Study of the Reactions $^{9}Be(p, \pi^-)^{10}C$ and $^{12}C(p, \pi^-)^{13}O$ at 613 MeV

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Negative-pion production leading to discrete excitation levels of the residual nucleus has been investigated on ^{9}Be and ^{12}C targets with 613-MeV protons. On the first seen spectra of ^{13}O a strong excited peak is observed at 2.82 ∓ 0.24 MeV in excitation energy. The resulting cross sections are found to be far below previously published theoretical predictions.

In the last few years an important effort has been made to investigate the (p,π) reactions. Most of the results[1] are concerned with the positive-pion production with almost all of them near threshold. Recent experiments performed at Saclay have extended this study much above the threshold.[2,3] All of these data have been extensively interpreted by means of more or less sophisticated models.

On the other hand there are very few results concerning the coherent production of negative pions. However, this reaction is very interesting from at least two points of view: (i) It implies a double charge exchange, a process whose mechanism can be usefully compared to the (p,π^+) reaction mechanism, the coherent positive-pion production has been often interpreted in terms of the one-nucleon model (ONM) which forbids the negative-pion production, whereas any other mechanism that one could imagine to describe the (p,π^-) reaction may be used to explain the (p,π^+) reaction.[1] (ii) From a spectroscopic point of view it leads to exotic proton-rich nuclei, about which little is known.

As for the experimental situation, since the pioneering work of Rohlin *et al.*[4] at CERN, who made the first comparison between the π^- and π^+ production cross sections at 0° on ^{9}Be at 600 MeV, all the other results have been obtained near the reaction threshold.[5,6] These last data have been interpreted in terms of models involving one or more nucleons in the target nucleus.[1,7] A recent and new approach, extended over a large incident-energy range, has been developed by Kisslinger and Miller[8] who attempted to describe the (p,π^-) reaction as a single-step Δ^{++} transfer.

Here, we present the experimental results for reactions $^{9}Be(p,\pi^-)^{10}C$ and $^{12}C(p,\pi^-)^{13}O$.[9] We also compare these results with some additional measurements of the reactions $^{13}C(p,\pi^-)^{14}O$ and $^{9}Be(p,\pi^+)^{10}Be$. The experiment was performed using a 613-MeV proton beam from the Saclay synchrotron Saturne. The negative pions were detected with the high-resolution magnetic spectrometer SPES I, using the same detection arrangement as for the previous (p,π^+) experiments.[2]

Because of the very low cross section to be measured, the background problems were handled very carefully. Part of these problems were automatically solved due to the negative charge of the pions in the magnetic spectrometer. Thus the average background counting rate was less than ten counts per hour in the whole useful part of the spectrometer focal plane corresponding to an excitation energy range of 15 MeV. Figure 1(a) displays a spectrum for the reaction $^{9}Be(p,\pi^-)^{10}C$ obtained on line. For the ground state, the signal-to-noise ratio is still less than 2. The remaining background was mainly due to random coincidences issued from the high noise level in the experimental area and enhanced by the time structure of the beam bursts. Off-line analysis was thus done under strict conditions, the procedure of which is the following: The deviation from a straight line of the positions of the events detected in the four drift counters in coincidence has a normal distribution of about 1.5-mm FWHM (full width at half-maximum). This FWHM corresponds to the spatial resolution on the focal plane including the multiple-scattering effects. Because of the low statistics we set a cutoff at 4 times the FWHM. Figure 1(b) shows that such a procedure, which we applied to all measurements, enabled us to eliminate most of the background

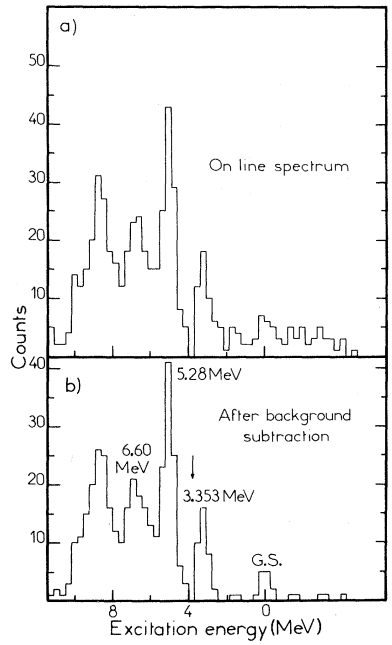

FIG. 1. Negative-pion spectrum from ^{9}Be target at $\theta_{\rm lab}=25$ (a) before and (b) after the background subtraction, the procedure of which is developed in the text. The arrow indicates the lower threshold of the many-body reactions. Because of a contraction of the energy scale, the visible resolution is 600 keV in this spectrum.

and in that way to measure cross sections down to an order of magnitude of 100 pb/sr.

The errors quoted in the text and the tables are only due to statistics and background subtraction. An overall error of 12% on the absolute normalization must be added; it takes into account the uncertainties on beam monitoring, solid angle, target thickness, intrinsic and geometrical detector efficiencies, muon contamination, and evaluation of pion losses by absorbtion in the detection system. In addition, all the cross-section values given in this Letter are averaged over the 2.8° angular aperture of the spectrometer.

We have measured the reaction ^{9}Be$(p,\pi^-)^{10}$C at two angles and one can recognize known states of ^{10}C (Ref. 10) in Fig. 1(b). The measured cross

TABLE I. Center-of-mass differential cross sections (in nb/sr) for the reaction ^{9}Be$(p,\pi^-)^{10}$C.

$\theta_{\rm lab}$	$\theta_{\rm c.m.}$	Ground state	3.35 MeV	5.28 MeV
5°	5.7°	0.24 ± 0.17	0.95 ± 0.38	1.90 ± 0.66
25°	28.3°	0.27 ± 0.07	0.73 ± 0.13	1.68 ± 0.22

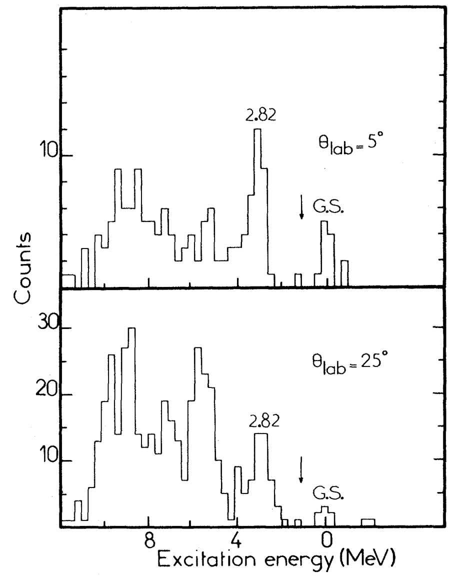

FIG. 2. Negative-pion spectrum from ^{12}C target at 5° and 25° leading to ^{13}O excitation levels after background subtraction (same comments as for Fig. 1).

sections for the first three states are given in Table I. The sum of those of the first two levels is in good agreement with previous CERN data,[4] where these two levels where unfortunately unresolved.

Figure 2 shows two spectra for the reaction ^{12}C$(p,\pi^-)^{13}$O. Very little is known about the ^{13}O nucleus.[11] Fortunately its mass was previously measured with precision[12] so that its ground state could be identified without ambiguity. Nothing is known about excited states in ^{13}O. We observed a peak at 2.82 ± 0.24 MeV in excitation energy and some other π^- groups. The structure above 3 MeV has not been analyzed because of insufficient statistics beyond the continuum due to many-body reactions (which have a low threshold) and a geometrical cutoff above 8-MeV excitation energy in the detection system.

Table II gives the cross sections measured at four angles for the ground state and the first pion group at 2.82 MeV. The corresponding angular distribution is plotted in Fig. 3. Nothing is known about the nature of these states and the known but complex spectrum of the ^{13}B mirror nucleus[11] is not very helpful in interpreting the observed ^{13}O spectra if one considers our 450-keV energy resolution.

Given the present status of the theory, it is difficult to extract information by direct comparison of our results to existing near-threshold data. As previously observed, we find that no evident q de-

TABLE II. Center-of-mass differential cross sections (in nb/sr) for the reaction $^{12}C(p,\pi^-)^{13}O$.

θ_{lab}	$\theta_{c.m.}$	Ground state	2.82 MeV
5°	5.5°	1.00 ± 0.39	3.22 ± 0.60
15°	16.6°	0.21 ± 0.12	1.40 ± 0.32
25°	27.6°	0.39 ± 0.17	2.76 ± 0.42
35°	38.4°	0.088 ± 0.088	0.83 ± 0.20

pendence appears in the angular distributions and that the cross sections have the same order of magnitude.

Kisslinger and Miller[8] have given some predictions for the π^- production by incident proton on different p-shell nuclei. Then, we have measured an additional point for the reaction $^{13}C(p,\pi^-)^{14}O$ at $\theta_{lab}=5°$; the resulting cross section is

$$d\sigma[^{14}O(g.s.)]/d\Omega_{c.m.}=1.01\pm0.51 \text{ nb/sr}.$$

Taking into account the experimental uncertainties, the ^{13}O(g.s.) to ^{14}O(g.s.) production ratio via the (p,π^-) reaction at the same angle ($\theta_{lab}=5°$) is then

$$\sigma[^{13}O(g.s.)]/\sigma[^{14}O(g.s.)]=1\pm0.6.$$

In the same way the ^{13}O(g.s.) to ^{10}C(g.s.) production ratio at $\theta_{lab}=5°$ is

$$\sigma[^{13}O(g.s.)]/\sigma[^{10}C(g.s.)]=4\pm3.$$

These ratios are smaller than what could be expected from Ref. 8, but, given the precautions taken by the authors concerning nuclear structure effects which could lessen these theoretical ratios, the experimental values are not in complete contradiction with their predictions. Nevertheless the measured absolute cross sections are far below the values that they predicted.

Lastly, the comparison of the π^- versus π^+ productions can be helpful for the understanding of the reaction mechanism. Because of the poor statistics of the present low-cross-section experiments the ratio of (p,π^+) (Ref. 3) to (p,π^-) reactions cross sections on ^{9}Be target nucleus at $\theta_{lab}=5°$ is obtained with large error bars. For the ground state and the first excited state (of ^{10}Be and ^{10}C) these ratios are found to be 270 ± 200 and 290 ± 120, respectively. These values are compatible with previous CERN results.[4]

In conclusion, we have obtained the first discrete level spectra for the (p,π^-) reaction far above the reaction threshold. We have presented absolute cross sections for some of them which

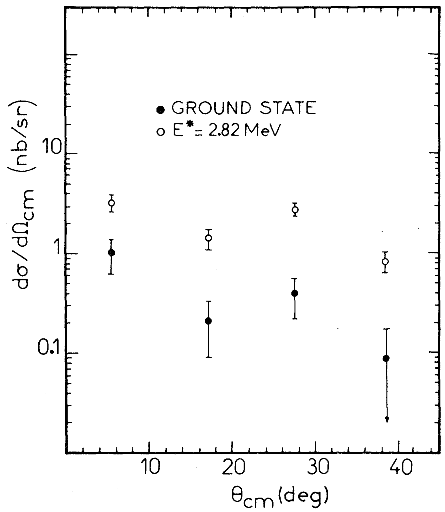

FIG. 3. Angular distributions of the center-of-mass differential cross section for the ground state and the first observed peak in the ^{13}O spectrum.

are much lower than the existing predictions[8] where Δ^{++} components in the nuclear wave functions have been introduced. The effects of a 0.25% Δ probability was predicted of the order of magnitude of the nonexotic nuclear processes which all need at least two-step reaction $[(p,n)\times(n,\pi^-)$ or $(p,\pi^0)(\pi^0,\pi^-)]$. Thus, either the Δ^{++} probability used in these calculations has to be reduced or some other theoretical grounds are questionable. Further theoretical analysis would be of great interest.

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Shell-Model Tests of the Interacting-Boson-Model Description of Nuclear Collective Motion

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Large shell-model calculations have been made of a pseudonucleus to see (1) what collective features appear and (2) what the resulting collective wave functions consistent with the assumption of the interacting-boson model are. In the calculations, sets of states with striking similarity to states in $K=0$ and $K=2$ rigid-rotor bands appear. For the $K=0$ bands, the lower states are dominated by states formed from coupling $J=0$ and $J=2$ two-neutron and two-proton states, consistent with the assumptions of the interacting-boson model.

An approach of great recent interest to the long-standing question of an adequate microscopic many-particle description of collective nuclear motion has been proposed—the so-called interacting-boson model (IBM). The IBM assumes that collective behavior arises from the coupling, through the neutron-proton interaction, of the separate low-lying state systems of valence protons and neutrons defined with respect to a major shell closure. The eigenstates of the proton (neutron) systems are assumed to be constructed purely from combining two-particle "bosons" with $L = 0$ and $L = 2$ to form many-particle states. Arima and Iachello[1] have studied the consequences of such assumptions in a phenomenological model (i.e., no microscopic structure to the "bosons," and parametrized one-boson and two-boson interactions). The model is capable of handling nuclear systems which are far beyond the domain of applicability of any reasonably complete shell-model calculation. It would be highly desirable to have an exact large shell-model calculation which could test some of the assumptions of the IBM. It is the purpose of this note to present the results of such a large shell-model calculation of a pseudonucleus which displays striking collective behavior suggestive of rotational phenomena. In these calculations, a specific and physically reasonable single-particle structure is given to the wave functions, and an explicit two-body residual interaction is used. Thus, the collective properties are not explicitly a part of the model.

The calculations discussed here are quite similar to earlier calculations of Hecht, McGrory, and Draayer.[2] The model space for the calculations reported here includes the $0f_{5/2}$, $1p_{3/2}$, and $1p_{1/2}$ proton single-particle orbits, and the $0g_{7/2}$, $1d_{5/2}$, $1d_{3/2}$, and $2s_{1/2}$ neutron single-particle orbits. The single-particle levels are taken to be degenerate. For a reasonably large number of particles, one-body spin-orbit effects should be minimal. For the residual shell-model Hamiltonian, the surface delta interaction[3] (SDI) is used with equal strengths in the p-p, p-n, and n-n systems. The SDI is known to be a useful approximation to more empirical and/or more realistic interactions. In one system treated here, the dimension of the $J=4^{+}$ space is on the order of 45 000. This is well beyond present

