Measurement of the Reactions ^{9}Be(p, $\pi^{\pm}$) at 800 MeV

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Angular distributions from the (p,π^+) and (p,π^-) reactions on ^{9}Be leading to discrete isobaric analog states in ^{10}Be and ^{10}C have been measured at 800 MeV over the momentum-transfer interval 600–800 MeV/c. The ratio between the (p,π^+) and (p,π^-) production cross sections is found to be much larger at 800 MeV than at lower energy. The angular distributions from the (p,π^-) reaction show a pronounced slope not observed in previous data.

The existing experimental information on the (p, π^+) reaction from nuclei have been primarily obtained at energies close to the threshold.[1] These data show large sensitivity to nuclear structure as well as the pion-nucleus interaction, and have thereby created great hope that the (p, π) reaction will be a useful tool for investigating these matters. However, extraction of any quantitative information from the (p, π) data has so far been prevented as a result of our poor knowledge of the details in the reaction mechanism. Very little data exist from the (p, π^-) reaction, partly because of the extremely small cross sections. Moreover, it is expected that the nuclear structure information from the (p, π^-) reaction is limited because of a very complex reaction mechanism. This is indicated by the almost isotropic (p, π^-) angular distributions obtained at low energies. However, very important information about the reaction mechanism can be extracted from a comparison between the (p, π^+) and (p, π^-) angular distributions, since each reaction mechanism gives its characteristic difference between the cross sections for the two production modes.[2,3] For example, π^- production is forbidden to first order in the pionic stripping process, described by the one-nuclear model. For a few light nuclei (p, π^+) data exist for some proton energies up to 700 MeV.[4] These limited data indicate only a moderate energy dependence of the (p, π^+) reaction, but much more experimental information is needed to establish such a feature. In fact, the new data presented in this paper indicate a much stronger energy dependence. The specific information which can be deduced from the (p, π) reaction at high energy is largely unknown, but in general one expects that the dynamics of the pion production and in particular the subsequent rescattering processes will have a major influence on the shape of the angular distributions.

In this paper we present the first data on the (p, π) reaction on nuclei ($A > 2$) at 800 MeV bombarding energy. These data, obtained with ^{9}Be as target, show some characteristics not observed previously at any energy. The ^{9}Be nucleus enables us to compare the (p, π^+) and (p, π^-) cross sections when isobaric analog states in the final nucleus are populated. Thereby, differences in the nuclear structure involved are minimized, facilitating the interpretation of the reaction process.

This experiment was performed with the 800-MeV proton beam from the Clinton P. Anderson Meson Physics Facility, using the high-resolution spectrometer (HRS) for pion detection and momentum analysis. A detailed description of HRS and its detector system is given by Blanpied *et al.* and Hoffman *et al.*[5] In the trigger electronics, the positive pions were selected from the large number of inelastically scattered protons of the same momentum by the difference in time of flight occurring in a 2-m flight path in the detector system, located near the focal plane of HRS. Additional rejection of proton events was obtained with a Lucite Cherenkov counter. In the final data reduction the pions were separated from background events by accurate measurements of time of flight and energy loss as well as by applying constraints on the outgoing particle trajectories.

Spectra from the (p, π^+) and (p, π^-) reactions on

^{9}Be are shown in Fig. 1. As can be seen, the background level is very small. This is especially true for the π^- spectrum where the ground-state peak corresponds to a cross section of only 0.5 nb/sr. The energy resolution was typically 350 keV [full width at half maximum (FWHM)], where the main contribution came from energy straggling in the 388-mg/cm^2 target. The ^{9}Be(p, π^+)^{10}Be spectrum exhibits three peaks which can be identified with single levels in ^{10}Be, namely, the ground state, the 3.37-MeV level, and the poorly known state at 11.8 MeV.[6] Although only one level is known at 11.8 MeV in ^{10}Be, the width of the peak in the (p, π) spectrum corresponding to this level indicates that the presence of several levels around 11.8 MeV cannot be excluded. The salient features of the spectrum in Fig. 1 are similar to those obtained at lower energies, in spite of large differences in the momentum transfer involved. In the negative-pion spectrum the first two peaks correspond to the levels in ^{10}C which are the analogs to the ground state and the 3.37-MeV state in ^{10}Be. The absolute cross section was determined by normalization to the known proton-proton elastic-scattering cross section.[7] The total error in the absolute cross section is estimated to be about ±15%. The main contributions to this error are due to uncertainties in the trigger efficiency including pion losses due to nuclear reactions in the detectors (±10%), the proton-proton cross section (±5%), the normalization measurement (±5%), and the Cherenkov efficiency (±6%).

In Fig. 2 the angular distributions from the π^+ and π^- production leading to the ground and first excited states in ^{10}Be and ^{10}C are presented as a function of momentum transfer, q. The difference in the (p, π^+) and (p, π^-) cross sections when these two levels are populated should mainly be due to the reaction process, because of the similarities in the nuclear structure involved. At 800 MeV the momentum transfer is very large even at small angles and hence there is little overlap between these data and those near threshold.[8] Nevertheless, a comparison between the data obtained at 800 and 185 MeV is meaningful in order to point out the specific characteristics of the (p, π) reaction at higher energies. From the angular distribution in Fig. 2 we observe the strong dominance of the π^+ production over the π^- production. In fact, the π^+/π^- ratio for the ground-

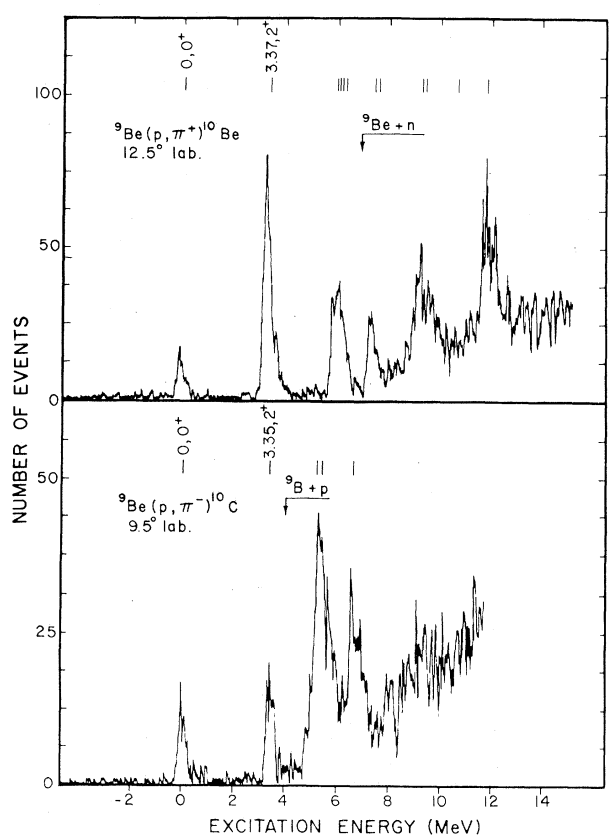

FIG. 1. Energy spectrum of π^+ and π^- production on ^{9}Be at 800 MeV plotted as a function of excitation energy of the residual nuclei ^{10}Be and ^{10}C.

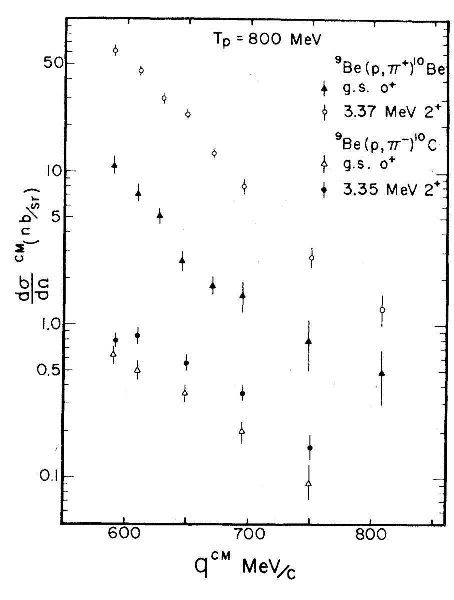

FIG. 2. Angular distributions of π^+ and π^- production on ^{9}Be leading to discrete isobaric analog states in ^{10}Be and ^{10}C. The angular range is from 9.5 to 32.5 deg in the laboratory system.

state transitions at $q = 600$ MeV/c is much larger at 800 MeV (about 15) than at 185 MeV (about 3). This is surprising, since at the very large momentum transfers one might expect that several nucleons are involved in the production process, and therefore no drastic differences in the (p, π^+) and (p, π^-) cross sections should occur. The large π^+/π^- ratio at 800 MeV can be a consequence of the particular dynamics of the reaction process at this energy. However, it should be pointed out that in a nucleon-nucleon collision inside the nucleus, the core nucleons can contribute in the π^+ production without being rearranged while the π^- production on a core nucleon involves a rearrangement leading to an intermediate excited state.

From Fig. 2 we also observe that the difference in the cross sections when the ground state and first excited state is populated, respectively, is larger for π^+ production than for π^- production. This is probably due to the low sensitivity of the (p, π^-) reaction to nuclear structure. Another experimental result seen in Fig. 2, which has no correspondence in previous data, is the nonisotropic (p, π^-) distribution. In fact, the slopes in the (p, π^+) and (p, π^-) distributions are almost identical, particularly if the ^{9}Be$(p, \pi^+)^{10}$Be(g.s.) data are considered above 650 MeV/c, where this angular distribution has a break in the slope. Since the isotropic angular distribution of the reaction ^{9}Be$(p, \pi^-)^{10}$C(g.s.) measured at 185 MeV reaches a maximum momentum transfer of only 600 MeV/c, those data give no indication whether the nonisotropic distribution at 800 MeV is a consequence of the very high momentum transfer or if it should be associated with the higher energy. Two existing data points obtained[9] at 613 MeV also suggest an isotropic distribution, although the true behavior is quite uncertain at this energy because of the large statistical errors in these points. However, in a recent measurement at Indiana University Cyclotron Facility[10] of the (p, π^-) reaction on ^{12}C at 200 MeV, which was extended to $q = 660$ MeV/c, preliminary results show that in this case the (p, π^-) angular distribution is indeed isotropic in the whole momentum-transfer region. Thereby we have an indication that the nonisotropic (p, π^-) distribution at 800 MeV is due to the energy at which the (p, π) reaction is studied rather than a consequence of the very large momentum transfer. In summary, there are two specific properties of the (p, π) data obtained at 800 MeV which most likely are an energy effect, namely the large π^+/π^- ratio and the nonisotropic (p, π^-) angular distributions.

The difference in the reaction process at 800 and 185 MeV indicated by the (p, π^-) angular distributions does not appear clearly in the (p, π^+) distributions. When the ground state in ^{10}Be is populated, the distribution follows a rough extrapolation of the 185-MeV data, when plotted as a function of momentum transfer. However, the data obtained for the 3.37-MeV level fall more rapidly with momentum transfer at 800 than at 185 MeV.

The general pattern in the (p, π) data observed in the transitions to the ground state and first excited state in ^{10}Be and ^{10}C also applies to the transitions to higher excited states. This can be seen in Fig. 3, in which the angular distributions from some transitions to excited states are presented. However, the magnitude of the (p, π^-) cross section, for the transitions to the group of levels at 5.3 and at 6.6 MeV is much larger than the cross section for the transitions to the ground and first excited states. It should be pointed out that this enhancement of the (p, π^-) cross section does not occur in the (p, π^+) reaction when the corresponding analog states are populated in ^{10}Be (see Fig. 1).

In conclusion, the experimental results from the (p, π^+) and (p, π^-) reactions at 800 MeV on ^{9}Be show some characteristic features different from

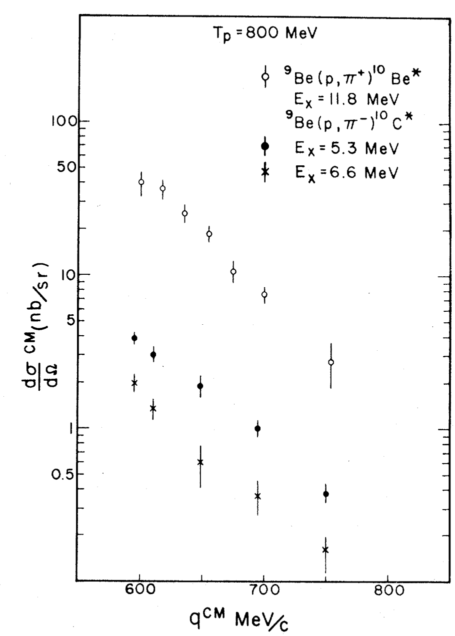

FIG. 3. Angular distributions of π^+ production on ^{9}Be leading to the level at 11.8 MeV, and of π^- production leading to the peaks around 5.3 and 6.6 MeV in ^{10}C.

those observed at energies near threshold. This is, of course, not very surprising since there is no reason to assume that the reaction process should remain the same over a large energy region. However, the very large π^+/π^- ratio at 800 MeV we find puzzling. This information should give a strong constraint on the reaction mechanism.

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Angular Momentum Selection Using Total Gamma-Ray Energies

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Use of a total γ-energy spectrometer in coincidence with a variety of detectors has led to the observation of the highest multiplicities yet achieved for compound nuclear products, allowing for the selection and study of high angular momentum states. A differential comparison of coincident γ spectra corresponding to slices of the total-energy spectrum yields a direct evaluation of the moment of inertia for a rotational nuclear structure.

The study of very high-spin states in nuclei is progressing along two rather different lines, according to whether the observed γ-ray spectrum is resolved or not. In the former case, level schemes are constructed, and spins as high as $37\hbar$ have been observed.[1-3] In the latter case, one must study the unresolved ("continuum") spectrum, and much progress has recently been made for the γ rays from evaporation residues following heavy-ion reactions. Studies have been made of the shapes of these continum spectra[4,5] as well as of their multiplicities,[6] angular distributions,[7] conversion coefficients,[8] and lifetimes.[9] It is now established that these spectra consist of a tail above ~2 MeV which decreases exponentially with increasing γ-ray energy, and usually a bump at lower energy which contains the transitions that remove the major part of the angular momentum of the system. The nature of these latter transitions appears quite sensitive to the nuclear structure, whereas the tail seems to be composed of statistical transitions that are