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Attempt to Determine the Elastic Proton-Nucleon Cross Section at 83 GeV

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An attempt has been made to measure the proton-nucleon elastic cross section using primary cosmic-ray protons with a mean energy of 83 GeV. A total of 10 m of primary proton tracks has been line-scanned for stars resulting from elastic scatterings on nucleons bound in emulsion nuclei. The probability of detecting an elastic scatter in emulsion is considered using an analysis similar to that of McCusker. Two elasticlike scatters were found, but these can be shown to be random track-intersection coincidences, consistent with the number of proton recoils expected from neutron stars. No elastic scatters in a path length of 10 m have been found. A Monte Carlo analysis, modeled after the suggestions of Goldberger and the calculations performed by Bernardini, has been used to calculate the probability of obtaining an observable proton associated with an elasticlike event in photographic emulsion. This analysis of the detection probability of an elastic scatter indicates that the proton-nucleon elastic cross section at 83 GeV is no greater than 3 mb with 95% probability.

I. INTRODUCTION

Previous Investigations

There have been some previous reports on measurements of the proton-nucleon elastic cross section at cosmic-ray energies. A line scan, in photographic emulsion, of tracks of protons having an average energy 3 TeV has been reported by McCusker *et al.*[1,2] No elastic scatters were detected in a scanned length of 5.9 m. A calculation of the probability of detecting an elastic scatter in emulsion within this path length yielded the proton-nucleon elastic cross section at 3 TeV to be less than 8 mb with 95% probability. A similar analysis by Rybicki[3] yielded three elasticlike events in a path length of 5.8 m for protons with energies above 1 TeV. The collected data, reported by Rybicki, yielded an elastic proton-nucleon cross section of $3.8^{+13}_{-1.5}$ mb at an incident proton energy of approximately 3 TeV.

In the report of McCusker, a calculation was performed to determine the probability of observing a proton resulting from an elasticlike collision of an incident proton with a nucleon in an emulsion nucleus. The probability is calculated that this struck nucleon escapes from the nucleus or is captured, with the excitation energy possibly contributing to observable particles escaping from the nucleus. McCusker's calculations neglected the effect of the Coulomb barrier, charge exchange, Fermi motion of the bound nucleons, and the exclusion principle.

Rybicki's analysis was based on the fraction of stars observed in 24-GeV proton collisions with emulsion nuclei giving particle evaporation without visible particle production.

Because collisions with a free proton in photographic emulsion amount to only about 5% of all proton-induced interactions, studies of elastic-like collisions of cosmic-ray protons with nucleons bound in emulsion nuclei have been made. Furthermore, one is limited by the amount of track length available for determining the elastic-scattering cross section because of the low flux of cosmic rays, which are the only currently available source of high-energy particles in the 100-GeV region. Therefore, cosmic-ray protons and their elastic-like collisions with nucleons bound in emulsion nuclei are used in an attempt to estimate the elastic proton-proton cross section.

Current Experiment

The current investigation involved an emulsion stack which was used in conjunction with an apparatus consisting of an ionization spectrometer, spark chambers, and an emulsion target.[4,5] This apparatus has been used to study the cosmic-ray energy spectrum[6] and properties of individual nucleon interactions in the energy range from 10 to 300 GeV. An analysis of the primary-energy determination of primary cosmic rays using emulsion methods compared to spectrometer measurements has been previously reported.[7]

II. DESCRIPTION OF ANALYSIS

$Z = 1$ Events

A line scan[8] in emulsion of the tracks of 63 primary protons with energies above 40 GeV, which did not interact in the emulsion target with particle production, has been made. All of the 63 primary particles were located in the emulsion target without ambiguity using measurements made on spark-chamber film. A description of these location measurements has been previously reported.[9] The mean energy of these events, based on the spectrometer information, was 83 GeV and the total path length scanned was about 10 m. No interactions were found which were consistent with the kinematics of elastic proton-proton scattering.

Background Investigation

During this line scan, two elasticlike events having low-energy evaporation protons were found. These events were consistent with proton collisions with nucleons bound in emulsion nuclei. However, it was noted in this line scan that there were a number of chance coincidences of radioactive α-particle tracks which appeared to originate from the proton tracks. A comparison of the α-particle density to the density of recoil protons from neutron stars was made. This comparison, and the number of α-particle tracks appearing to originate from the primary proton tracks, indicated that two to three chance coincidences should be expected as random coincidences of recoil protons from neutron stars appearing to originate from the proton tracks. It was then concluded that the two events which appeared to be elasticlike were indeed random coincidences and not genuine. Therefore, it is concluded that no elasticlike events were observed in this study.

It should be mentioned that the events found by Rybicki in emulsion could have been inelastic events involving π^0 production, since his observed stars included protons with energies up to 280 MeV. The triggering coincidences and spark-chamber pictures of our apparatus would have indicated events including π^0 production as being events involving interactions in the emulsion. This would have automatically excluded elasticlike events which included π^0 production.

Trident Production

A check was made on the reliability of the line scan with respect to trident production associated with the primary protons. A calculation was performed using the cross section per nucleus of Block *et al.*[10] to determine the number of tridents expected in this line scan. This calculation for photographic emulsion indicated that we should have expected 1 ± 1 trident. One trident was found.

III. PROGRAM

Program Description

A Monte Carlo program has been written to calculate the probability of obtaining an observable particle associated with an elasticlike event. The program was modeled after the suggestions of Goldberger[11] and the calculations performed by Bernardini *et al.*[12] (at 400-MeV incident energy). The program, as written, includes the effect of the Coulomb barrier, the Fermi motion of the bound nucleons, and the exclusion principle, all neglected by McCusker.

The zero-temperature Fermi-gas model of the emulsion nucleus is assumed. The ground state of the emulsion nucleus is assumed to involve a non-interacting fermion gas of neutrons and protons bound in a uniform potential well. The depth of the well is equal to the sum of the maximum Fermi energy and the binding energy per nucleon. The nucleons are assumed to have a vector momentum with a magnitude between zero and the maximum value, called the Fermi momentum. In this approximation, the interaction process inside the nucleus is represented as a cascade of free nucleon-nucleon scatterings. The influence of the other nucleons is felt only through the potential barrier, the initial Fermi-momentum distribution, and the exclusion principle which forbids collisions corresponding to final states already filled by other nucleons. Furthermore, the scattering collisions inside nuclear matter are described by known free nucleon-nucleon scattering cross sections. As it is necessary, in this analysis, to know the probability that one or more protons besides the primary will be scattered out of the nucleus, the charge of each target nucleon is randomly chosen. For events in which one or more protons are not scattered out of the nucleus, it is necessary to determine the excitation energy and the probability of one or more evaporation particles being subsequently ejected.

Various experiments[1,2] have shown that at high energies the primary particles do not lose much energy in elasticlike collisions. Therefore assuming the elastic-scattering mechanism is unchanged from 30 to 38 GeV, we can extrapolate the known experimental behavior and find the mean four-momentum transfer applicable at 83 GeV. The mean value of the kinetic energy of the scattered nucleons (E_{sec}) has been calculated to be 46 MeV at this energy, using the values of the transverse momentum given by Morrison.[13] The energies of the scattered nucleons (E) are assumed to have a distribution of the form $\exp(-E/E_{sec})$. This distribution was used to determine the amount of energy given to the target nucleon in the primary-nucleon collisions. The calculation was made in the rest system of the target nucleon. For subsequent collisions of the scattered nucleon with bound nucleons, the scattering process uses the known elastic cross section at low energies.[14] This elastic cross section was used to select randomly the path length between interactions. The vector Fermi momentum of the emulsion nucleons and the center-of-mass scattering angles have also been randomly selected based on uniform and isotropic distributions, respectively.

Consequently, randomly selected scattering angles and values of the vector Fermi momentum are used to follow the scattering of the first scattered nucleon as it moves through the nucleus. This procedure for the incident and first-scattered nucleon was followed for all products of the nucleonic cascade until either they reached the edge of the nucleus and escaped, or their energy fell below the nuclear barrier and they were considered captured. Another important change over the analysis of McCusker *et al.* was the inclusion of the exclusion principle. If a collision causes either particle to have an energy after the collision less than the maximum Fermi energy, the collision is forbidden to take place, and the particle continues in its original direction.

Figure 1 illustrates the results of a sample calculation for the interaction of the primary proton with a nucleon in the emulsion nucleus. The solid circles show the locations of the permitted interactions, and the open circles show the forbidden interactions for the subsequent scattering process. For allowed collisions, the charge of the scattered nucleon is randomly chosen, consistent with the density of neutrons and protons in the nucleus.

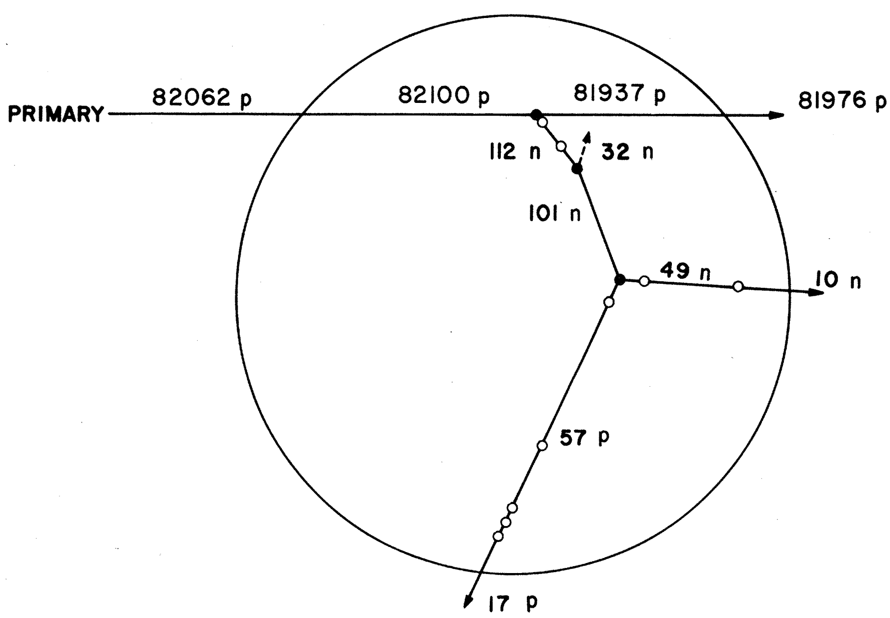

FIG. 1. A target diagram used in the calculations, illustrating an interaction and the development of the subsequent nucleonic cascade. The numbers refer to kinetic energy in MeV and the symbols p and n refer to proton and neutron, respectively. The solid circles refer to allowed collisions and the open circles to forbidden collisions.

TABLE I. Comparison of results obtained by Bernardini with the results obtained in this experiment.

	Bernardini	This experiment	
Number of primary interactions	60	60[a]	10 000[b]
Mean number of interactions per primary interaction	4.5 ± 0.5	5.2 ± 0.5	5.66 ± 0.03
Mean excitation energy (MeV)	$50\ \pm5$	$59\ \pm6$	$79.8\ \pm0.5$
Mean number of protons which escape with energy (MeV)			
≥ 100	0.6 ± 0.1	0.6 ± 0.1	0.48 ± 0.01
30–100	0.4 ± 0.1	0.4 ± 0.1	0.45 ± 0.01
<30	0.6 ± 0.1	0.6 ± 0.1	0.73 ± 0.01

[a]Using the same nuclear parameters as Bernardini.
[b]Using more recent nuclear parameters of the composite emulsion nucleus.

Comparison of Program with Bernardini's Results

For comparative purposes, Table I shows the results of a similar calculation by Bernardini *et al.*[12] The first and second columns are a direct comparison with the calculations done here for 60 primary interactions using the same parameters as Bernardini. The agreement between the mean number of interactions, mean excitation energy, and mean number of protons which escape are within 1 standard deviation. The third column includes more recent values of nuclear parameters.[14]

Since photographic emulsion is made up of a number of elements from Ag^{107} to C^{12}, we have made the calculation for a composite emulsion nucleus and for the individual nuclei which make up the emulsion, properly weighted with the known emulsion composition and nuclear size. No significant differences were observed. The results quoted were obtained using the composite emulsion nucleus. Several researchers[15,16] have suggested the use of a Gaussian momentum distribution rather than the Fermi distribution used by Bernardini and in this analysis. A Gaussian distribution was incorporated into this analysis, and no statistically significant differences were found. Also the initial elastic cross section must be assumed. Values were varied from 1 to 10 mb. No changes in the results were observed, since the primary effect of the value of the assumed elastic cross section for the first scattering is to determine only the depth of penetration of the incident nucleon into the nucleus. It has no significant effect on the subsequent nucleonic cascade within the nucleus.

Probabilities for Escape and Excitation

The probability of having an observable recoil track in the emulsion is shown in Table II. This was calculated from the probability P_p that a proton other than the primary will be scattered out of the nucleus, and from the probability P_{ex} of a visible excitation or evaporation particle being emitted by the nucleus if no proton is directly scattered out of the nucleus. The values of P_{ex} are calculated from the distribution of the excitation energy for events in which no proton is scattered out of the nucleus. Approximately 40 MeV are necessary to produce one excitation track.[17–19] The probability of an observable track (P_{ob}) in the emulsion is given by $P_{ob}=P_p+(1-P_p)P_{ex}$. The final result using this analysis indicates that the probability P_{ob} is $(50\pm5)\%$ that there will be an observable track in the emulsion for the interaction of an 83-GeV primary. The error indicates the effects of the variations of the parameters associated with this Monte Carlo model. The result of this calculation at the energies of McCusker *et al.*[1,2] is 45%. This is to be compared with the result quoted by McCusker *et al.*[2] of 25% when the effect of the Coulomb barrier, the Fermi motion of the bound nucleons, and the exclusion principle were neglected.

IV. RESULTS

Table III shows the results of this calculation for estimating the elastic cross section for protons with a mean incident energy of 83 GeV. The first

TABLE II. Percent probability of obtaining an observable particle in an elasticlike collision between a proton and a nucleon bound in an emulsion nucleus.

Element	$\%P_p$	$\%P_{ex}$	$\%P_{ob}$
Ag^{107}	26.8	31.9	50.2
S^{32}	40.6	18.3	51.5
C^{12}	46.2	9.8	51.5
Mean[a]	32.9	25.1	50.5
Composite emulsion nucleus ($_{22}X^{48}$)	32.8 ± 0.6	25.2 ± 0.6	49.7 ± 0.7

[a]Weighted mean of all elements making up photographic emulsion.

TABLE III. Probability of finding no elasticlike events in 988 cm for different values of the elastic cross section.

Elastic cross section (mb)	$\lambda_{\text{emulsion}}$ (cm)	$\lambda_{\text{expected}}$[a] (cm)	Prob.[b] of no event in 988 cm (%)
5	105	210	1
4	128	256	2
3	168	336	5
2	250	500	14
1	500	1000	37

[a] $\lambda_{\text{expected}} = \lambda_{\text{emulsion}}/0.5$.
[b] Prob. $= 100 \exp(-988/\lambda_{\text{expected}})$.

column shows various values of the cross section in mb. The second and third columns give the corresponding mean interaction length in emulsion[20] and the mean track length expected per interaction that yields an observable secondary track. The last column indicates the corresponding probability in percent of finding no interaction in the scanned path length of 988 cm.

The background analysis has indicated that the two elasticlike events which were found were probably random coincidences. Therefore, the result of this investigation would indicate that the elastic proton-nucleon cross section at 83 GeV is no greater than 3 mb with 95% probability.

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