plateaus were redetermined for each proton energy, to take into account new delays introduced to compensate for changes in time of travel for incident and scattered protons.

According to the second method, counter 3 was set at variable angle $(+\theta)$ at 30-inch radius from the scattering center to detect the elastically scattered protons, and counter 4 was placed to extend from +5 to −20 degrees to detect deuterons. Counters 1, 2, and 3 were connected in coincidence and counter 4 was connected in anticoincidence (1, 2, 3, −4). Accordingly (1, 2, 3, −4) measured all charged particles scattered at angle θ in coincidence with an incident proton, if no charged particle reached counter 4 simultaneously. So all events $p+p\rightarrow d+\pi^+$ were eliminated, even when the deuteron was subjected to Rutherford scattering in the target.

Furthermore, counter 4 extended over much more than the solid angle in which deuterons could emerge in order to eliminate most of the events in which a pion is accompanied by a free proton and neutron. This occurs in only about 1 out of 5 pion productions[2] at 350 Mev and is probably infrequent at 429 Mev also. A third possible process is $p+p\rightarrow\pi^0+p+p$, but this was improbable of detection because (*a*) it is about 8 times less probable than charged pion production,[3] (*b*) the decay gamma ray was detected with very low probability in counter 3, and (*c*) due to the virtual diproton state the two protons tended to emerge in the same solid angle as the deuterons, and so very probably trigger counter 4.

The ratio $(1, 2, 3, -4)/(M, 2)$ was measured at high beam intensity and the ratio $(M, 2)/(1, 2)$ was measured at low beam intensity, with and without hydrogen. The cross section is proportional to the product of the ratios with hydrogen minus the product of the ratios without hydrogen.

At 54° the cross section obtained by the first method was found to be equal within experimental error to that obtained by the second method. The results are summarized in Table I. There is

TABLE I. Differential elastic *p-p* scattering cross section at 429 Mev. Method *a* is detection of two scattered protons. Method *b* is detection of the more energetic scattered proton in anticoincidence with a second charged particle emitted at small angles.

Millibarns per steradian	Method	Barycentric angle
3.42 ±0.13	*a*	90°
3.51 ±0.23	*a*	80°
3.11 ±0.19	*a*	65°
2.84 ±0.12	*a*	54°
2.80 ±0.21	*b*	54°
3.18 ±0.21	*b*	43°
2.86 ±0.20	*b*	28°

no certain deviation from isotropy within the statistical errors of these results, but there is an indication of some decrease in cross section at smaller angles. A similar behavior is suggested by the corresponding data at 345 Mev,[4] although there also the trend is not much larger than the experimental errors.

The isotropic character of the present data at 429 Mev is in considerable disagreement with the shape of the elastic-scattering curve observed by Mott *et al.*, at 435 Mev.[5] On the other hand, the absolute value of the cross section in the neighborhood of 90° is in good agreement with their data.

It is interesting to compute the total *p-p* cross section at 429 Mev using the present data. Assuming isotropy and a differential scattering cross section of 3.3 mb/sterad one computes 20.7 mb for the total elastic scattering. To this must be added the π^0 production cross section, 0.45 mb,[3] and the π^+ production cross section. A measurement of the latter is being made by A. H. Rosenfeld of this laboratory, who privately reported a preliminary value of 3 mb. One finds 24.2 mb for the sum of these data. This is to be compared with, and agrees well with, the value 24±1 mb determined by transmission at the same energy.[6]

The cross sections reported in Table II for lower energies are much smaller than values reported by previous workers[7-10] although in agreement with a new result, 3.5±0.4 mb/steradian for the energy interval 150 to 350 Mev, from the Berkeley group, written to us by Owen Chamberlain. Our work differs from previous counter experiments in that the incident protons are counted individually. Previous workers have used radioactive methods, Faraday cages, or ion chambers to determine the incident flux.

TABLE II. Differential elastic *p-p* scattering cross section at 90° barycentric angle.

Millibarns/steradian	Energy (Mev)
3.21 ±0.11	144 ±5
3.67 ±0.34	271 ±9
3.42 ±0.13	429 ±14

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The Attenuation Cross Sections of 37-Mev Pions in Hydrogen

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We previously reported[1] 16.0±1.0 millibarns for the attenuation cross section of 37-Mev positive pions and 17.3±1.4 millibarns for negative pions in hydrogen. In arriving at these numbers we overlooked an important correction[2] due to the $\pi-\mu$ decays which occur between the second and third crystals of the telescope. Applying this correction and a further small correction due to a refinement in the calculation of our geometry, these numbers become $\sigma(\pi^+)=11.8\pm1.0$ millibarns and $\sigma(\pi^-)=12.9\pm1.7$ millibarns.[3] The π^+ value agrees with that obtained from our measured angular distribution.[4] The measurement of the π^- angular distribution at this energy is not yet completed.

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Neutron Total Cross Section for Bismuth and Uranium between 45 and 160 Mev*

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NEUTRON total cross sections for bismuth and uranium have been measured in a good geometry transmission experiment, using a time-of-flight instrumentation.[1,2] The source of neutrons was the stripped deuteron beam of the 184-inch synchrocyclotron. The results are shown in Fig. 1. Uncertainties are shown in terms of standard deviations, due to counting statistics only, and to energy channel width.

The distribution of values indicates a "dip" in cross section in the vicinity of 60 Mev for the two elements, similar to results first obtained by Taylor and Wood for lead.[2-4]

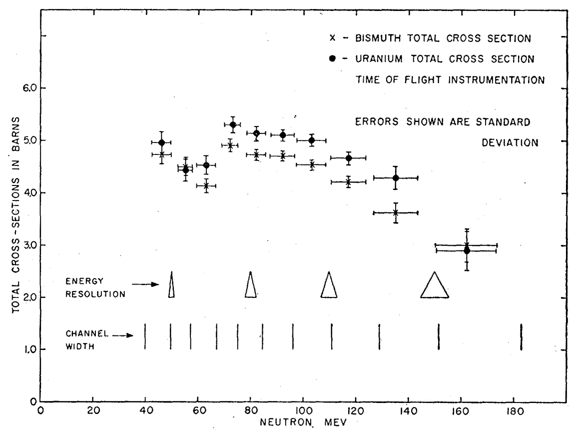

FIG. 1. The variation with energy of the neutron total cross section for bismuth and uranium, measured by time-of-flight instrumentation. The errors shown are standard deviations based on total counts and on energy channel width.

Absolute values of the cross section may be in error by a constant estimated to be ±0.2 barn because of beam intensity variations. Inasmuch as such a constant would be added to all the points for an element, it would not affect the variation of cross section with energy.

The energy scale was calibrated by time-of-flight of gamma rays. The time-of-flight of a neutron or photon could be measured with a probable error of $\pm 0.2\times 10^{-8}$ second, including the effect of neutron production time (this leads to a resolution of 5×10^{-11} second per meter at the flight distance of 43.7 meters). At 90 Mev the absolute value of the quoted energy seems to be in error by not more than ±2 Mev.

We wish to thank Professor H. F. York for suggesting this technique and Professor L. W. Alverez, under whose guidance this work was carried out, for valuable suggestions; also James Vale, Lloyd Hauser, and the cyclotron crew for much cooperation. Thanks are due also Robert Silver and John Leahy whose help at times of runs was particularly welcome, and Vern Ogren and Don Paxson, both of whom rendered expert electronics assistance in many ways.

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The Giant Nuclear Dipole Resonance*

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WE have applied the collective description of nucleon interactions[1] to the investigation of the giant dipole resonance in heavy nuclei.[2] Our method follows closely that developed by Bohm and Pines[3] for the treatment of electron-electron interactions in metals. We start with a system of individual nucleons, interacting via short-range two-body forces, and investigate to what extent these forces lead to collective behavior. We find that the part of the nucleon-nucleon potential V_{ij} which is proportional to $\tau_z^i\tau_z^j$ can lead to an oscillation of the nucleus as a whole, similar to the dipole oscillation suggested by Goldhaber and Teller,[4] and investigated by Steinwedel and Jensen.[4] The excited level corresponding to this oscillation lies at an energy

$$\hbar\omega = W_0 A^{-\frac{1}{3}} \tag{1}$$

above the ground state, where a rough calculation indicates $W_0 \approx 80$ Mev, a result which is in agreement with the experimentally observed position of the giant resonance. We find the γ-ray width of this level to be proportional to $A^{\frac{1}{3}}$, and use the width to obtain the cross sections for absorption and scattering of γ rays in this region. Throughout we have neglected certain effects of the $(\tau_x^i\tau_x^j + \tau_y^i\tau_y^j)$ terms in the potential, which are known to give rise to an increase in the frequency of the oscillation, as can be seen from the sum rule calculations of Bethe and Levinger.[5] Preliminary results indicate that such corrections are not large. Surface effects are also neglected, an approximation which restricts the application of our method to heavy nuclei.

Our approach consists in concentrating our attention on the following portion of the nuclear Hamiltonian,

$$H_0 - \sum_i \frac{p_i^2}{2M} + \sum_{\mathbf{k}} \sum_{i\neq j} \frac{V_k}{2}\tau_z^i\tau_z^j e^{i\mathbf{k}\cdot(\mathbf{x}_i - \mathbf{x}_j)}, \tag{2}$$

where the V_k are the Fourier components in a box of nuclear dimensions of a nucleon-nucleon potential of range μ^{-1}. The potential V is formally repulsive since $\tau_z^i\tau_z^j$ appears in the complete Hamiltonian as part of an exchange operator, which we take to be that of Majorana. We perform a canonical transformation directly analogous to that applied by Bohm and Pines[3] in the electron case. We are then able to isolate a part of the Hamiltonian corresponding to harmonic oscillations of the quantities

$$\rho_{\mathbf{k}} = \Sigma_i \tau_z^i e^{-i\mathbf{k}\cdot\mathbf{x}_i} \quad (\mathbf{k}\neq 0), \tag{3}$$

which are the fluctuations in the difference between neutron and proton densities.

The lowest mode of oscillation $[k\approx \pi/R = (\pi/R_0)A^{-\frac{1}{3}}]$ is weakly coupled to the motions of individual nucleons, to the ordinary density fluctuations of the nucleus, and to the terms in the nuclear Hamiltonian that are omitted in (2). The higher modes are strongly coupled, appreciably damped, and thus unimportant. The frequency of the lowest mode is

$$\omega = \left(\frac{Ak^2V_k}{M}\right)^{\frac{1}{2}} = \left[\frac{3\pi^2 D_0}{MR_0^5\mu(\mu^2+k^2)}\right]^{\frac{1}{2}} A^{-\frac{1}{3}} = \frac{W_0}{\hbar}A^{-\frac{1}{3}}, \tag{4}$$

if V is chosen to be a Yukawa potential of depth D_0. The value of W_0 quoted above is obtained by fitting D_0 and μ to low-energy two-particle data.

We identify the giant dipole resonance with the first excited state of our lowest oscillator mode, and calculate the γ-ray width of this level by expressing the dipole moment operator in terms of the $\rho_{\mathbf{k}}$, (3). The matrix elements of the $\rho_{\mathbf{k}}$ are the well-known oscillator matrix elements. The result for the γ-ray width at resonance is

$$\Gamma_\gamma = \frac{1}{6}\frac{e^2}{\hbar c}\frac{\hbar^2\omega^2}{Mc^2}A = \frac{1}{6}\frac{e^2}{\hbar c}\frac{W_0^2}{Mc^2}A^{\frac{1}{3}} \tag{5}$$

for equal numbers of neutrons and protons. Γ_γ depends on V_k only through ω and is very much smaller than the total level width Γ. Inserting (5) in the Breit-Wigner formulae, one may obtain the γ-ray scattering and absorption cross sections in the neighborhood of resonance. Thus,

$$\sigma_{\text{scatt}}(\text{res.}) = \frac{\pi}{6}\left(\frac{e^2}{\hbar c}\right)^2\left(\frac{W_0}{\Gamma}\right)^2\left(\frac{\hbar}{Mc}\right)^2 A^{4/3}, \tag{6}$$

which, for example, ≈ 3 millibarns for Ta^{181}.

It is of interest to compare our results for the absorption cross section with the sum rules of Bethe and Levinger, (not including their exchange-force corrections). For the integrated absorption cross section, $\int\sigma dE$, we obtain $\frac{1}{2}\pi^2(e^2\hbar/Mc)A$, which is just their result, showing that our single dipole level "exhausts" the sum rule, just like the level of Goldhaber and Teller. On the other hand, we find for both the mean and harmonic mean energies for photon