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Low-energy pionic double charge exchange on the $\beta\beta$-instable nuclei ^{128,130}Te

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Data of the (π^+,π^-) reaction on ^{128}Te and ^{130}Te at $T_\pi = 48$ MeV are presented, which constitute also the first observation of pionic double charge exchange (DCX) on heavy nuclei at energies below the (3,3) resonance. For the ground state transitions in these isotopes we find very small cross sections of about 15 nb/sr only at 30° and a ratio of $\sigma(^{130}\mathrm{Te})/\sigma(^{128}\mathrm{Te}) = 1.5^{+1.8}_{-0.8}$. The experimental results and their impact on the understanding of the $\beta\beta$ decay of the Te isotopes are discussed within the framework of recent proton-neutron quasiparticle random phase approximation calculations. For the transitions to the double isobaric analog states in ^{128}Xe and ^{130}Xe we obtain cross sections in the range 1 μb/sr which fit very well into a systematics, that is in accordance with a dominance of the short-range part of the DCX operator in analog transitions at low pion energies. [S0556-2813(96)50105-6]

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The (π^+,π^-) reaction has the unique property of changing the charge of a nucleus by two units while leaving the number of nucleons unchanged. Since these constraints force at least two nucleons to be involved in this process, this reaction has been thought for long to be an ideal probe for investigating correlations between bound nucleons. Unfortunately, measurements conducted in the past in the region of the (3,3) resonance and above show that in this energy region correlation effects in the cross sections are hidden beneath other dominating effects such as absorption phenomena. To overcome this problem double charge exchange (DCX) measurements have been carried out at energies well below the (3,3) resonance, where the mean free path of pions in nuclei is very large. The subsequent discovery [1] of a particular sensitivity of low energy pionic double charge exchange to nucleon-nucleon (NN) correlations of short range has stimulated systematic investigations of the low energy DCX [2]. In parallel to this it has been realized that also in double β ($\beta\beta$) decay particle-particle correlations play a crucial role changing the calculated lifetimes up to several orders of magnitude [3,4]. The common dependence on internucleon correlations puts both these processes, which connect the

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same initial and final states, in a very close relation to each other in as far as the NN-matrix elements are concerned, though both processes are driven by totally different interactions. Thus the DCX reaction on $\beta\beta$-instable nuclei can, in principle, serve as a critical test of the nuclear structure part relevant for the understanding of $\beta\beta$ decay.

Fazely and Liu [5] have studied the connection between neutrinoless $\beta\beta$ decay ($0\nu\beta\beta$) and DCX at resonance energies. Since there nonanalog ground state transitions (GST) are dominated by Δ processes they examined the role of those also in $0\nu\beta\beta$ decay and arrived at a data-to-data relation between forward angle GST and $0\nu\beta\beta$ lifetime by eliminating the NN-matrix elements common to both processes. In a subsequent measurement [6] of the GST's in ^{128}Te and ^{130}Te at $T_\pi = 164$ MeV a ratio of $\sigma(^{130}\mathrm{Te})/\sigma(^{128}\mathrm{Te}) = 2.9(14)$ was obtained and a corresponding ratio for the NN-matrix elements was derived. However, realizing the small mean free path of resonant pions in nuclei and thus their restriction to the nuclear surface region, the relevance of DCX measurements at resonance energies for the extraction of NN-matrix elements has been questioned by the authors [6] emphasizing instead the need for measurements at low energies. Since the low-energy DCX is not dominated by Δ processes we will discuss the connection to the $\beta\beta$ decay here in a different approach by comparing our experimental DCX results on the Te isotopes with microscopic calculations performed in the framework of the proton-neutron quasiparticle random phase approximation (pnQRPA), i.e., the same model which has been very successful in the description of single [4,7] and double β decay [3,4].

Aside from these very interesting interrelations DCX measurements on heavy nuclei are interesting in their own right. So far low-energy DCX data are available only for light nuclei up to ^{56}Fe [2,8], and at a single energy and a single angle for ^{93}Nb [9]. At resonance energies and above the dependence of the forward angle DCX cross section on the target mass A is well described [10] by simple scaling laws predicted in a strong absorption model [11]—both for transitions to the double analog state (DIAT) and for those to the ground state (GST). At $T_\pi \approx 50$ MeV the situation is more complex. The forward angle cross sections of the DIAT in $T=1$ nuclei (^{14}C-^{42}Ca) have turned out to be approximately independent of A, and the DIAT's in $T>1$ nuclei appear to fit into a systematics which emphasizes the dominance of short-range effects in the DCX transitions at low energies [9]. For the GST's on the other hand, low energy data show no systematic A dependence; they rather appear to be very sensitive to individual nuclear structure effects at small NN distances [2,12].

Here we report on DCX measurements on Te isotopes at low energies performed at $\Theta_{\mathrm{lab}} = 30°, 45°$ and $T_\pi = 48$ MeV midtarget energy, with the Low Energy Pion Spectrometer LEPS [13,14] at the $\pi E3$ channel of the Paul Scherrer Institut (PSI). Outstanding features of LEPS, which are crucial for reliable studies with small cross sections, are high background suppression in combination with a good energy resolution utilizing time of flight and energy loss techniques for particle identification as well as vertex reconstruction. The information for the latter is supplied by a six-plane multiwire proportional chamber at the intermediate focus and a vertical drift chamber at the focal plane, which both determine position and angle of incidence of the detected particles. The particle identification is done with a range telescope consisting of a stack of scintillators in the focal plane as well as by time of flight measurements against the radio frequency of the cyclotron. Application of all the different constraints results in a background reduction of up to 10^5 in the focal plane. Thus very clean π^- spectra are obtained. The DCX runs have been normalized to calibration runs of elastic π scattering calibrated in turn with the ‘‘lepton normalization technique’’ [14] which gives absolute cross sections accurate to within five percent. As target we used self-supporting wafers of 99.4% isotopically enriched material (^{128}Te: 800 mg/cm^2 of size 10 cm$\times$10 cm; ^{130}Te: 550 mg/cm^2 of size 9 cm$\times$9 cm), which are identical to those used in previous DCX measurements at LAMPF [6,15] at higher energies.

Two sets of measurements have been performed with these targets, the first one still on the old $\pi E3$ channel and with an ≈ 200 μA proton beam incident on the production target E. At $T_\pi = 50$ MeV this leads to a flux of about $6\times10^6 \pi^+$/s at the place of the scattering target. The second set of runs has been carried out already on the new $\pi E3$ channel with about 800 μA primary beam and a flux of about $2\times10^7 \pi^+$/s. Specifications of the new beamline are given in Ref. [16]. Since the time resolution of the beam particles in the new beamline is somewhat worse than in the old one ($\Delta t = 2$ ns full width at half maximum compared to $\Delta t = 1$ ns [14]), a thin (2 mm) scintillator has been installed at the entrance of LEPS in the runs with the new beamline in order to obtain an additional time of flight measurement with good time resolution between entrance and focal plane of LEPS. With this setup measurements have been performed at two LEPS momentum settings, the first one centered around the reaction Q values of the GST's (^{128}Te: $Q = +1.89$ MeV; ^{130}Te: $Q = +3.56$ MeV), and the second one centered around the region expected for the DIAT's (^{128}Te: $Q = -25.8$ MeV; ^{130}Te: $Q = -25.5$ MeV [15]). Note that for the ground state setting the collection of one spectrum typically took one week of running time.

DCX spectra from these measurements are shown in Figs. 1 and 2. Figure 1 displays the results for the region of the GST in ^{128}Te (top) and ^{130}Te (bottom). The dashed lines represent the momentum acceptance of LEPS as determined by elastic π scattering at various field settings of the spectrometer. The solid curves indicate the position of the peak expected for the GST. The line shape has also been extracted from measurements of the elastic π scattering. The number of DCX events observed in these spectra is largest at the most negative Q values falling off smoothly towards less negative Q values. At $Q>0$ there are only a few counts, some in the region expected for the GST and very few also above. These latter, of course, are a measure of the background in our spectra and have been taken into account for the determination of the GST cross sections and their uncertainties. The shape of the observed spectra is comparable to that obtained at $T_\pi = 164$ MeV [6]. The observed continuum with its onset at about $Q \approx 0$ has to be associated with unresolved transitions to bound states as well as with transitions to continuum states ($Q < -6.3$ MeV and -5.1 MeV, respectively) in ^{128}Xe and ^{130}Xe. The levels closest to the ground state in ^{128}Xe and ^{130}Xe are of spin 2 and higher; in particu-

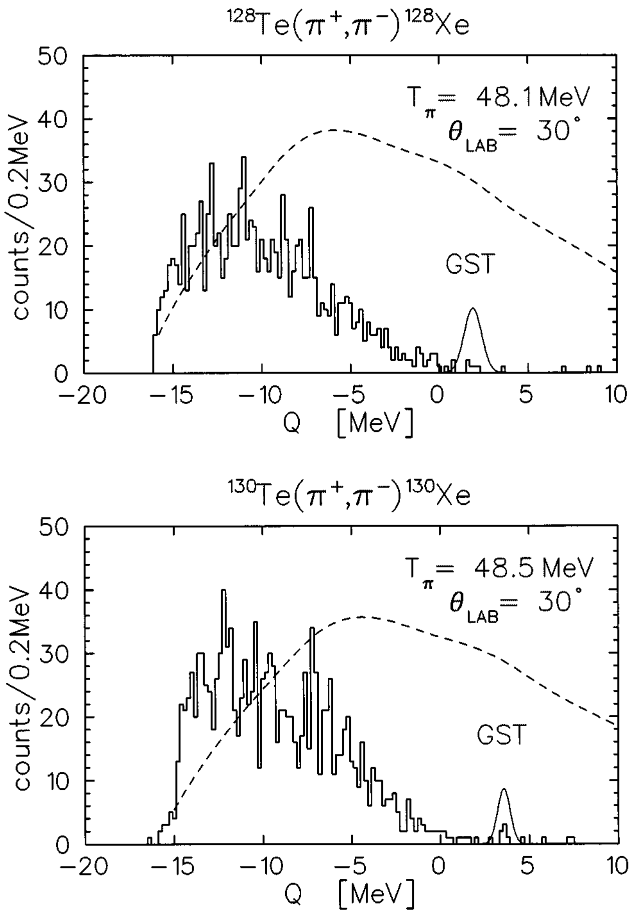

FIG. 1. DCX spectra for ^{128}Te (top) and ^{130}Te (bottom) at a spectrometer setting in the region of the ground state transition (GST). The solid curve gives the expected response for the GST; the dashed lines illustrate the acceptance of the LEPS spectrometer.

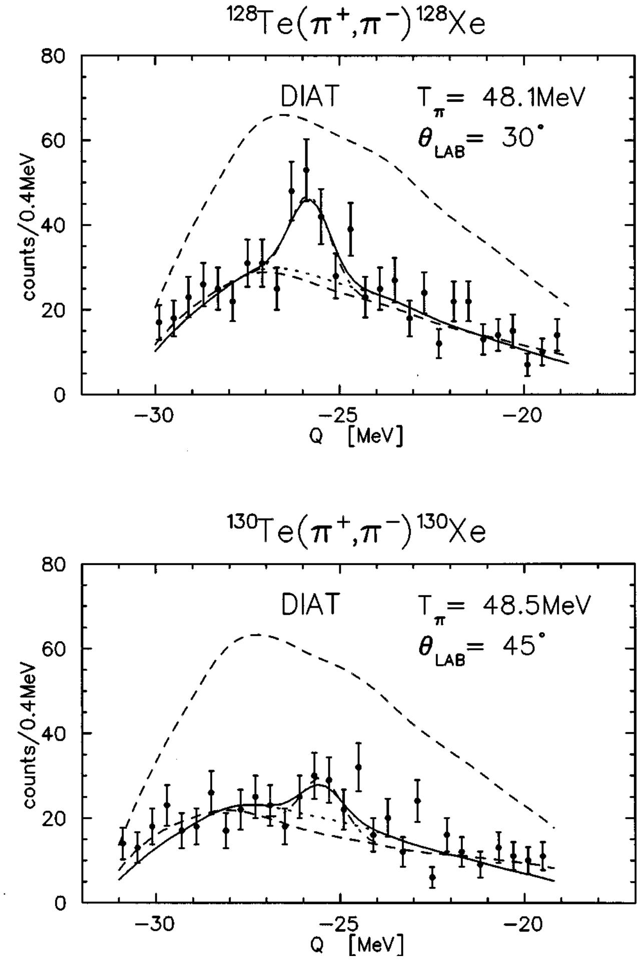

FIG. 2. Sample DCX spectra for ^{128}Te (top) and ^{130}Te (bottom) at a spectrometer setting in the region of the double isobaric analog state transition (DIAT). The solid and dash-dotted curves show the DIAT peak fitted onto a smooth background with linear (dotted lines) and quadratic (dashed lines) momentum dependence, respectively, and folded with the LEPS momentum acceptance (short-dashed lines).

lar there are no excited 0^+ states below an excitation energy of $E_x = 1.5$ MeV. Since in all previous DCX measurements at forward angles and low energies no sizeable strength of transitions to other than 0^+ states [2] has been observed, and since our experimental resolution is in the order of 1 MeV, we are confident that at the position of the GST (solid curves in Fig. 1) there are no counts due to other transitions. We then deduce cross sections of 12(6) nb/sr and 19(7) nb/sr for the GST in ^{128}Te and ^{130}Te, respectively, at $T_\pi = 48$ MeV and $\Theta_{\rm lab} = 30°$.

From our 30° values we may extrapolate forward angle cross sections of $\sigma(0°) = 54(27)$ and 83(30) nb/sr, respectively, based on the shape of angular distributions predicted in pnQRPA calculations (Fig. 4 with $g_{\text{p-p}} = 1.2$ in Ref. [17]) which will be discussed below. These cross sections are of similar magnitude as those obtained at $T_\pi = 164$ MeV and $\Theta_{\rm lab} = 5°$ [24(7) and 70(26) nb/sr [6], respectively]. In the present case the ratio of cross sections is $\sigma_{\rm GST}(^{130}\text{Te})/\sigma_{\rm GST}(^{128}\text{Te}) = 1.5^{+1.8}_{-0.8}$, whereas at $T_\pi = 164$ MeV a value of 2.9(14) has been obtained. Within their large statistical errors these values are compatible with each other.

Figure 2 displays sample spectra for the region of the DIAT in ^{128}Te (top) and ^{130}Te (bottom), respectively. We associate most of the observed events with a continuous physical background represented by dotted and dashed lines, respectively. These were obtained by least-squares fitting of the data with first and second order polynomials, respectively, multiplied by the momentum acceptance of LEPS; the latter is indicated by the long-dashed curve. Also included in the fit procedure was the height of a peak at the position of the DIAT ($Q \approx 26$ MeV) with the shape being deduced from elastic scattering at accordingly reduced channel momentum. The uncertainties in the DIAT cross sections due to these different assumptions for the description of the background are 10–20 % only in case of ^{128}Te, but as much as 50% in case of ^{130}Te due to the inferior statistics accumulated in these spectra.

Our results for the DCX cross sections on the Te isotopes are summarized in Table I. The observed DIAT cross sections are in accordance with the systematics from DIAT data at $T_\pi \approx 50$ MeV, which is shown in Fig. 3. Our values included there have been extrapolated to forward angles based on our 30° and 45° values as well as on the typical slow angle dependence of DIAT's known for lighter nuclei. As can be seen in Fig. 3, the forward angle DIAT cross sections divided by $(N-Z)/(N-Z-1)$ are approximately constant

TABLE I. Cross sections found in this work for GST and DIAT in ^{128}Te and ^{130}Te (in nb/sr) with statistical errors (1σ).

T_π (MeV)	Θ_{lab}	State	^{128}Te	^{130}Te
48	30°	GST	12(6)	19(7)
	30°	DIAT	1300(300)	1100(500)
	45°		500(300)	900(500)

with values between (1–2) μb/sr. In Ref. [9] it has been pointed out that this approximate constancy reflects the dominance of the short range part in the DCX transition operator at $T_\pi \approx 50$ MeV. Our results for the DIAT's in the Te isotopes extend the validity of these findings up to heavy nuclei. They also indicate that distortion effects obviously play a minor role at low energies even for heavy nuclei.

In contrast to the situation for the DIAT's there is no simple systematic behavior for nonanalog GST's at low energies. At energies in the (3,3) resonance and above the forward-angle cross sections are well accounted for by the black disk limit $\sigma_{\mathrm{GST}} \sim A^{-4/3}$ and thus do not exhibit much sensitivity to nuclear structure effects. Since the DIAT systematics at low energies indicates that distortions are of no major importance there, we would expect a very flat A dependence for the nonanalog GST's, if they were not dominated by individual nuclear structure effects. However, the latter is in fact the case at low energies as has been demonstrated in several investigations [2,12].

In case of the GST's in ^{128,130}Te microscopic calculations [17] predict large cancellations between different components in the transition matrix element due to short-range particle-particle correlations, which lead to very small DCX cross sections. The same correlations are simultaneously quoted as the origin for the very long $\beta\beta$-decay lifetimes of these Te isotopes.

In the following we compare our experimental DCX results on the Te isotopes with microscopic calculations performed in the framework of the proton-neutron quasiparticle random phase approximation (pnQRPA), i.e., the same model which has been very successful in the description of single [4,7] and double β decay [3,4]. The DCX calculations, the details of which are given in Ref. [17], utilize a realistic effective NN interaction derived from the Bonn potential [18]. For a complete determination of the pnQRPA solution two parameters need to be fixed which renormalize the bare Bruckner two-body matrix elements: the particle-hole strength $g_{\text{p-h}}$ and the particle-particle strength $g_{\text{p-p}}$. Ideally these parameters should be unity. Deviations from this value are caused by a limited model space as well as by the density dependence of the effective NN interaction. The particle-hole strength $g_{\text{p-h}}$ can be fixed easily by the experimental excitation energy of the isobaric analog state in the intermediate nucleus which depends approximately linearly on $g_{\text{p-h}}$ [17]. The particle-particle strength $g_{\text{p-p}}$, however, can only be fixed by processes which depend strongly on two-nucleon properties like $\beta\beta$ decay and pionic DCX. Assuming a $\beta\beta$ decay associated with the emission of two neutrinos ($2\nu\beta\beta$) the pnQRPA calculations [3,4] reproduce the experimental lifetimes of ^{128}Te and ^{130}Te for two solutions of $g_{\text{p-p}}$ in the range 0.8 to 1.0, the exact values of which critically depend [3,4] on the model space used in the calculation. In the model space of the pnQRPA calculations discussed here for the interpretation of the DCX data the corresponding solutions are $g_{\text{p-p}} \approx 0.9$ and 1.1, respectively. As shown in Fig. 6 of Ref. [17] an increase of $g_{\text{p-p}}$, which is connected with an increasing role of NN correlations, causes a drastic reduction of the DCX cross section similar to the reduction observed in calculations of β^+, $2\nu\beta\beta$, and $0\nu\beta\beta$ decays [3,4,7,19]. The DCX calculations come closest to the data for $g_{\text{p-p}} > 1$ though even there the predicted cross sections are too high by roughly a factor of 3–4. Reasons for this may be sought in a number of simplifications still

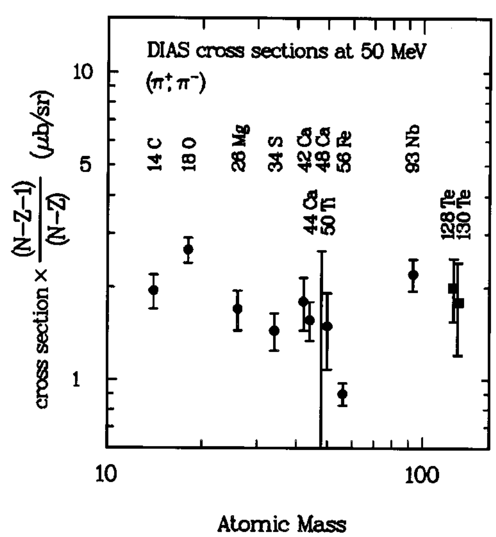

FIG. 3. Forward angle cross sections for the DIAT's at $T_\pi \approx 50$ MeV divided by $(N-Z)/(N-Z-1)$. The figure is an update of Fig. 3 in Ref. [9] with our values for ^{128,130}Te extrapolated to forward angles.

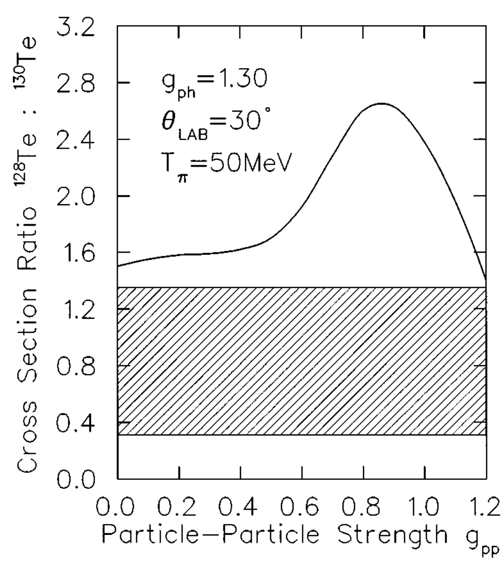

FIG. 4. Ratio of forward angle cross sections for the GST in ^{128}Te to the one in ^{130}Te in dependence of the particle-particle strength $g_{\text{p-p}}$. The solid curve represents a calculation of Ref. [17] with a particle-hole strength parameter $g_{\text{p-h}} = 1.30$. The hatched area gives the experimental result of this work.

present in these calculations [17] which do not account yet for distortions in entrance and exit channels as well as for nuclear recoil and proper particle number projection, and still consider the πN Hamiltonian in the nonrelativistic limit. To minimize these deficiencies, which are expected to affect the calculations for ^{128}Te and ^{130}Te in a similar manner, we next consider the ratio of these cross sections, the theoretical prediction of which should be much more reliable. The dependence of the cross section ratio on $g_{\text{p-p}}$ is shown in Fig. 4. The theoretical prediction comes closest to the experimental result for $g_{\text{p-p}}>1.1$, i.e., the DCX data clearly favor the second solution (with the larger $g_{\text{p-p}}$). Hence it appears that pnQRPA calculations are able to provide a reasonably consistent description for both the DCX on the Te isotopes and their lifetime assuming $2\nu\beta\beta$ decay. If the decay of ^{128}Te and ^{130}Te is assumed to be of the $0\nu\beta\beta$ type, then an interpretation of the geochemical decay rates with $g_{\text{p-p}}\gtrsim 1.1$ results in a limit for the Majorana neutrino mass of $m_\nu < 1.5$ eV [19].

We finally note that a shortcoming of pnQRPA calculations has been that they violate the Pauli exclusion principle and lead to an eventual collapse of the pnQRPA ground state close to the region of realistic strength parameters $g_{\text{p-p}}$. This difficulty has been resolved recently by the so-called renormalized pnQRPA approximation [20].

We have observed the GST's and DIAT's in ^{128}Te and ^{130}Te, which constitute the first DCX measurements on heavy nuclei at pion energies below the (3,3) resonance. The GST's have very small cross sections with values of 12(6) and 19(7) nb/sr at 30°, which are indicative of forward angle cross sections less than 100 nb/sr. Within the large uncertainties the observed cross section ratio $\sigma(^{128}\text{Te})/\sigma(^{130}\text{Te})$ is in reasonable agreement with microscopic calculations in the pnQRPA framework, which also quantitatively establish an intimate connection between pionic DCX and $\beta\beta$ decay with regard to their strong dependence on NN correlations characterized in the calculations by the particle-particle strength $g_{\text{p-p}}$.

The DIAT's have forward angle cross sections which are an order of magnitude larger than those of the GST's. They agree very well with the systematics of the DIAT data on the lighter nuclei at $T_\pi = 50$ MeV, which reflects the importance of the short-range part in the DCX transition operator as well as the subordinate role of distortions at low energies even for heavy nuclei.

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