PHYSICAL REVIEW C VOLUME 26, NUMBER 1 JULY 1982

Excitation functions of the $^{127}I(\pi^{\pm},\pi N)^{126}I$ reactions in the vicinity of the (3,3) resonance

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(Received 12 January 1982)

Excitations functions for the formation of ^{126}I from ^{127}I have been determined with 60–350 MeV π^+ and π^-. The contributions of both direct nucleon knockout and pion inelastic scattering followed by neutron evaporation are visible in the excitation functions. The results are compared with a cascade-evaporation calculation, the Sternheim-Silbar nucleon charge exchange models, and the semiclassical model of Ohkubo and Porile.

NUCLEAR REACTIONS $^{127}I(\pi^{\pm},\pi N)^{126}I$, excitation functions (activation), $T_\pi = 60-350$ MeV. KI targets. Comparison with various models.

I. INTRODUCTION

Single nucleon removal reactions induced by pions have attracted considerable interest in recent years because they provide information about the effect of the nuclear environment on the free π-N scattering amplitudes. Because of its use as a beam intensity monitor, the ^{12}C $(\pi^{\pm}, \pi N)$ reaction has received the greatest amount of attention in the energy interval spanning the (3,3) resonance.[1-3] The currently accepted value of the ratio,

$$R_n = \sigma(\pi^-,\pi^- n)/[\sigma(\pi^+,\pi^+ n)+\sigma(\pi^+,\pi^0 p)] ,$$

at the resonance is 1.59 ± 0.07 (Ref. 3). This value is much lower than the free particle ratio, i.e., 3, and also lower than the value of 2.4 obtained by means of the widely used ISOBAR-DFF Monte Carlo intranuclear cascade-evaporation (INC) calculation.[4,5]

The energy dependence of R_n for the $^{12}C(\pi,\pi N)$ reaction has been sucessfully reproduced by the Sternheim-Silbar model[6] with a single normalization at 180 MeV. This calculation is based on a semiclassical colinear transport model in which the struck nucleon is allowed to undergo charge exchange scattering (CEX) with other nucleons. The CEX probability was found to decrease from about 40 to 15% as the pion energy was increased from 50 to 300 MeV. Since the INC calculation contains all the ingredients of the Sternheim-Silbar model as well as additional features that may play an important role, the discrepancy between the two calculations was surprising. Karol[7] has recently examined the Sternheim-Silbar model from this point of view and has found that a questionable averaging procedure is responsible for the high values of the CEX probability. When modified, the model predicts a much lower CEX probability and a value of R_n in agreement with the INC calculation, and thus, larger than the experimental cross section ratio.

More recently, Ohkubo and Porile[8] calculated the excitation functions of $(\pi, \pi N)$ reactions by means of a semiclassical model in which the nuclear structure of the target is explicitly included by means of the harmonic oscillator shell model. This calculation, which is an adaptation of the Benioff model for (p,pn) reactions,[9] predicts excitation functions for the $^{12}C(\pi^{\pm},\pi N)$ reaction which are in good agreement with experiment. The CEX probability P was obtained from a fit to the experimental R_n values and was found to decrease from about 0.3 to 0.2 between 100 and 300 MeV.

Additional data on single nucleon removal in pion-induced reactions on light elements are also available,[10,11] and a detailed confrontation with the various models has been reported for the $^{25}Mg(\pi,\pi N)$ reaction.[11] Generally, similar results as those outlined above for the $^{12}C(\pi,\pi N)$ reaction were obtained. The INC calculation was thus found to be in poor agreement with the excitation functions and to overestimate the π^+/π^- cross section ratio. On the other hand, the Sternheim-Silbar model predicted cross section ratios in good agreement with experiment. Even better agreement was obtained with a modified version of this model,[12] in which the CEX process was assumed to proceed predominantly through the isobaric analog state. Ohkubo and Porile[8] reported an excellent fit to the excitation functions of the ^{25}Mg(π,πN) reaction, using comparable values of the CEX probability as for ^{12}C.

In contrast to the situation for light elements, little is known about the (π,πN) reaction for heavy target elements. The only reaction for which results have been published to date is the ^{197}Au ($\pi^{\pm}$,πN) reaction.[11] Comparison of these data with theory indicated that neither version of the Sternheim-Silbar model was able to match the experimental values of R_n. On the other hand, the INC calculation now gave a good fit to the cross sections, and thus to their ratios. A good fit to these data was also obtained by Ohkubo and Porile,[8] but now for a much smaller value of the CEX probability. The decrease in P for heavy elements was attributed to a combination of nuclear structure and size effects.

In view of this apparent dependence of the applicability of various models on the mass of the target, it is clearly desirable to obtain additional data on single nucleon removal reactions for medium to heavy target elements. We present here a study of the ^{127}I(π,πN)^{126}I reaction. The excitation functions have been measured for both π^+ and π^- betweem 60 and 350 MeV and the results are compared with the various models discussed above.

II. EXPERIMENTAL

The irradiations were performed in the P^3 and low energy pion (LEP) channels of the Clinton P. Anderson Meson Physics Facility (LAMPF) with π^+ and π^- ranging in energy between 60 and 350 MeV. The P^3 beams had a momentum bite of $\pm 6\%$ while the LEP beams (60 MeV pions) had a bite of $\pm 4\%$. Protons were removed from the π^+ beams by differential energy degradation.

The targets consisted of KI pellets made by compressing the powder to a thickness of ~ 120 mg/cm^2. They were circular, had a diameter of 1.5 cm, and were mechanically stable and of good uniformity ($\sim 2\%$). The target stack consisted of a pellet surrounded by thin Mylar guard foils and preceded on the upstream side by a Si monitor disc having the same diameter and a comparable surface density. The beam intensity was monitored by means of the Si(π,x)^{24}Na reaction, whose cross sections have been determined.[13] The fluctuations in the pion intensity during the 7 h irradiation periods were monitored by means of a scintillation counter located near the target. While in most instances no corrections were required, in occasional runs the ^{24}Na monitor activity had to be corrected by $1-2\%$. In view of the long ^{126}I half-life (13.0 d), the activity of this nuclide was unaffected by variations in beam intensity.

Following irradiation, the target and monitor discs were separately assayed with Ge(Li) γ-ray spectrometers. The ^{126}I product was identified in the spectra by means of its characteristic γ rays (388.6 and 666.3 keV) and half-life. The abundances of these γ rays (35% and 34%, respectively) were obtained from a recent compilation.[14] The γ ray spectra were analyzed with the code SAMPO (Ref. 15). The decay curves were fitted with the CLSQ code[16] and showed the presence of a single component. The γ-ray intensities were corrected by $\sim 1\%$ for γ-γ coincidence summing using a code based on the analysis by McCallum and Coote.[17]

The possible contribution of secondary reactions to either the ^{127}I (π,πN) or the monitor reaction was investigated in experiments in which the target thickness was varied by about a factor of 3. From the constancy of the cross section we conclude that any net secondary contribution to either reaction must be less than 1%. More complete details concerning the experimental procedure may be found elsewhere.[18]

III. RESULTS AND DISCUSSION

The measured cross sections and their ratios are summarized in Table I. Since ^{126}I is isobarically shielded by stable isotopes, the cross sections reflect the independent production of this nuclide. The tabulated uncertainties ($\pm 1\sigma$) are due to those from the SAMPO and CLSQ fits, the γ-ray abundances, and the cross sections of the monitor reaction, combined in quadrature.

The excitation functions and cross section ratios are displayed in Fig. 1. The effect of the (3,3) resonance is apparent in the peak observed at ~ 180 MeV. In contrast to the (π,πN) reaction on light elements, the peak is not very pronounced. The (π^-,$\pi^- n$) excitation also features an upturn at the lowest energies, although the large uncertainty in the 60 MeV datum makes this feature rather questionable. At any rate, both excitation functions are rather flat at low energies and thus differ from those for the ^{12}C(π,πN) reaction, the only reaction

TABLE I. Cross sections for the $^{127}I(\pi,\pi N)^{126}I$ reaction.

T_π (MeV)	σ^-[a] (mb)	σ^+[b] (mb)	R_n[c]
60	153±31[d]	57.3±6.2[d]	2.67±0.61[d]
100	128±9	59.0±6.0	2.17±0.27
140	133±8	62.8±4.4	2.12±0.20
180	146±9	70.5±3.8	2.07±0.17
210	133±9	68.6±4.4	1.94±0.18
250	111±7	65.0±4.4	1.70±0.16
300	105±7	54.3±3.3	1.93±0.17
350	82.3±5.9	53.9±2.6	1.53±0.13

[a] Cross section for the π^--induced reaction.
[b] Cross section for the π^+-induced reaction.
[c] $R_n = \sigma^-/\sigma^+$.
[d] Uncertainties represent $\pm 1\sigma$.

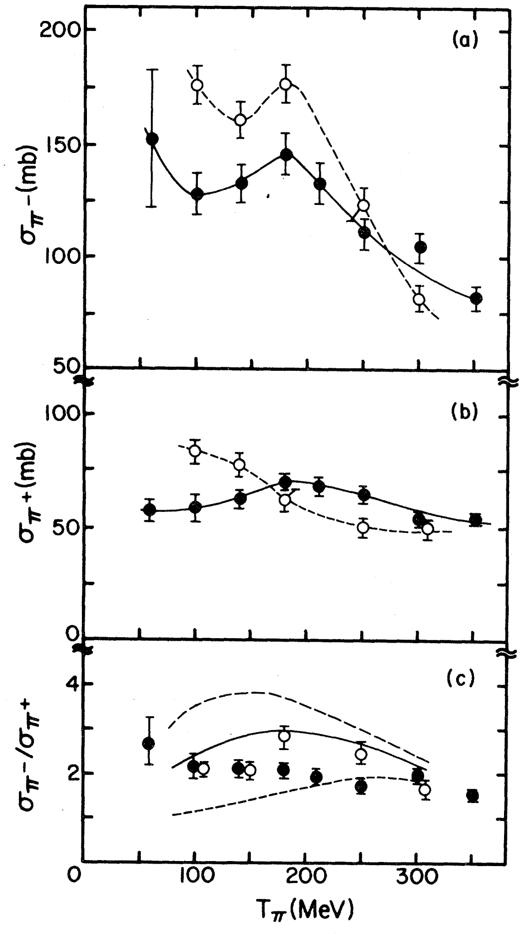

FIG. 1. Excitation functions for the reactions (a) $^{127}I(\pi^-,\pi N)^{126}I$ and (b) $^{127}I(\pi^+,\pi N)^{126}I$. ●, experiment; ○, INC calculation. The solid and dashed lines show the trends in the data and calculation. (c) σ^-/σ^+ ratio; solid curve, free-particle ratio; short-dashed curve, Sternheim-Silbar model; long-dashed curve, analog-dominance CEX model.

investigated below 100 MeV. The curves for the latter thus drop off sharply with decreasing energy in this regime.[3] Figure 1 also includes the results of the ISOBAR-DFF calculation.[4,5] Although the cross sections generally are in rather poor agreement with the data, the general features of the excitation functions are more or less reproduced. In particular, the calculation also shows a low energy upturn in the $(\pi^-,\pi^- n)$ excitation function, albeit at somewhat higher energies than is observed experimentally.

The cross-section ratios show a slow and featureless decrease with increasing pion energy and the values of R_n are generally somewhat smaller than the free particle ratios. The INC ratios are in good agreement with experiment at both low and high energies, but are somewhat larger in the vicinity of the resonance. Also shown are the ratios predicted by the two versions of the Sternheim-Silbar calculation. These ratios were obtained by scaling the ratios calculated for ^{12}C and thus contain no adjustable parameters.[12] The model involving CEX via the analog states[12] predicts R_n values that are much too high, higher in fact than the free particle ratios. On the other hand, the original CEX model[6] predicts too low a ratio except at the higher energies, where good agreement is obtained. These results are qualitatively similar to those reported for ^{197}Au, where similar discrepancies between experiment and the Sternheim-Silbar calculations were noted.[11] However, the agreement with the INC calculation is distinctly superior for ^{197}Au than for ^{127}I.

It is known that in addition to direct nucleon knockout (DKO), with or without CEX, inelastic scattering followed by neutron evaporation (ISE) also contributes to single neutron removal reactions.[4,11] The INC calculation allows us to decompose the calculated excitation functions into the separate contributions from the DKO and ISE mechanisms. The results of this analysis are presented in Fig. 2. The DKO excitation functions are seen to be strongly resonance dominated and qualitatively similar to the experimental excitation functions for single nucleon removal reactions in light elements.[1,3,10,11] The ISE cross sections initially decrease sharply with increasing pion energy and level off by ~150 MeV. Table II lists the percentage contribution of the DKO mechanism to the ^{127}I(π,πN) reaction. Because of the shapes of the excitation functions for the two processes, the largest contribution of the DKO mechanism occurs at the resonance, where it accounts for 65–75 % of the cross section. The relative contribution of the ISE process is more important at other energies, and at 100 MeV accounts for ~70% of the (π^+,π^+N) cross section. This value seems surprisingly large and may be the source of the discrepancy between experiment and the INC calculation, particularly at low energies.

Figure 3 shows a comparison with the semiclassical model of Ohkubo and Porile.[8] The cross sec-

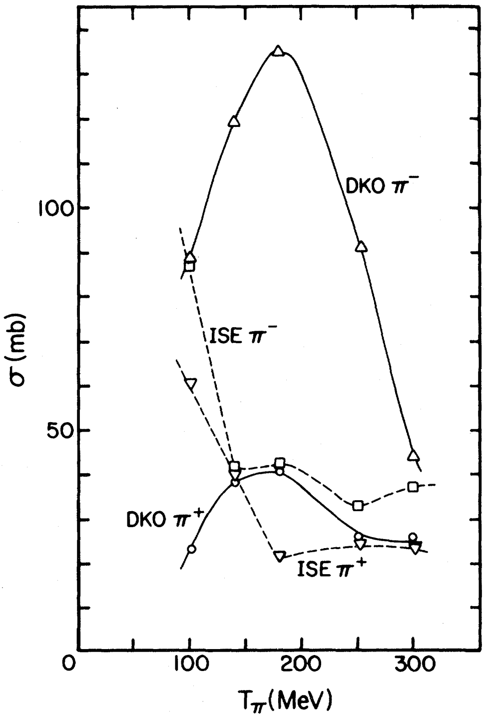

FIG. 2. Excitation functions for the ^{127}I(π,πN) reactions calculated with the ISOBAR-DFF cascade-evaporation code (Refs. 4 and 5).

TABLE II. Percentage contribution of direct knockout (DKO) to the ^{127}I(π,πN) reaction as given by the ISOBAR-DFF cascade-evaporation calculation (Refs. 4 and 5).

T_π (MeV)	π^+ (%)	π^- (%)
100	28	51
140	50	74
180	65	76
250	51	73
300	53	54

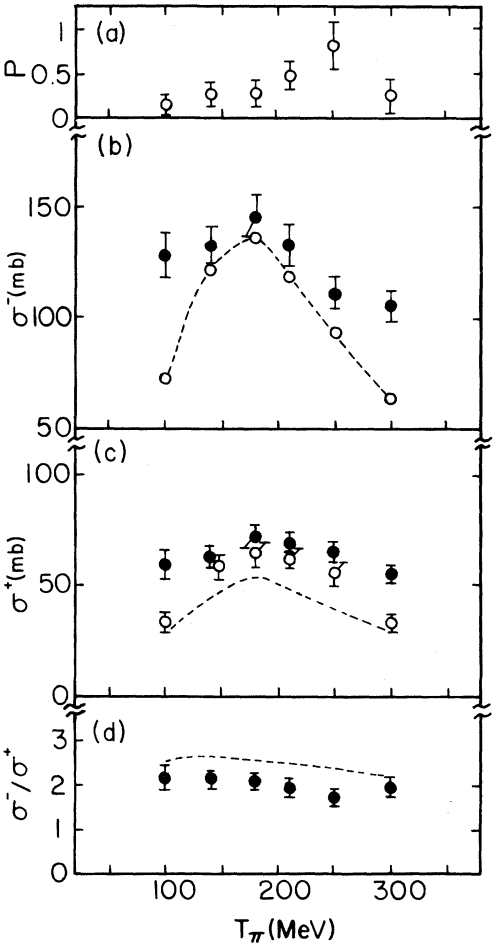

FIG. 3. Comparison of the results with the semiclassical model of Ohkubo and Porile (Ref. 8). (a) the CEX probability P. (b) ^{127}I(π^-,π^-n) results: ●, experiment; ○, calculation; dashed line, σ_{cl}. (c) ^{127}I(π^+,π^+N) results. (d) Cross section ratio, $R_n=\sigma^-/\sigma^+$ [symbols in (c) and (d) have the same significance as in (b)].

tions were evaluated by means of the following expressions:

$$\sigma^{-}=\sigma_{\mathrm{cl}}(\pi^{-},\pi^{-}n)+P\sigma_{\overline{\mathrm{cl}}}(\pi^{-},\pi^{-}p)\ ,$$

$$\sigma^{+}=\sigma_{\mathrm{cl}}(\pi^{+},\pi^{+}n+\pi^{\circ}p)+P\sigma_{\overline{\mathrm{cl}}}(\pi^{+},\pi^{+}p)\ ,$$

where σ_{cl} is the cross section for direct knockout involving only a single collision in the struck nucleus, i.e., the π-n collision; $\sigma_{\overline{\mathrm{cl}}}$ is the cross section for direct knockout involving a final state interaction of the outgoing nucleon; and P is the fraction of $\sigma_{\overline{\mathrm{cl}}}$ involving charge exchange. The values of σ_{cl} and $\sigma_{\overline{\mathrm{cl}}}$ were evaluated by an adaptation of the Benioff model,[9] while P was obtained by fitting the experimental values of R_n. The calculation evaluates the probability of nucleon removal from the highest energy shell model states. These states are specified by the requirement that the removal of a nucleon must leave the residual nucleus in a particle-bound state. The neutrons available for the clean knockout are those in the $1g_{7/2}$, $2d_{5/2}$, and $1h_{11/2}$ shells, 24 in number, while only the three $1g_{7/2}$ protons are available for unclean knockout.[18] The radial density distributions of these nucleons were obtained on the basis of $r_0=0.95$ fm, a value obtained by fitting the Fermi density distribution derived from electron scattering data[19] with a harmonic oscillator distribution.

It is seen in Fig. 3 that the calculated excitation functions are in very good agreement with experiment in the vicinity of the resonance. However, at higher, and especially at lower energies, the calculated cross sections are much smaller than the experimental values. This discrepancy presumably reflects the importance of the ISE mechanism which, of course, is not considered in the calculation. The similarity between the calculated excitation functions and the DKO curves displayed in Fig. 2 confirms this supposition. Also shown in Fig. 3 are the values of σ_{cl}. The clean knockout process accounts for essentially the entire yield of the $(\pi^{-},\pi^{-}n)$ reaction, whereas a contribution from the unclean process is needed to match the $(\pi^{+},\pi^{+}N)$ cross sections. This difference reflects the fact that the π^{+}-p scattering amplitude is much larger than the π^{+}-n amplitude. Since the CEX contribution to the $(\pi^{+},\pi^{+}N)$ reaction results from π^{+}-p scattering, the effect is much larger than for the $(\pi^{-},\pi^{-}n)$ reaction, where the CEX process involves $\pi^{-}p$ scattering, which has a much smaller scattering amplitude.

The values of the CEX probability P, derived by fitting the experimental σ^{-}/σ^{+} ratios, have rather large uncertainties and scatter widely. This is a reflection of the fact that $\sigma_{\overline{\mathrm{cl}}}$ is much smaller than σ_{cl}, which results in turn from the much smaller number of available protons than neutrons. Consequently, the value of R_n is not very sensitive to that of P and the latter cannot be accurately determined. It was previously shown[8] that P is very small ($\lesssim 0.05$) for ^{197}Au. That estimate could be made with some degree of confidence because the number of available neutrons and protons was comparable, thereby making R_n quite sensitive to the value of P. We believe that P is also quite small for ^{127}I. Figure 3 thus shows the values of R_n calculated on the basis of the clean process only. The results differ only slightly from the experimental values, the difference being comparable to that obtained for ^{197}Au.

IV. CONCLUSIONS

Cross sections for the $^{127}\mathrm{I}(\pi,\pi N)^{126}\mathrm{I}$ reaction have been determined between 60 and 350 MeV for both π^{+} and π^{-}. Although the role of the (3,3) resonance is discernible as a peak in the excitation functions at 180 MeV, the effect is not very pronounced. The excitation functions are rather flat, particularly at the lowest energies, and this is taken as evidence for the contribution of a two-step mechanism, involving pion inelastic scattering followed by neutron evaporation (ISE).

The results are compared with various models of single nucleon removal reactions. The ISOBAR-DFF cascade-evaporation calculation[4,5] (INC) is in qualitative but not quantitative agreement with the data. The calculation thus appears to overestimate the contribution of the ISE process at the lowest energies. Neither version of the Sternheim-Silbar nucleon charge exchange model[6,12] predicts the observed values of the cross section ratio R_n. The original version of this model[6] yields R_n values that are generally too low, while the analog dominance version[12] predicts just the opposite. The semiclassical model of Ohkubo and Porile[8] predicts the correct cross sections in the vicinity of the resonance but substantially lower values at lower and higher energies. This difference may be a reflection of the ISE process, which is not considered in this calculation. The CEX probability P, which can be extracted by fitting the calculation to the experimental values of R_n, is not very well determined due to the unusually large ratio of the number of available neutrons to protons in ^{127}I. In general, the comparisons confirm the conclusions drawn by Kaufman *et al.*[11] These workers thus found that the Sternheim-Silbar models work well for light target elements but not for heavy ones, while the ISOBAR-DFF cascade-evaporation calculation works well for heavy elements but not for light ones. Only the semiclassical model of Ohkubo and Porile appears to work moderately well for both light and heavy elements.

ACKNOWLEDGMENTS

We thank Dr. L. C. Liu for performing the ISOBAR-DFF calculations and Dr. B. J. Dropesky for facilitating the irradiations. This work was financially supported by U. S. Department of Energy.

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