$.

To calculate the cross section of the inelastic processes from these events with secondary annihilations it was necessary to assign a weight to

each event. This weight was equal to the reciprocal of the average probability that the antinucleon from such an event would produce an annihilation with more than two charged prongs in the 72-inch chamber. For an antiproton with a momentum equal to the beam momentum in this experiment, the calculation of this probability is straightforward because we have measured the fraction of antiproton interactions that are four- or six-prong events. To extend this to all energies we used the measured total $\bar{p}$-p cross sections[3] for Reactions (1) and (2), and for Reaction (3) we used the measured $\bar{p}$-n cross section,[4] assuming on the basis of charge independence that this is equal to the $\bar{n}$-p cross section. We took the annihilation cross section to be $\pi(\lambda\!\!\!^{-} + 0.975\ f)^2$, a form which agrees with the experimental data. To predict what fraction of the annihilations had more than two charged prongs, we used a Lorentz-invariant Fermi statistical model with an interaction volume of five times the volume having a radius of one pion Compton wave length. Such a statistical model fits fairly well the observed charged pion multiplicities.

After weighting, we estimated the number of each of these events in the film: Reaction (1), 331± 64;

(2), 236± 56;

(3), 208± 48.

No event was observed for the reaction $\bar{p} + p \rightarrow \bar{p} + p + \pi^+ + \pi^-$ or for the reaction $\bar{p} + p \rightarrow \bar{n} + n + \pi^+ + \pi^-$ with a subsequent annihilation of the antinucleon with more than two charged prongs. This sets an upper limit of about 0.1 mb for the cross section of these reactions.

After correcting for scanning efficiency and making use of the known antiproton-proton cross section,[3] we obtained

$$\sigma \text{ for } \bar{p} + p + \pi^0 = 1.6 \pm 0.3 \text{ mb},$$

$$\sigma \text{ for } \bar{p} + n + \pi^+ = 1.15 \pm 0.3 \text{ mb},$$

$$\sigma \text{ for } p + \bar{n} + \pi^- = 0.96 \pm 0.22 \text{ mb}.$$

If either the isobaric model[5] or the statistical model[6] is assumed, the cross sections for Reactions (1) and (4) are equal. On the basis of the assumption that they are indeed equal, the total inelastic cross section is $\sigma_{inel} = 5.3 \pm 1$ mb. It is interesting to note that this value is small compared with the nucleon-nucleon inelastic cross sections. These cross sections[7] are 21 ± 1 mb for the sum of the proton-proton inelastic reactions and 21 ± 4 mb for the sum of the neutron-proton inelastic reaction at this energy.

The sum of the inelastic plus the annihilation cross sections at this energy has been measured[3] as 56 ± 2 mb. Therefore the annihilation cross section is 51 ± 3 mb.

Partly as a check on this method of measuring cross sections, we calculated the differential elastic cross section from the elastic events in this sample of connected events. In about 70% of these elastic events the recoil proton stopped in the chamber, and the scanning-table measurement of its range gave a determination of the center-of-mass angle to a precision of less than 1 deg. For those events in which the proton did not stop in the chamber, the accuracy of the center-of-mass angle determination was about 3 deg. Figure 2 shows how these measurements agree with previous measurements of the elastic-scattering differential cross section in the forward diffraction peak at this energy. In addition to these events in the forward peak, there were 10 events with center-of-mass angles fairly evenly distributed between 50 and 152 deg, and there were five events in the far backward region with center-of-mass angle greater than 152 deg, where the antiproton has such a low energy that it usually stops inside the chamber. The partial cross sections for these regions are

$$\sigma_{el}(50 \text{ to } 152 \text{ deg}) = 1.4 \pm 0.5 \text{ mb}$$

and

$$\sigma_{el}(152 \text{ to } 180 \text{ deg}) = 0.05 \pm 0.02 \text{ mb}.$$

Test of Charge-Conjugation Invariance in Strong Interactions

Many experiments test parity conservation in strong interactions. But, as far as we know, there is still no experimental test of charge-conjugation invariance in strong interactions; that is to say, there is no published experimental result which is predicted by charge-conjugation invariance and is not also predicted by some other generally accepted symmetry principle.[8] Bernstein and Michel[9] have pointed out that one way of testing C in strong interactions is to look for the decay of the π^0 into three photons. This decay mode is forbidden by charge-conjugation invariance. The experimental upper limit for the branching ratio for this decay mode is about 1%.[10] This limit is of insufficient accuracy to test C in π^0 decay because one would expect the three-photon decay to be less than the two-photon decay by a factor of $\frac{e^2}{\hbar c} = \frac{1}{137}$ even if the C-conserving amplitude and the C-violating amplitude were equal.

For an unpolarized beam and target, the $\bar{p} + p$ system is invariant under the operators CP or CR, where R is a rotation of 180 deg around any axis perpendicular to the direction of motion of both the p and $\bar{p}$. We assume R invariance to be true and therefore treat a test of CR as a test of C alone. For Reaction (1), C and CP both make the following predictions in the center-of-mass system: (a) the angular distribution of the π^0 is symmetric about 90 deg; (b) the angular distribution of the proton is equal to the reflection of the angular distribution of the antiproton; and (c) the energy distributions of the proton and the antiproton are identical.

Figures 3 and 4 show that the angular distributions agree very well with these predictions. The π^0 distribution seems to be isotropic. The other distributions are very anisotropic. The antiproton tends to go forward and the proton tends to go backward relative to the incident antiproton. Figure 5 is a Dalitz plot of the $\bar{p} + p + \pi^0$ events. There is fairly good agreement with

the predictions of C and CP, which is that there will be symmetry about the diagonal line at which the proton and antiproton have the same energy.

The final states in Reactions (2) and (3) are charge conjugates of each other. Pais has shown[11] that CP conservation predicts

$$W(E_{\bar{p}}, \theta_{\bar{p}}, E_n, \theta_n, \phi_{\bar{p}n}) = W(E_p, \pi-\theta_p, E_{\bar{n}}, \pi-\theta_{\bar{n}}, \phi_{p\bar{n}}),$$

and that CR conservation predicts

$$W(E_{\bar{p}}, \theta_{\bar{p}}, E_n, \theta_n, \phi_{\bar{p}n}) = W(E_p, \pi-\theta_p, E_{\bar{n}}, \pi-\theta_{\bar{n}}, -\phi_{p\bar{n}}),$$

where E and θ are the energy and center-of-mass angle; ϕ_{12} is the azimuthal angle in the plane normal to the incident antiproton direction between Particle 2 and Particle 1; $W(E_1, \theta_1, E_{21}, \theta_2, \phi_{12})$ represents the relative probability of finding Particles 1 and 2 with these energies and angles. By integrating over all or some of the variables we get the relations

$$\sigma \text{ for } \bar{p} + n + \pi^+ = \sigma \text{ for } p + \bar{n} + \pi^-,$$

$$W(E_{\bar{p}}, E_n) = W(E_p, E_{\bar{n}}),$$

$$W(\theta_{\bar{p}}) = W(\pi - \theta_p); \; W(\theta_n) = W(\pi - \theta_{\bar{n}})$$

as predictions of either C or CP. If CP is conserved, we have $W(\phi_{\bar{p}n}) = W(\phi_{p\bar{n}})$, whereas if C is conserved, we have $W(\phi_{\bar{p}n}) = W(-\phi_{p\bar{n}})$. In this anlaysis any two of the three particles could have been used. Therefore the prediction $W(\theta_{\pi^+}) = W(\pi - \theta_{\pi^-})$ is also made by C and CP.

We have already seen that the two cross sections are in agreement as predicted. Figure 6 is a Dalitz plot of these two reactions. A good many more events have a high-energy π^+ than have a high-energy π^-. However, the difference between the two distributions does not seem to be statistically significant. Figures 7, 8, and 9 show the angular distributions of all the

products of these reactions. The symmetries predicted by C and CR are observed.

In all the above tests the predictions of C and CP are identical. It is in the distribution in the angle ϕ that these predictions differ. Figure 10 shows the $\phi_{\bar{p}n}$ and the $\phi_{p\bar{n}}$ distributions. The prediction of C is that the two distributions should be reflections of each other. Within the statistics the data are in agreement with each of these predictions. Although these statistics do not make possible a very accurate test of charge conjugation, the results do illustrate a method for testing this symmetry principle in strong interactions.

Interpretation of the Results

A statistical-model calculation[6] predicts the ratio 4:5:5:4 for the cross sections of Reactions (1), (2), (3), and (4). The isobaric model[5] predicts the ratio 2:1:1:2. To check how well our data agree with these predictions, we averaged the cross sections for Reactions (2) and (3) (because these two must be equal by CP invariance) and compared this average with the cross section for Reaction (1). Our results are consistent with the isobar-model prediction, the probability being 0.36 that our data should deviate from the prediction of this model as much as they do. This confidence level corresponds to a discrepancy of 0.9 standard deviation for a Gaussian distribution. The data are rather inconsistent with the prediction of the statistical model, for which the probability is 0.026, which corresponds to a 2.2-standard-deviation discrepancy.

The Dalitz plots for the three reactions show a fairly uniform distribution of events. If a pion-nucleon (or pion-antinucleon) isobar corresponding to the 3-3 resonance were formed, the other antinucleon (or nucleon) would have a kinetic energy of 67±31 Mev. This resonance is so broad that the

horizontal and vertical bands which correspond to it (outlined by dashed lines on the plots) take up most of the area of the Dalitz plot. For this reason our energy distributions do not provide a very sensitive test of the isobar model.

In Figure 11 the angular distribution of each particle has been combined with the angular distribution of its antiparticle in accordance with the predictions of C and CP. In this case the pions do not seem to be isotropically distributed. Just as in the $\bar{p}$-p-π^0 reaction, these reactions have the antinucleon going forward and the nucleon backward relative to the incident antiproton. The angular distributions of the protons and the neutrons look identical. This symmetry is not predicted by C, CP, nor charge independence alone. It would be predicted if the reactions proceeded through only one I-spin channel, as is predicted in the isobaric model where the reaction must go through the I = 1 channel. However, one could still obtain this symmetry if the reactions involved both the I-spin channels (0 and 1) but there were no interference at any angle.

Acknowledgments

We wish to thank Professor Luis Alvarez for his foresight and planning, which made this experiment possible, and for his encouragement during the experiment. This paper is one of many to be published from this antiproton experiment, which was the result of the efforts of many people. Credit for the design of the beam goes to Professor M. Lynn Stevenson, Dr. Phillippe Eberhard, and Dr. George Kalbfleisch. The successful operation of the run was the result of the work and insight of these three and of Drs. Janice Button, Joseph Lannutti, Bogdan Maglić, and Mr. Morris Pripstein. Members of the bubble chamber crew not only carried out the operation of the 72 inch chamber but also assisted in the beam development. During the analysis of these data the advice of Professor Stevenson and Dr. Kalbfleisch was very helpful and the contribution of Dr. Button was significant. The analysis of the antineutron data was made possible through the organization of John Poirier and the work of Phil Ogden. Discussions with Professor Abraham Pais were very useful and stimulating. The aid of Robert Foulks was much appreciated.

REFERENCES

1. J. Button, P. Eberhard, G.R. Kalbfleisch, J.E. Lannutti, G.R. Lynch, B.C. Maglić, M.L. Stevenson, and N.H. Xuong, The Reaction $\bar{p}+p \rightarrow \bar{Y}+Y$, Phys. Rev. 121, 1788 (1961).
2. A.H. Rosenfeld and J.N. Snyder, Digital Computer Analysis of Data from Bubble Chambers. II. Kinematic Analysis of Complete Events, UCRL-9098, Feb. 1960.
3. T. Elioff, L. Agnew, O. Chamberlain, H. Steiner, C. Wiegand, and T. Ypsilantis, Phys. Rev. Letters 3, 285 (59); R. Armenteros, C.H. Coombes, B. Cork, G.R. Lambertson, and W. Wentzel P.R. 119, 2068 (1960).
4. T. Elioff, Antiproton-Nucleon Cross Section from 0.5 to 1.0 Bev, (Thesis), UCRL-9288, July 1960.
5. S.J. Lindenbaum and R.M. Sternheimer, Phys. Rev. Letters 5, 24 (1960).
6. J. McConnell (Fordham University, New York), private communication.
7. A.P. Batson, B.B. Culwick, J.G. Hill, and L. Riddiford, Proc. Roy. Soc. (London) 251 218 (59).

   A.P. Batson, B.B. Culwick, H.B. Klepp and L. Riddiford, Proc. Roy. Soc. (London) 251 233 (59).
8. Gerson Goldhaber has communicated to us that his group is making a test of charge conjugation by looking at the pions from antiproton annihilations in propane.
9. J. Bernstein and L. Michel, Phys. Rev. 118, 871 (59).
10. R.P. Ely and D.H. Frisch, Phys. Rev. Letters 3, 565 (1959).
11. A. Pais, Phys. Rev. Letters 3, 242 (1959).

FIGURES

Fig. 1. A bubble chamber picture of one of the $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ events with the antiproton subsequently annihilating.

Fig. 2. The differential $\bar{p}$-p elastic scattering as measured by three experiments near 930 Mev. The solid curve is an optical-model fit to the data of the type described by Elioff, et al. (Ref. 4).

Fig. 3. Angular distribution of neutral pions from the reaction $\bar{p}+p \rightarrow \bar{p}+p+\pi^0$.

Fig. 4. Angular distributions of protons and antiprotons from the reaction $\bar{p}+p \rightarrow \bar{p}+p+\pi^0$.

Fig. 5. Dalitz plot of the $\bar{p}+p \rightarrow \bar{p}+p+\pi^0$. The area of each circle is proportional to the statistical weight assigned to the event. The dashed lines outline the horizontal and vertical bands corresponding to the energy of the recoil nucleon or antinucleon if an isobar in the 3-3 resonance is formed.

Fig. 6. Dalitz plot of the reactions $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ (solid circles) and $\bar{p}+p \rightarrow p+\bar{n}+\pi^-$ (open circles). The area of each circle is proportional to the statistical weight assigned to the event. The dashed lines are the same as those in Fig. 5.

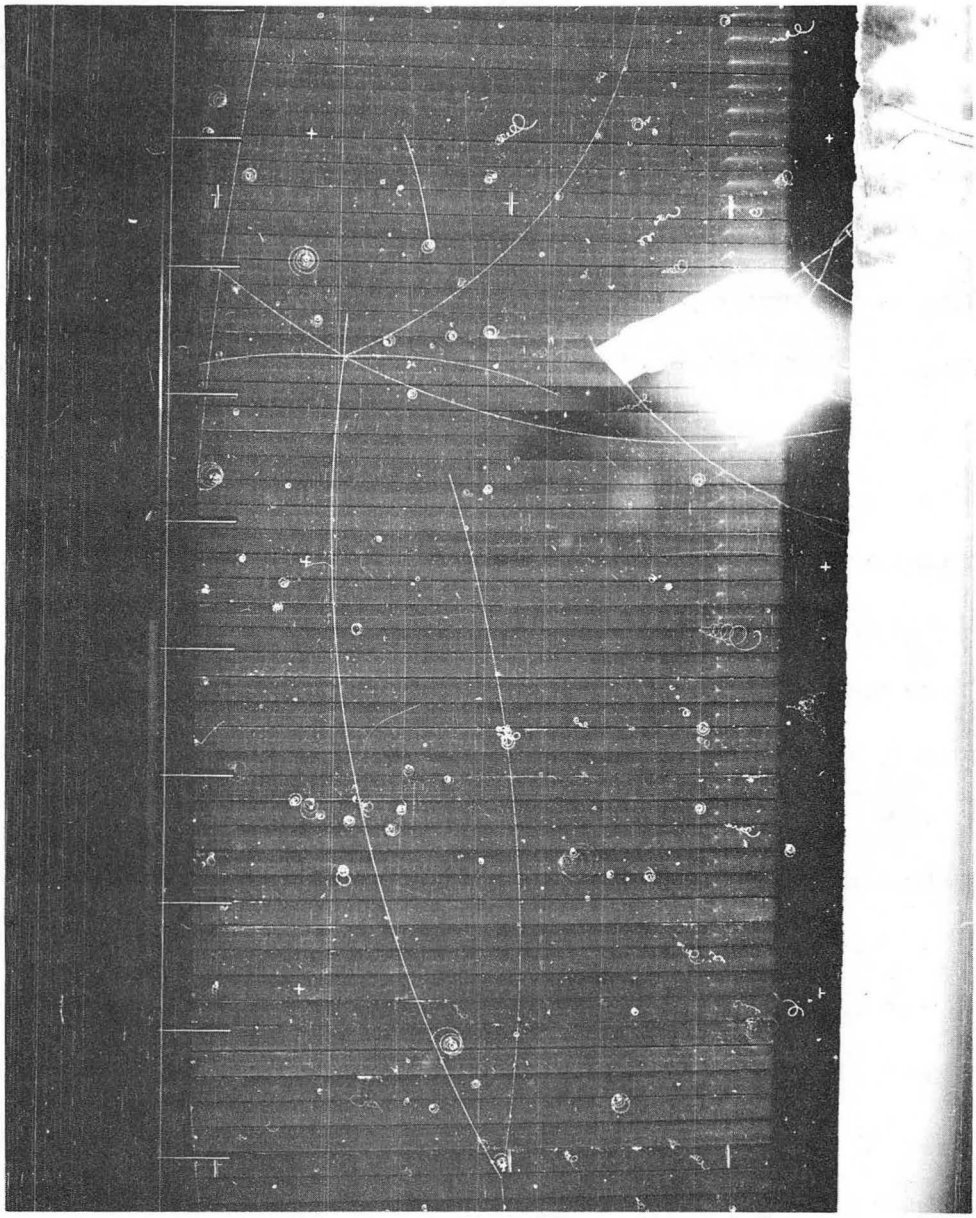
Fig. 7. Angular distributions of protons and antiprotons from the reactions $\bar{p}+p \rightarrow p+\bar{n}+\pi^-$ and $\bar{p}+n+\pi^+$.

Fig. 8. Angular distributions of neutrons and antineutrons from the reaction $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ and $p+\bar{n}+\pi^-$.

Fig. 9. Angular distributions of positive and negative pions from the reaction $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ and $p+\bar{n}+\pi^-$.

Fig. 10. Distributions in the angle ϕ for the reactions $\bar{p}+p \rightarrow \bar{p}+n+\pi^+$ and $p+\bar{n}+\pi^-$.

Fig. 11. Angular distributions of the products of $\bar{p}+p \rightarrow p+\bar{n}+\pi^-$ and $\bar{p}+n+\pi^+$ after combination according to the predictions of CR and CP.



ZN-2764

Fig. 1.

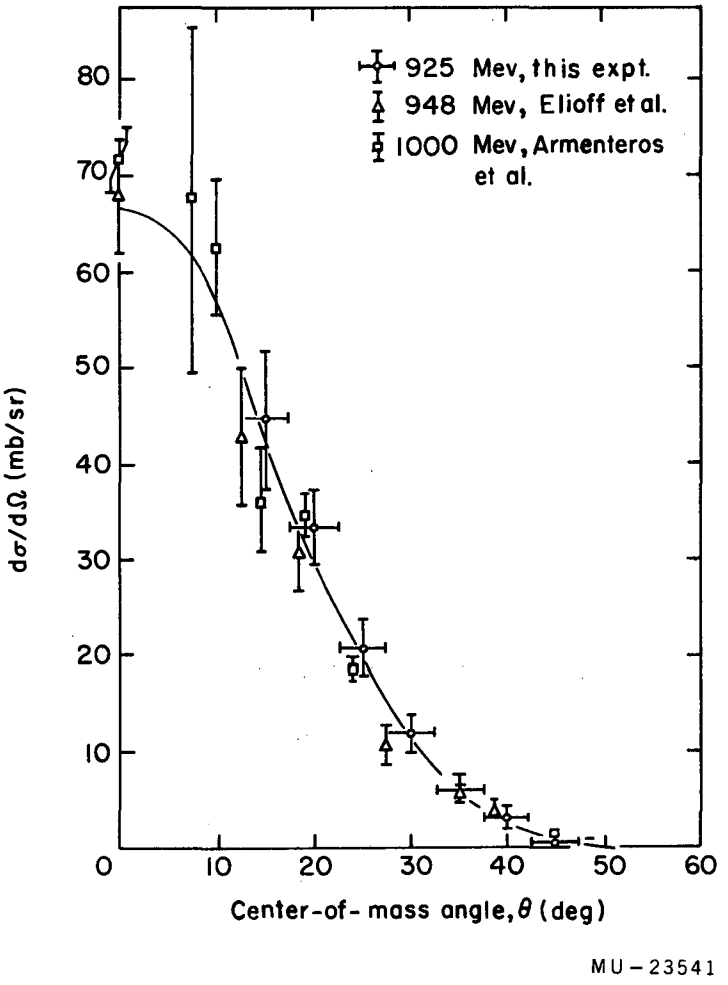

925 Mev, this expt.
948 Mev, Elioff et al.
1000 Mev, Armenteros et al.
dσ/dΩ (mb/sr)
Center-of-mass angle, θ (deg)
0
10
20
30
40
50
60
70
80
MU-23541

Fig. 2.

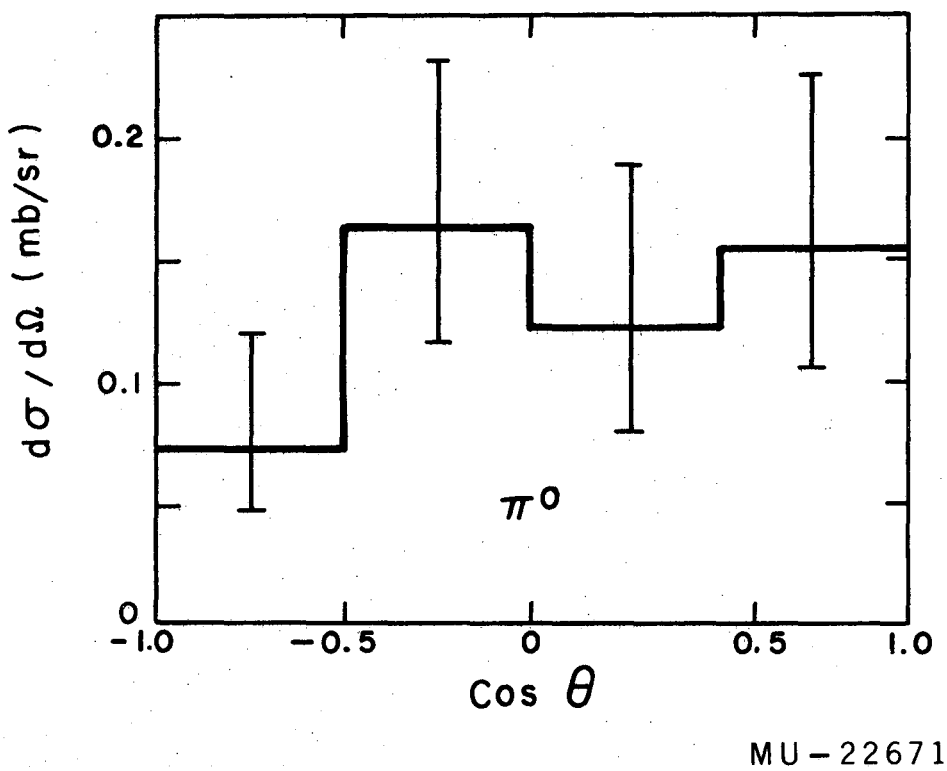


Fig. 3.

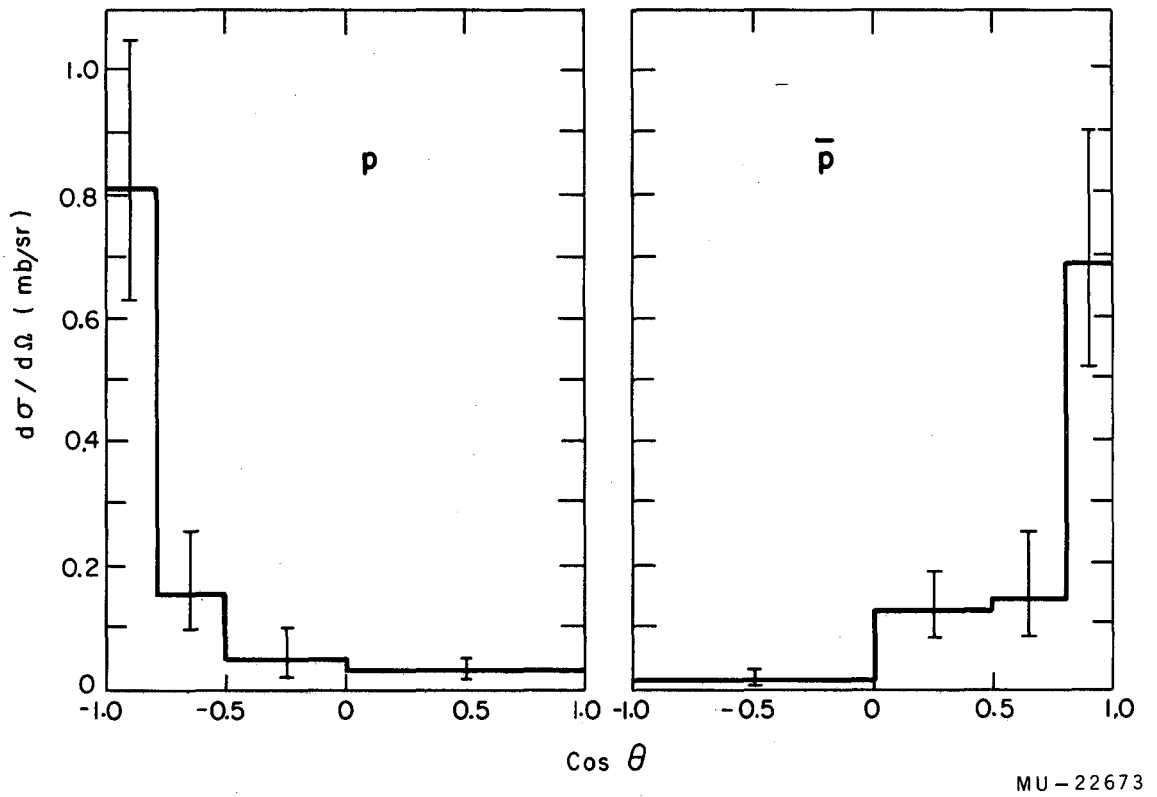


Fig. 4.

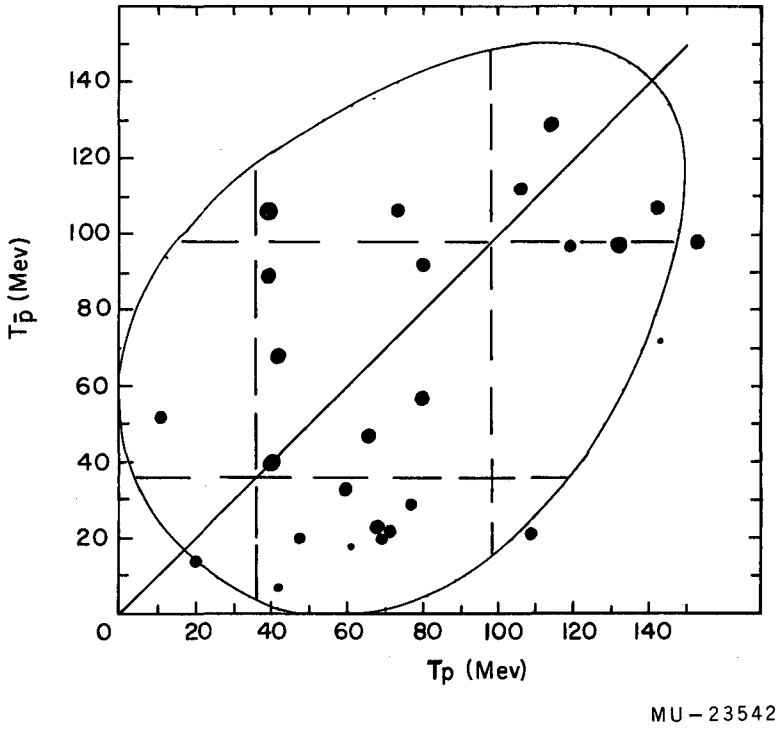
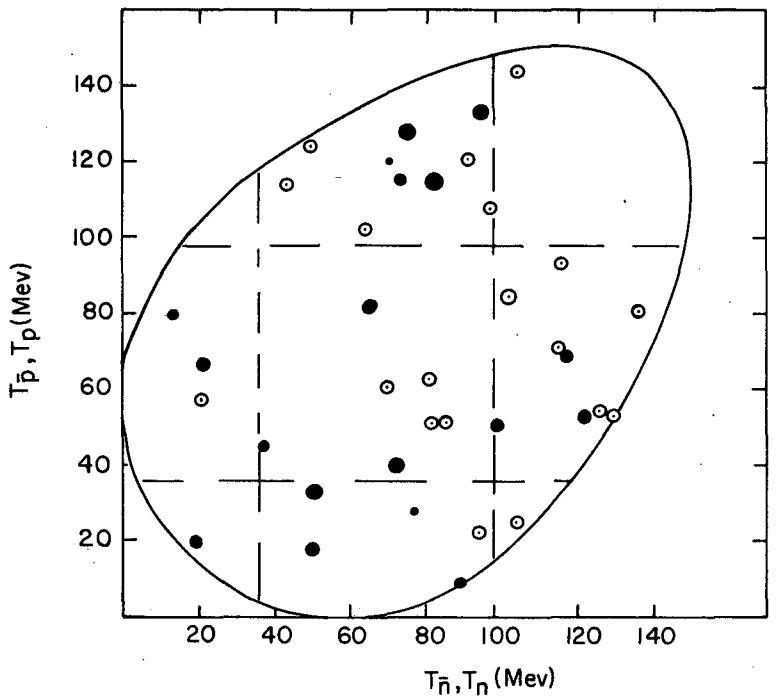

140
120
100
80
60
40
20
0
20
40
60
80
100
120
140
$T_{\bar{p}}$ (Mev)
Tp (Mev)
MU-23542

Fig. 5.



MU-23543

Fig. 6.

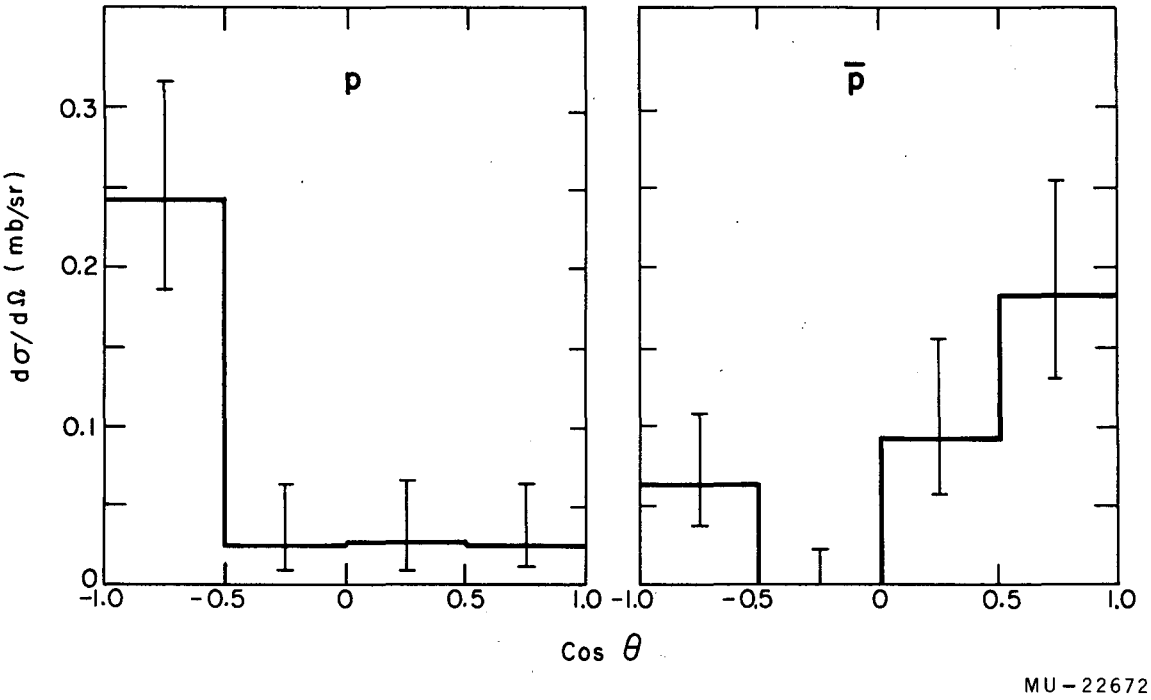


Fig. 7.

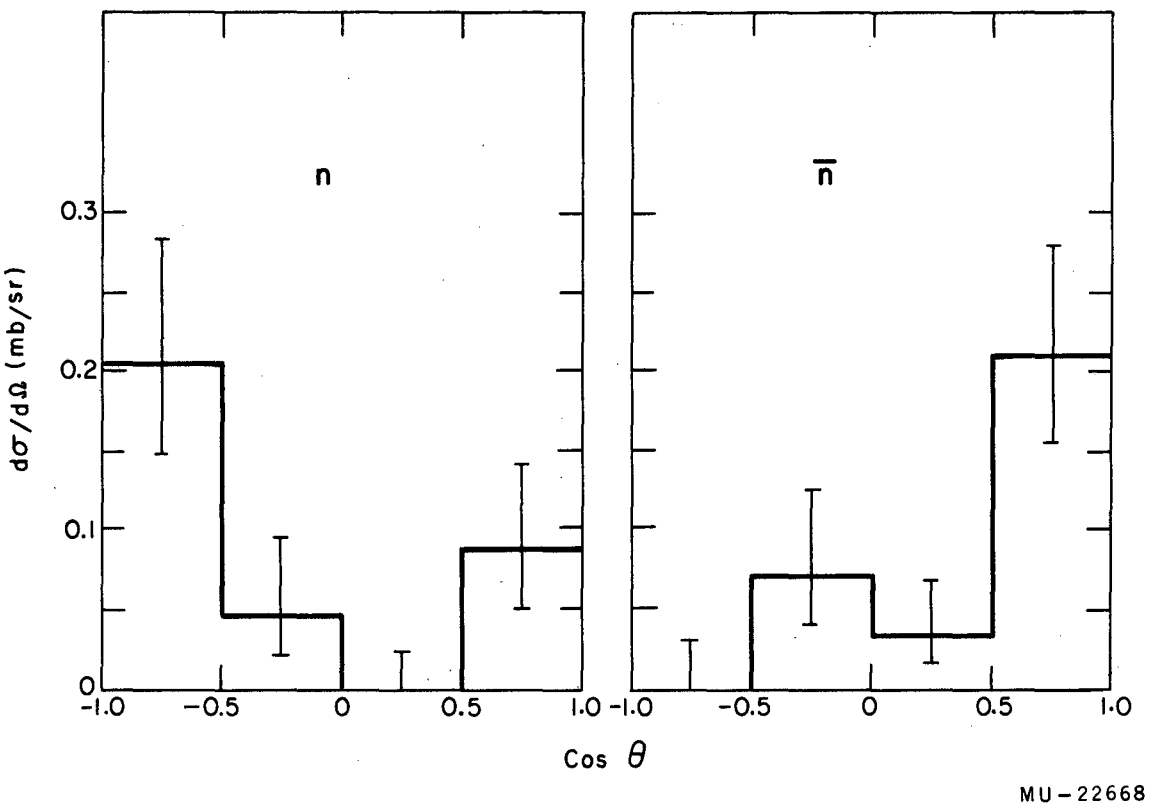


Fig. 8.

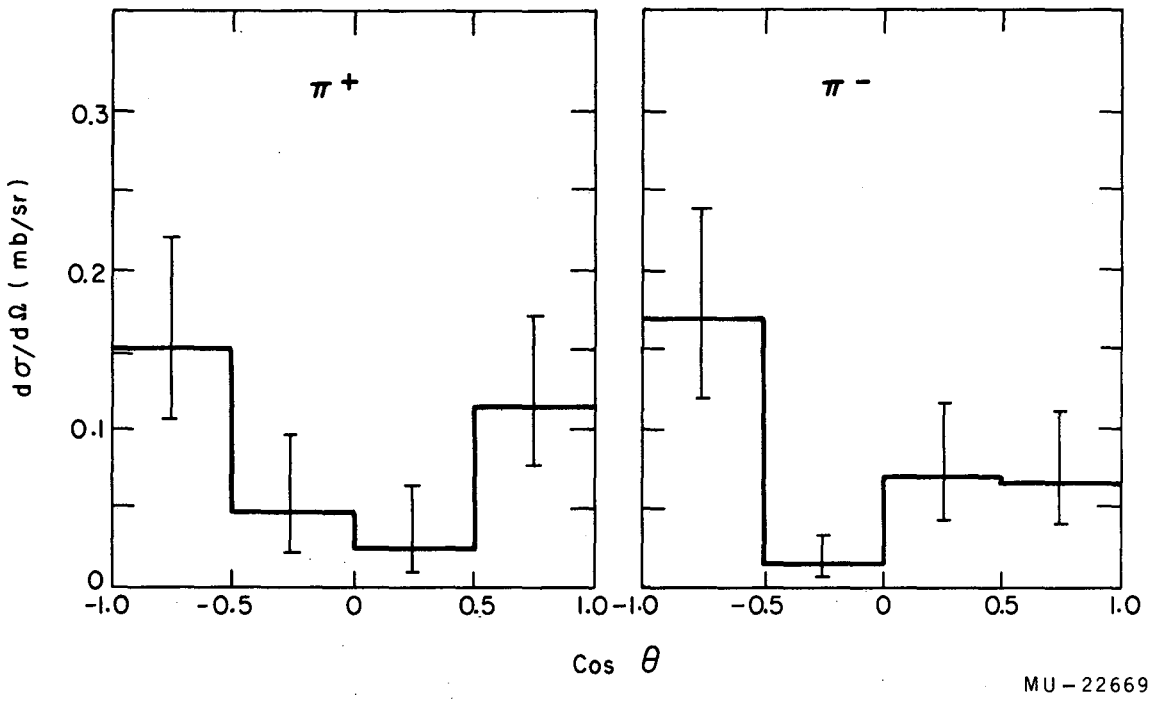


Fig. 9.

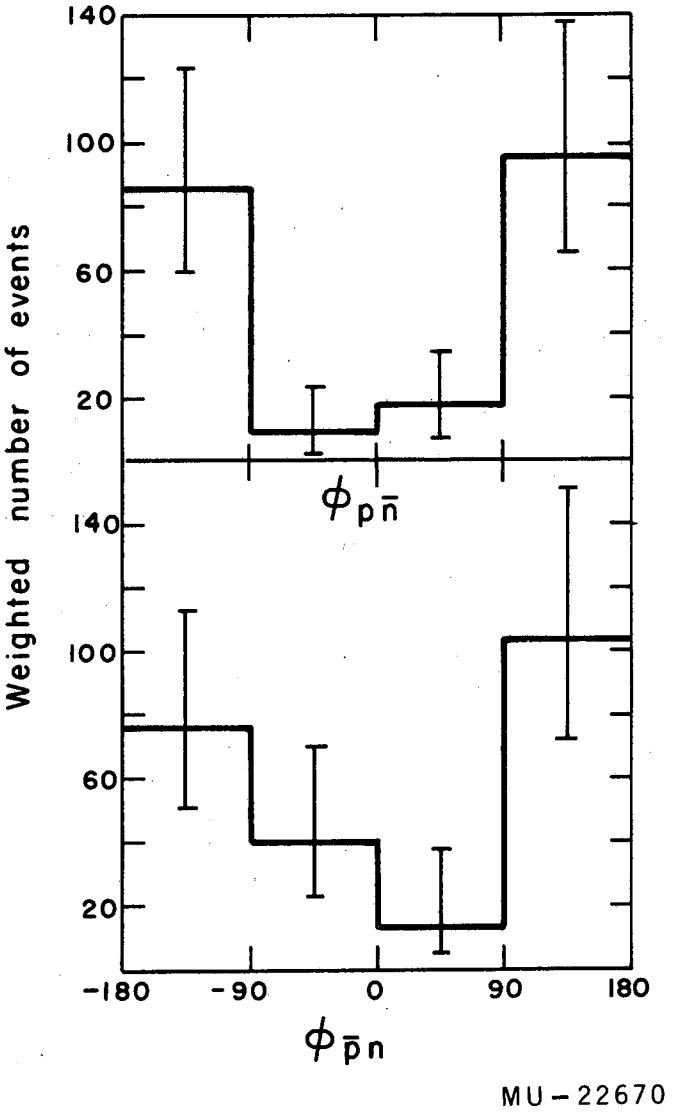

140
100
60
20
Weighted number of events
$\phi_{p\bar{n}}$
140
100
60
20
-180
-90
0
90
180
$\phi_{\bar{p}n}$
MU-22670

Fig. 10.

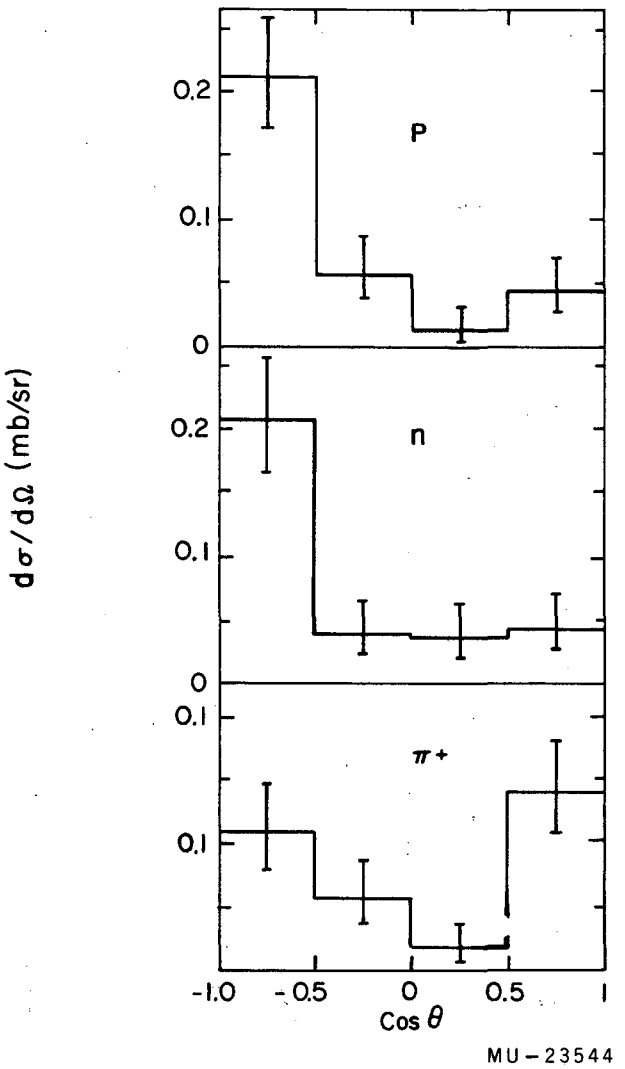


Fig. 11.

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.