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Abstract

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PHYSICS

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EXCITATION OF C^{12} NUCLEI BY 660-MeV PROTONS

The problem of slightly inelastic scattering of high-energy protons by complex nuclei is of interest both from the standpoint of elucidating the mechanism by which a fast proton transfers a small fraction of its energy to a nucleus, and in connection with the study of polarization effects in the diffraction scattering of protons by nuclei, when slightly inelastic scattering appears as an accompanying process that complicates the interpretation of polarization data.

In the present work we report the results of an experiment in which slightly inelastic scattering of 660-MeV protons on C^{12} nuclei was observed. The experiment was undertaken in connection with the study, in the region of small angles where interference between Coulomb and nuclear scattering is observed, of polarization effects in the scattering of protons of the indicated energy by carbon nuclei.

In order to separate diffraction scattering of protons on carbon nuclei from accompanying inelastic processes, we measured, at angles of 4.2, 5.2, 7.0, 8.3, 9.1, and 10.7°, the energy spectra of secondary particles from $p + \mathrm{C}$ collisions. The direction of the primary beam and the position in it of the scatterer T (graphite or polyethylene) were chosen so that the beam of secondary particles, selected by collimators K_1 and K_2 and scattered through a specified angle θ, was directed to the center of the analyzing magnet (see Fig. 1). At the location of the scatterer T, the proton energy was 660 ± 3.0 MeV, and the flux density in the beam was $\sim 3 \cdot 10^9$ protons/cm$^2\cdot$ sec.

The secondary particles, after passing through the analyzing field and collimator K_3 in a 4-meter shielding wall, were recorded either by a telescope consisting of three scintillation counters or by an argon-filled ionization chamber M_2. The relative width $\Delta p/p$ of the momentum interval selected by the analyzer was about 1.7%. From the results of measurements of the number of secondary

Fig. 1. Diagram of the magnetic analyzer.

Figure 1: Fig. 1. Diagram of the magnetic analyzer.

particles at the exit of the analyzer as a function of the magnetic-field strength, a relative momentum spectrum was constructed in equal intervals of $H\rho$; this was then transformed into an energy spectrum on the assumption that the secondary particles were protons.

The curves in Fig. 2 are typical energy spectra of secondary protons near the diffraction peaks. It is seen that, as the observation angle increases, in each spectrum on the left side of the diffraction peak there becomes increasingly distinct a characteristic shoulder corresponding to protons that have lost part of their energy in exciting carbon nuclei. The possibility of explaining these shoulders by partial slowing down of the protons as they pass through the collimating system of the analyzer is excluded, since the peaks observed in the same way and at the same angles, corresponding to protons from elastic $p+p$ scattering, had a strictly symmetric shape.

The determination of the fraction of protons that underwent slightly inelastic scattering in the total spectrum of secondary particles was carried out by subtracting the areas under the curves representing the energy spectrum of protons

from $p+C$ collisions and the peak corresponding to protons from elastic $p+p$ scattering. In this procedure the peak from $p+C$ collisions and the peak from elastic $p+p$ scattering were normalized to the same height and their maxima were superposed. Since the energy spread of the primary beam and the resolution of the analyzer remained unchanged when secondary protons were observed both from $p+C$ and from $p+p$ collisions, it was to be expected that the shapes of these peaks and their widths at half-height would be the same. This is confirmed by the fact that, when their maxima were superposed, the right-hand branches of both peaks always coincided.

Fig. 1. Diagram of the magnetic analyzer. T—cylindrical scatterer, 80 mm high and 10 mm in diameter, made of graphite (when observing the proton peak from elastic $p+p$ scattering, an equivalent polyethylene scatterer was used); M_1—primary-beam monitor; H—analyzing magnet; M—quadrupole lens; K_1, K_2, K_3—collimators; M_2—ionization chamber; C_1, C_2, C_3—scintillation counters.

As an example, Fig. 3 shows the procedure for subtracting the areas under the normalized peaks and the proton spectrum obtained in this way, for an angle of 9.1°, for protons that underwent slight inelastic scattering. At all angles the maximum of this spectrum was shifted by approximately 25 MeV toward lower energies relative to the center of the diffraction peak. Meanwhile, under the conditions of these experiments, up to a scattering angle of 9.5° the mean energy that could have been lost by a proton in a quasielastic collision with an individual nucleon in the nucleus should have been less than 25 MeV. Thus, the spectra of inelastically scattered particles observed at small angles cannot

Fig. 2 and Fig. 3: spectra and separation curves

Figure 2: Fig. 2 and Fig. 3: spectra and separation curves

be explained as the result of quasielastic scattering of protons by individual nucleons in nuclei.

Attention is drawn to the fact that the magnitude of the energy most often transferred by the proton to the nucleus corresponds roughly to the position found for the maximum of the giant photoresonance curve of the C^{12} nucleus (see, for example, (^{1})). However, the width (at half-height) of the spectrum of slightly inelastically scattered protons is about 30 MeV for an angle of 5.2° and about 50 MeV for an angle of 10.7°, which is considerably greater than the width of the giant-photoresonance region in the C^{12} nucleus. This feature of the spectrum of slightly inelastically scattered protons cannot be explained by the energy spread of the primary beam or by the finite resolving power of the analyzer, although, for the reasons indicated, in the present experiments the possibility of detecting groups of protons corresponding to excitation of individual levels of the C^{12} nucleus was excluded. According to an estimate, the integral yield of slightly inelastically scattered protons corresponds to a differential cross section whose value for an angle of 7° is close to $\sim 130 \cdot 10^{-27}$ cm^2/sterad.

In connection with the experiments of Tyren and Maris (^{2}) on inelastic scattering of 180 MeV protons, the mechanism of excitation of nuclei by fast protons was considered theoretically, taking into account both the Coulomb (^{3}) and the nuclear interaction ($^{4-6}$) of the incident protons with nucleons in nuclei. It was established that excitation of nuclei by means of the Coulomb interaction (the differential cross section of this process is proportional to $1/\theta^2$) should appear only in the region of very small scattering angles. Nuclear interactions between incident protons and bound nucleo-

can induce stable collective excitations of nuclei, namely spin, isospin, and coupled spin–isospin waves (^{7}, ^{8}). These types of collective oscillations correspond to terms in the effective potential V_{ij} of the nucleon–nucleon interaction proportional, respectively, to $(\vec{\sigma}^{(i)}\vec{\sigma}^{(j)})$, $(\vec{\tau}^{(i)}\vec{\tau}^{(j)})$, and $(\vec{\tau}^{(i)}\vec{\sigma}^{(i)})(\vec{\tau}^{(j)}\vec{\sigma}^{(j)})$, where $\vec{\sigma}$ and $\vec{\tau}$ are the spin and isospin operators of the nucleon. In the case of proton scattering at small angles, when a multipole expansion of the transferred perturbation is possible, the isospin type of excitation is responsible for the appearance of dipole oscillations, which are so strongly manifested in photonu-clear reactions in the form of a giant resonance. Spin and coupled spin–isospin types of excitations were recently considered by Balashov and Tulinov (^{9}). The analysis carried out by these authors showed that, in inelastic scattering of fast protons at small angles, along with excitation of the levels of the giant photoresonance, a giant resonance of spin-wave excitations of the nucleus can arise in approximately the same energy region; moreover, owing to the broadening of the spin-wave excitations, the width of the spectrum of inelastically

Fig. 2. Typical energy spectra for several observation angles. The statistical errors of the measurements are represented by vertical bars. Beneath the diffraction peaks is shown the shape of the analyzer resolution curve.

Fig. 3. Separation of the spectrum of slightly inelastically scattered protons for the angle 9.1°. 1 –total spectrum of protons scattered by carbon nuclei; 2 –left side of the peak corresponding to protons from elastic $p + p$ scattering (this peak is shifted to the right by the magnitude of the difference in proton energies in elastic scattering on carbon nuclei and, correspondingly, in elastic $p + p$ scattering); 3 –energy spectrum of protons that have undergone slightly inelastic scattering.

the elastically scattered protons should be much greater than the width of the giant photoresonance.

In the present experiments it was established that, in the case of $p + \mathrm{C}^{12}$ collisions: (a) slightly inelastic scattering of protons noticeably competes with elastic (diffraction) scattering by nuclei even in the angular region lying far below the first diffraction minimum; (b) the value of the energy most often transferred to nuclei by protons in scattering through small angles approximately corresponds to the position of the maximum of the giant photoresonance curve of the C^{12} nucleus and does not depend on the angle, but the spectra of slightly inelastically scattered protons are considerably broader than the region of the giant photoresonance. These results indicate that, in the scattering of protons with an energy of 660 MeV through small angles by carbon nuclei, a noticeable contribution is made by collective nuclear excitations that do not manifest themselves in photonuclear transitions. It seems quite probable that here we are encountering a case in which spin-wave types of excitation, due to the $(\vec{\sigma}^{(i)}\vec{\sigma}^{(j)})$- and $(\vec{\tau}^{(i)}\vec{\sigma}^{(i)})(\vec{\tau}^{(j)}\vec{\sigma}^{(j)})$-parts of the two-nucleon potential, play an essential role.

The conclusion that protons with an energy of 660 MeV often undergo slightly inelastic scattering by C^{12} nuclei can also be extended to other nuclei, since characteristic tails on the left side of diffraction peaks were observed earlier ([10,11]) also in the spectra of Li, Be, Cu, and U at an angle of 7°. It follows from these experiments that, even at relatively high energies ($E > 600$ MeV), reliable information on the magnitudes of the differential cross sections for elastic scattering of protons by nuclei and on proton polarization in this process can be obtained only if the elastically scattered protons are carefully separated from protons that have undergone slightly inelastic scattering.

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Note: Figure translations are in progress. See original paper for figures.