RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 45, NUMBER 2 FEBRUARY 1992

Pion absorption in neavy nuclei

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(Received June 26, 1991)

Cross sections have been measured for proton emission following π^+ absorption on ^{6}Li, ^{12}C, ^{27}Al, ^{58}Ni, ^{118}Sn, ^{208}Pb, and ^{238}U for pion kinetic energies of 50, 100, 150, and 200 MeV by using a large-solid-angle bismuth germanate detector array. An increasing fraction of transitions to states of large missing energy and with particles other than protons is observed as the energy and mass increase.

PACS numbers: 25.80.Ls

Despite much study [1], pion absorption is still not well understood in detail, even in light nuclei. Most studies of absorption have used small-solid-angle detector systems and detected final states including two nearly coplanar outgoing protons. Consequently, the cross section for absorption leading to two protons whose total energy is well below the available energy is very poorly known. Even the magnitude of the total absorption cross section is not very well known [2–4], with uncertainties in the absolute magnitude usually of the order of 20%, and sometimes greater.

A major issue in pion absorption studies is the fraction of the absorption cross section due to the "quasideuteron" mechanism, i.e., absorption of the pion on an *np* pair. Measurements of π^+ absorption leading to two-proton emission indicate that about two-thirds of the absorption can be attributed to quasideuteron absorption (QDA) in lighter nuclei, falling to 50% or less in heavy nuclei [5–11]. Due to the importance of initial and final state interactions (ISI/FSI), only a small fraction of the observed two-proton final states actually have quasideuteron kinematics, in which the two protons are nearly back-to-back and carry most of the available energy. The corrections required to estimate the QDA are thus substantial, and there is no generally accepted method of making them [12, 13].

In this paper we report the results of an experiment in which a detector with a large solid angle, the LAMPF BGO ball, was used to study proton emission following π^+ absorption on heavy nuclei. Measurements were made for pion kinetic energies of 50, 100, 150, and 200 MeV using thin targets of ^{6}Li, ^{12}C, CD_2, ^{27}Al, ^{58}Ni, ^{118}Sn, ^{208}Pb, and ^{238}U with thicknesses of 0.21, 0.10, 0.19, 0.25, 0.29, 0.14, 0.21, and 0.45 g/cm^2, respectively. These measurements are the first of proton emission with little restriction on the correlations of the outgoing particles, and the first direct measure of the cross section for noncoplanar three-proton emission for a variety of nuclei at several energies. A detailed discussion of the ^{6}Li data has already been published [14, 15]. A description of the BGO ball and its operation is given in Refs. [14] and [15]. Protons with energies less than about 12 MeV were stopped in one target thickness, and the experimental threshold on the observed outgoing proton energy was about 22 MeV, corresponding to an original proton energy of about 25 MeV. The target was too close (6 cm) to the detectors to make time-of-flight measurements, although particles from pions in previous or subsequent beam buckets could be eliminated since the production beam had a 5-ns microstructure.

Absolute normalization and energy calibration of the

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measurements were established by measuring pion absorption on deuterium in the CD_2 target. The observed cross sections were compared with the accepted cross sections [16] giving correction factors for missing solid angle and reaction losses in the ball of 1.7, 2.7, 3.5, and 3.4 at the four energies, respectively. Estimates of the correction factors, based on the geometry and known properties of the detectors, agree within 15% with these measured values. The variations of measured cross sections in different runs with the same target lead to an estimate of the uncertainty in the absolute values of about 10%.

The bulk of the cross sections with two or more protons contains only two protons. The observed cross sections, with no correction for missing solid angle or losses due to nuclear reactions in the detectors, are given in Table I. The statistical precision is typically 1% for the $2p$ cross sections, much less than the systematic uncertainty, so all cross sections have been rounded to two significant figures. The "$2p$ inclusive" cross sections represent events with only two protons, no identified pion, fewer than two identified neutrals, but with no restriction on deuterons, low-energy charged particles, or unidentified particles. The exclusive cross sections (two protons and no other particles detected) show little dependence on A, and vary from 80–85 % of the inclusive cross section for 50-MeV pions to 60–65 % for 200-MeV pions. Events with two identified neutrals are usually due to charge exchange, which will be discussed elsewhere [17].

The $2p$ inclusive cross sections for proton energies greater than the total pion energy minus the binding energy of the least bound np pair minus 50 MeV, i.e., an excitation energy of less than 50 MeV, are listed in the "$2p$ 50" column. This excitation energy was chosen both to allow a comparison with other experiments [8] and to allow a comparison of the low excitation cross section of various nuclei. The most striking feature of all the data is the small fraction of events with more than two protons. The four-proton cross section is always negligible (less 0.5 mb even for 200-MeV pions) and generally statistically consistent with zero.

The estimated total cross sections for events leading to two or more protons and for three protons are shown as the second value in the "$2p$ inclusive" and "$3p$ inclusive" columns, respectively. These estimates were obtained using the method described in Ref. [15]. See Ref. [15] for a discussion of the ^{6}Li total cross section estimates. Modeling of the final states is more uncertain than that described in Ref. [15]. The extrapolation to zero energy is

TABLE I. Observed cross sections in mb. See text for description of cross sections. The second value in $2p$ and $3p$ columns is the estimated total cross section.

Energy (MeV)	Nucleus	$2p$ inclusive	$2p$ 50	$3p$ inclusive	Deuteron	$2pn$	2 hit	2 hit-b	Total
50	^{6}Li	16	11	0.22	2.7	0.06	32	30	28
	^{12}C	22/50	16	0.42/1.3	4.0	0.10	53	45	88
	^{27}Al	29/76	15	0.37/1.6	4.5	0.09	77	62	240
	^{58}Ni	40/100	18	0.56/3.1	6.3	0.08	140	100	440
	^{118}Sn	42/120	17	0.37/2.0	11	0.3	240	143	870
	^{208}Pb	42/130	17	0.40/2.2	14	0.00	290	142	1700
	^{238}U	36/100	15	0.40/2.2	10	0.3	440	144	1800
100	^{6}Li	30	16	1.2	4.5	0.4	62	46	70
	^{12}C	50/100	26	2.2/5.6	9.9	0.6	110	78	130
	^{27}Al	55/120	17	2.1/6.5	11	0.7	140	83	290
	^{58}Ni	97/240	26	4.0/12	17	1.1	290	143	460
	^{118}Sn	112/280	23	4.0/12	28	1.5	420	176	1000
	^{208}Pb	112/300	24	2.3/8.5	32	1.9	480	183	1500
	^{238}U	94/240	19	1.8/6.6	27	1.4	480	168	1600
150	^{6}Li	36	14	2.6	5.2	1.4	90	51	120
	^{12}C	52/110	18	5.4/14	11	1.6	160	69	190
	^{58}Ni	124/300	19	11/33	23	2.9	410	123	560
	^{118}Sn	124/320	13	10/31	36	2.2	590	135	1000
	^{208}Pb	159/400	19	7.7/24	45	2.8	710	156	1400
200	^{6}Li	31	7	3.8	5.1	3.0	102	38	65
	^{12}C	58/140	11	9.4/24	13	4.0	150	54	160
	^{27}Al	65/160	8	10/28	14	4.1	210	53	330
	^{58}Ni	133/330	11	19/53	27	7.0	410	84	600
	^{118}Sn	174/440	9	20/59	45	6.8	560	88	830
	^{208}Pb	216/540	14	18/53	59	7.7	700	101	1000
	^{238}U	177/440	10	12/34	48	6.9	720	87	1100

based on the observed energy distributions and so should be used with some care. We do not have a good measure of the cross section for protons with energies less than 20 MeV and there may be significant cross section for two or more protons in which one or more has an energy less than 20 MeV. Based on the uncertainties in the corrections for the deuterium absorption cross section and the variance in the estimated total for different models of the final states, we believe these estimated totals are good to about 20%.

Except for ^{6}Li, discussed previously [14, 15, 18, 19], the missing-energy spectra show no particular structure. The cross sections at large missing energy increase with A and with pion energy. Figure 1 shows a sample of the summed proton energy for 150-MeV pions. There is significant cross section for 150- and 200-MeV pions in which the total observed energy is less than the pion kinetic energy, thus absorption is not assured. However, even for 200-MeV pions the observed $\pi 2p$ cross section is never more than a few percent of the observed $2p$ cross section, and there is no change in shape in the missing-energy spectrum near the point where nonabsorption is possible, so contamination of the $2p$ spectrum by nonabsorption events seems to be negligible.

In addition to final states in which two or more protons are observed, there is a significat t fraction of events in which deuterons, neutrons, or low-energy charged particles are observed. Some of these are given in Table I. All cross sections shown include the requirement of no observed pion and fewer than two neutrals observed in the ball. The column labeled "deuteron" gives the cross sections for events with one or more identified protons and one or more deuterons; "$2pn$" are those events with two observed protons and one observed neutral; "2 hit" is the total cross section for two or more hits and restricted only that there be no pion and fewer than two neutrals; "2 hit-b" is the same as "2 hit" but with a total observed energy greater than the kinetic energy of the pion. The column labeled "Total" contains total cross sections as estimated from previous experiments [2, 3].

The cross sections for deuteron emission are relatively large at all energies, with cross sections 10% to 30% of the $2p$ inclusive cross section. The ratio is fairly constant as a function of A at a particular energy, although there is a distinct increase of about 30% in the ratio between ^{58}Ni and ^{118}Sn. This is about the same as the increase in the ratio N/Z, which is about 1 for nickel and lighter nuclei and about 1.3 for ^{118}Sn, ^{208}Pb, and ^{238}U. The energy distribution of the deuterons varies little with A, and the maximum energy increases smoothly with increasing incident pion energy. The ratio of the cross section for deuteron emission to two-proton emission shows very little energy dependence. Since the angular distribution of the deuterons follows that of the protons, we conclude that most deuteron emission is probably due to neutron pick-up by protons, as in ^{6}Li [15].

Observed neutron emission is not as large as deuteron emission, but the maximum efficiency for detection is 25% for a 100–200-MeV neutron, with the efficiency dropping quickly at lower energies. Since we know neither the primary neutron energy spectrum nor the efficiency, only lower limits on the total cross section for neutron emission can be determined. For an incident pion energy of 50 MeV, the $2pn$ cross sections are less than 1% of the observed $2p$ inclusive cross sections. For T_π = 200 MeV the fraction increases to 7% for ^{12}C and to about 4% for ^{208}Pb. These results suggest that at least 28% of the events in ^{12}C and 16% in ^{208}Pb contain an energetic neutron. However, if the neutron energy distribution follows the proton distribution, the fraction could be much higher, since most of the neutrons will be at an energy where the detection efficiency is small. The proton spectra show a higher mean proton energy for ^{12}C than ^{208}Pb, and one would expect a similar result for neutrons, so the lowered percentage for heavier nuclei is likely due to a drop in detection efficiency rather than fewer neutrons being emitted.

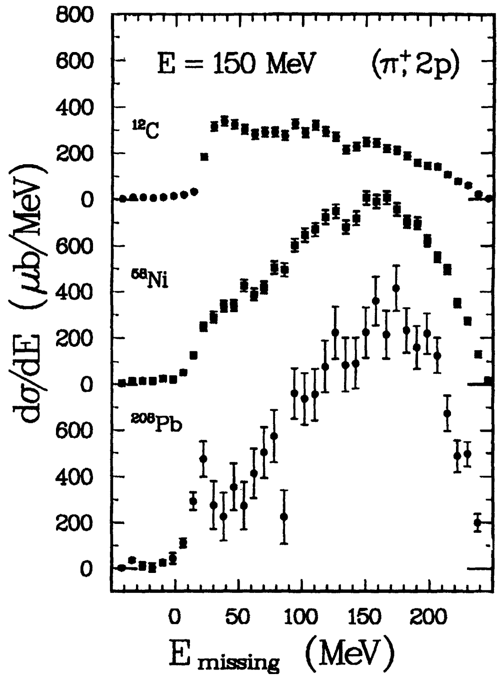

FIG. 1. Summed proton energy for T_π = 150 MeV.

There is a substantial cross section for events which do not contain at least two protons. This can be seen by the large differences between the "2 hit" cross sections and the sum of the "$2p$" and "$3p$" cross sections. Most of the additional cross section is due to events with low-energy charged particles. As can be seen from the cross sections in the column "2 hit-b," the bulk of the cross section at larger energies has an observed total energy too low to guarantee that the pion was absorbed. However, the summed energy spectra do not show an increase near the pion energy, so it is believed that much of this cross section is in fact due to absorption.

Exact comparisons between this work and other studies is complicated by differing experimental details. Two previous experiments detected three protons following absorption on ^{12}C [20, 21]. Tacik *et al.* [20] required three coplanar protons with an energy threshold of 50 MeV for T_π=130, 180, and 228 MeV. In that work the three-proton emission was well described by three-body phase space, and the quoted cross sections for three-proton emission extrapolated to zero threshold were 7.9, 19.9, and 22.5 mb. Our observed values are 2.2, 5.4, and 9.4 mb at 100, 150, and 200 MeV, respectively. The estimated totals, assuming a three-body phase space distribution, are 5.6, 13.5, and 23.5 mb. Thus, the two experiments seem to be in approximate agreement. Reference [21] reported a value of 55 ± 3 mb for three-proton emission at 130 MeV with a threshold of 12 MeV, nearly ten times our measured values. It is in clear disagreement with that of Tacik *et al.*, although some of the discrepancy could be due to a large cross section for low-energy proton emission.

Burger *et al.* [8] studied ^{58}Ni$(\pi^+, 2p)$ at 160 MeV with a detection threshold of 25 MeV for each proton. That work found an estimated total cross section of 608 ± 60 mb for both protons above 25 MeV, and a cross section of 58 ± 6 mb for events with an excitation energy of 50 MeV or less. Our corresponding values with a 22-MeV observed energy cut are 124 mb and 19 mb. Using the correction factors determined from the measured deuterium cross section, as discussed above, these total cross sections would be 430 mb and 66 mb, with uncertainties of at least 15%. Although the second value is in good agreement with Burger *et al.*, the first is substantially lower. Since the correction overestimates the actual value, the discrepancy appears to be substantial. We have no explanation for the rather large discrepancy at this time.

Altman *et al.* [6] studied the $(\pi^+, 2p)$ reaction for three nuclei at 165 and 245 MeV. At 165 MeV they found values of about 17, 27, and 29 mb for ^{12}C, ^{56}Fe, and ^{209}Bi, respectively, with an overall normalization uncertainty of 9%. If we identify the cross section below 50-MeV excitation with their "narrow Gaussian" cross section, our values at 150 MeV for ^{12}C, ^{58}Ni, and ^{208}Pb are 18, 19, and 19 mb, respectively. Assuming our correction factors, our total cross sections would be 63, 66, and 66 mb. These are about a factor of two higher than those in Ref. [6]. Hyman *et al.* [22] concluded the data on ^{16}O from Ref. [6] were low by a factor of 2.3.

Yokota *et al.* made measurements [23–25] on ^{6}Li, ^{7}Li, and ^{12}C, detecting *pp*, *pn*, and *pd* coincidences. For ^{12}C they found the 2*p* cross section to be about 15, 16, and 16 mb at 70, 130, and 165 MeV. Our uncorrected cross sections were 22, 50, 52, and 58 mb, already significantly more than the earlier values. References [23–25] measured two-proton coincidences for very nearly coplanar events, integrated those cross sections, and used an internucleon cascade (INC) code to estimate the rest of the cross section, yielding correction factors of 1.3, 2.2, and 2.1. We can only conclude that the INC substantially underestimates the noncoplanar part of the cross section.

A comparison with the total absorption cross sections of Refs. [2–4] shows systematically lower values for our data, with the discrepancy increasing with A. This is true at all energies. It cannot be due to an overall normalization problem, because the measurements on CD_2 agree within 15% of the accepted value, while for heavier nuclei we miss as much as half of the cross section. We must conclude that, if the results of Refs. [2–4] are correct, much of the absorption in medium to heavy nuclei leads to the emission of several protons and neutrons below our thresholds, with energies lower than about 20 MeV for protons and 50 MeV for neutrons.

In summary, the measurements reported here have shown several features of π^+ absorption in nuclei. Much of the absorption cross section appears to lead to final states with large missing energy. For heavier nuclei, much of the absorption cross section is missed, and only a small part of the observed cross section contains two or more protons. The cross section for emission of three or more protons is never more than 15% of the two-proton cross section. A full understanding of these data will require extensive theoretical modeling of the reaction. We hope these data will encourage more work in this area.

This work was supported in part by the U. S. Department of Energy, the National Science Foundation, NATO collaborative research Grant No. CRG890498, and the Robert A. Welch Foundation.

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