ELSEVIER

9 November 1995

Physics Letters B 362 (1995) 34–38

PHYSICS LETTERS B

Search for double Gamow-Teller strength by heavy-ion double charge exchange

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Received 28 June 1995; revised manuscript received 7 September 1995
Editor: J.P. Schiffer

Abstract

We have carried out a search for double Gamow-Teller excitations, employing the ^{24}Mg(^{18}O,^{18}Ne)^{24}Ne reaction at 100 and 76 MeV/nucleon at NSCL-MSU and GANIL, respectively. The cross sections for low-lying excitations are typically a few nb/sr, providing evidence for a strong suppression of double Gamow-Teller excitations in heavy-ion double charge exchange, compared to pion-induced reactions. This result does not give good hope that heavy ions at intermediate energies could be used to probe double Gamow-Teller strength.

Keywords: Double Gamow-Teller strength; ^{24}Mg(^{18}O,^{18}Ne)^{24}Ne differential cross sections; Heavy-ion double charge exchange; $E = 76 \cdot A$ MeV

In the 1950's, beta decay was the principal technique for studies of spin-isospin degrees of freedom in nuclei. In beta decay, only a very small fraction of the total Gamow-Teller strength can be identified, since most of it is located in the Gamow-Teller giant resonance, which is energetically out of reach. Since the early 80's, experiments utilizing the (p,n) and (n,p) reactions have dramatically improved our knowledge on spin-isospin properties of nuclei, by probing also the Gamow-Teller resonance region. For a review, see e.g. Ref. [1].

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SSDI 0370-2693(95)01190-0

Recently, double beta decay has been identified in several experiments. (See e.g. Ref. [2] for a review.) Also in this case, only a minor fraction of the total appropriate strength can be studied. Experiments aiming at examining a major part of the double Gamow-Teller strength might improve our understanding of spin-isospin properties of nuclei, as did the single Gamow-Teller investigations.

Lately, double giant resonances have been of considerable interest, both theoretically and experimentally. Up to now the double isobaric analogue state (DIAS), the double isovector dipole resonance (DIVDR), and the dipole built on the analogue state have been identified, using the (π^+, π^-) reaction and its inverse at LAMPF [3]. In addition, evidence of Gamow-Teller strength built on the isobaric analogue state has been found [4]. It is expected that double giant resonances are general features of nuclei, and evidence for two-phonon resonances have now been found in several experiments. For a review of the field, see Ref. [5].

Among the two-phonon resonances, the double Gamow-Teller (DGT) resonance is of particular interest, because of links to particle and astrophysics via the connection to the double beta decay and its implications for the neutrino mass [6–8].

Auerbach, Zamick and Zheng predicted the existence of collective isotensor resonances in double charge-exchange reactions as a new mode of collectivity in nuclei [9,10]. Observation of DGT strength will be experimentally difficult, since there are no simple elementary probes available (the pion has zero spin and at the nucleon level a probe like (p,Δ^-) would be required). The DGT resonance can in principle be excited in pion double charge exchange [11], but the mechanism is assumed to be weak. Experimental efforts with this reaction are presently underway at LAMPF [12].

Heavy-ion double charge exchange has also been suggested as a probe for DGT strength [10,13]. Studies at NSCL-MSU and GANIL of the $(^6Li,^6He)$ and $(^{12}C,^{12}N)$ reactions at 35 and 70 MeV/nucleon, respectively, show that heavy ion reactions can be used to extract (single) Gamow-Teller strength [14,15]. However, the double charge-exchange (DCX) reaction rates are expected to be small. A way of increasing them is to use a projectile and an ejectile which belong to the same SU(4) multiplet in S and T. This is in practice fulfilled only when the projectile and ejectile are located symmetrically around $N = Z$.

The lightest non-radioactive $T = 1$ beam is ^{18}O. With the $(^{18}O,^{18}Ne)$ reaction, the target isospin is raised, restricting the scope to relatively light targets so as not to Pauli block the Gamow-Teller strength. The $V_{\sigma\tau}/V_\tau$ ratio in the effective nucleon-nucleon interaction should be as large as possible to enhance spin-transfer modes relative to non-spin-flip. This ratio reaches a maximum around 200 MeV/nucleon, which should be the ideal energy, but charge exchange above 50 MeV/nucleon should still be useful for spin-flip excitations.

Calculations for the nuclear structure part of the double Gamow-Teller strength involve the double application of the $\sigma\tau$ operator. (These excitations are sometimes referred to as direct – or mesonic – double charge exchange to distinguish them from two-step neutron/proton mutual transfer reactions.) Such calculations should be particularly reliable for the *sd* shell nuclei. The experimental values for essentially all measured $B(\mathrm{GT})$ obtained in beta decay have been compared to those calculated in the full *sd* shell-model space with the wave functions obtained from Wildenthal's USD interaction [16]. The experimental values are systematically about 60% of those calculated; this reduction can be understood as a combination of higher-order configuration mixing and delta-admixture effects [16]. The $J^\pi = 1^+, T = 0$ to $J^\pi = 0^+, T = 1$ transition in $A = 18$ displays particularly good SU(4) symmetry in that nearly 100% of the GT sum-rule strength of $3(N-Z)$ is exhausted by the lowest energy 1^+ state [16]. The ^{18}O, $0^+, T = 1$ to ^{18}Ne, $0^+, T = 1$ double GT transition through this intermediate $1^+, T = 0$ state provides a particularly strong and simple transition to use for this study. One also wants the complementary double GT channel in the target to be as strong as possible. With the available stable nuclei this is maximized for the cases with $N = Z$ and in particular for ^{28}Si [17]. The strength for ^{24}Mg is also reasonably large and is in good agreement with the *sd* shell calculations [18,19].

Our calculations indicate that significant concentration of DGT strength in ^{24}Ne should be found in the ground state and excited states at 4.7 and 7.0 MeV, with the remaining strength spread broadly at higher energies, when employing reactions with ^{24}Mg as target (see Fig. 1c). 60% of the exhausted DGT strength

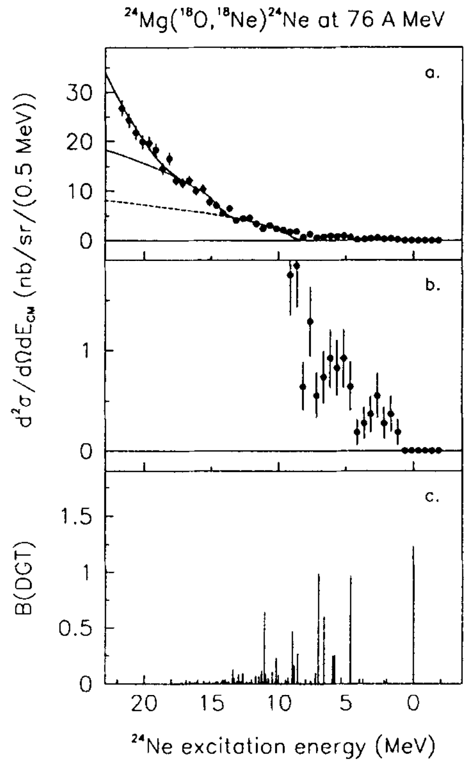

Fig. 1. The differential cross section for the ^{24}Mg(^{18}O,^{18}Ne)^{24}Ne reaction at 76 · A MeV, for the entire solid angle covered. Panel (a) shows a fit of a sum (solid) of the phase-space distributions for one-neutron(dashed), two-neutron (dotted) and one-proton breakup (solid). Panel (b) shows the ground-state region with an expanded vertical scale. In panel (c), our DGT strength calculation calculation is displayed. See the text for details.

was calculated to lie below the neutron break-up threshold (E_x = 8.9 MeV), which should provide a reasonable chance to observe it if the cross sections are not too small. In these calculations, the first ten intermediate states in ^{24}Al have been considered, as displayed in Table 1.

The only giant resonance for which both the one- and two-phonon cross sections have been measured with similar reactions is the IVDR, which has been studied by the ($\pi^{\pm}$,π^0) (one-phonon) [20] and the (π^+,π^-) (two-phonon) [3] reactions. The ratio of the two- to one-phonon cross sections, taken at the maximum of the two excitations, is about 0.003. The single Gamow-Teller cross section at zero degrees in heavy-ion reactions are typically a few mb/sr for light nuclei. An estimate based on such an approach, using a B(GT) calibration from single charge exchange, the shell model calculation above, and a simple model for the DCX cross section in terms of the SCX cross sections by Bertsch [21], yields a cross section of 24 μb/sr. In this model, it was assumed that the ratio SCX/DCX is the same as for pion-induced charge exchange.

Table 1
Intermediate states in the strength calculation

E_X (MeV)	B(GT)
9.990	0.058
10.634	0.965
12.753	0.521
13.141	0.039
14.032	0.059
14.453	0.010
14.627	0.030
15.072	0.020
15.410	0.000
15.656	0.008

Excitation energy is relative to the ^{24}Mg ground state. See the text for details.

Bertulani [22] has developed an eikonal approximation model for heavy-ion charge exchange reactions, in which he predicted that the cross sections for DGT excitation in heavy-ion reactions should be – at most – in the μb/sr region. It was pointed out that there is a suppression mechanism of heavy-meson exchange in heavy-ion reactions. Instead of a large contribution from ρ mesons in the reaction mechanism – which is the case for reactions induced by pions and nucleons – the larger interaction distance in heavy-ion reactions favour pion exchange. This results in a much weaker charge-exchange, and hence much smaller cross sections. Thus, these two predictions differ by several orders of magnitude.

Guided by this, we have carried out a search for double Gamow-Teller excitations, employing the ^{24}Mg(^{18}O,^{18}Ne)^{24}Ne reaction at 100 and 76 MeV/nucleon at NSCL-MSU and GANIL, respectively. The first attempt was made at NSCL-MSU, where an upper limit of the cross sections to low-lying states in the 100 nb/sr region was established. The meagre statistics prompted a second experiment at GANIL, where substantially more intense beams can be delivered, although at a slightly lower energy. The results presented here are from the GANIL run only.

In the experiment, $^{18}O^{8+}$ ions of 76 · A MeV, with an intensity of 100–200 nA (electric), were extracted from the GANIL accelerator system. The energy and emittance of the beam were defined by a 270° magnetic analysing system. The momentum analysis of the ejectiles was performed by means of the energy-loss spectrometer SPEG [23] and its standard detector system [24]. SPEG was located at a central angle of 1° with respect to the beam throughout the data taking, covering an angular range from −1° to +3°.

A self-supporting ^{24}Mg target, 3.5 mg/cm^2 thick, and with an isotopic purity of 99%, was mounted in the scattering chamber. The energy resolution of 1.0 MeV was dominated by the target energy loss difference for ^{18}O and ^{18}Ne.

Very few of the particles arriving at the focal plane of the spectrometer were ^{18}Ne ions. Because the experiment was limited by the acquisition rate, movable slits were used to reduce the active focal-plane length to cover only the first 25 MeV of excitation energy in ^{24}Ne. The solid angle acceptance was defined by entrance slits, set to $(-1.0 \pm 1.0)°$ vertically and $(-1.0 \pm 3.0)°$ horizontally.

In the absence of suitable reactions for calibration of the magnetic rigidity, we adopted a two-step procedure. First, a calibration by elastic scattering of ^{18}O ions and by the neutron-transfer reaction ^{24}Mg(^{18}O,^{19}O)^{23}Mg was performed. Second, the magnetic fields were scaled by about 25% to match the rigidity of the ^{24}Mg(^{18}O,^{18}Ne)^{24}Ne ground-state transition. The uncertainty of this scaling has been estimated to be less than 0.5 MeV.

The reliability of the rigidity scaling technique was tested using a fit to the break-up part of the spectrum, i.e., reactions like ^{24}Mg(^{18}O,^{18}Ne+n)^{23}Ne. We assumed the cross section to be dominated by a sum of the phase-space distributions for one-neutron, two-neutron and one-proton breakup reactions. Simple analytic expressions were used for the neutron distributions [25], with a Coulomb term added for the proton breakup. The magnitudes of each distribution and the location of the one-neutron breakup threshold were fit parameters, while the relative location of the two other contributions were kept fixed with respect to the one-neutron threshold. The best result of this fit is displayed in Fig. 1a. The result of this analysis implies that the energy scale is correct to within 0.5 MeV. An error of that magnitude will not affect the conclusions of this paper.

The data for the entire solid angle acceptance are displayed in Figs. 1a, 1b. No pronounced peaks are present in the spectrum. In Fig. 1b, which displays the ground-state region, there might be structures at excitation energies of 2.8 and 6.2 MeV in ^{24}Ne. These structures do not correspond to any known states in ^{24}Ne. Angular distributions for different excitation-energy intervals are displayed in Fig. 2. The statistical uncertainty prevents any far-reaching conclusions. One feature to observe, however, is the rather flat angular distributions for the low-energy excitation intervals. This does not support a double Gamow-Teller origin of these excitations, at least not as two consecutive $L = 0$ transitions, which can be expected to be more forward-peaked.

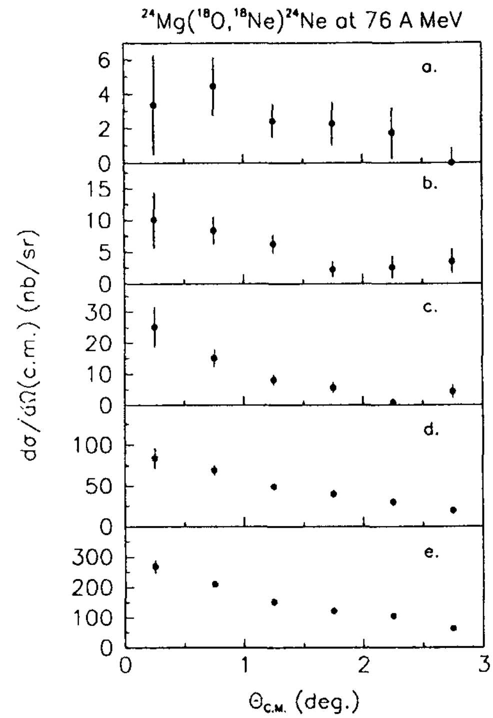

Fig. 2. Angular distributions for different excitation-energy intervals. (a) E_x = 0.0–4.5 MeV, (b) E_x = 4.5–7.5 MeV, (c) E_x = 7.5–10.0 MeV, (d) E_x = 10.0–15.0 MeV, (e) E_x = 15.0–20.0 MeV.

From the data, we can deduce that in the 0–1°(C.M.) interval, the average differential cross section to states which are unambiguous excitations in ^{24}Ne, i.e., which lie below the neutron breakup threshold (E_x = 8.9 MeV), is 20.1 ± 2.9 nb/sr, while the structures at E_x = 2.8 and 6.2 and MeV have average cross sections of 4.2 ± 1.3 and 8.9 ± 1.9 nb/sr, respectively, in the same angular interval. The errors quoted are statistical. The systematic error is estimated to be about 30%.

The present results provide evidence for a strong suppression of double Gamow-Teller excitations. Thereby, they are qualitatively compatible with the Bertulani model [22]. However, we can only deduce an upper limit of the cross section, and it cannot be excluded that the DGT excitation is even weaker. This result seems to preclude the use of heavy ions at intermediate energies for probing double Gamow-Teller strength.

The question arises how "clean" the reaction mechanism will be at these energies. Lenske, Wolters and Bohlen [26] have developed a fully microscopic analysis of SCX in (^{12}C,^{12}N) reactions including direct (mesonic) charge exchange and two-step neutron/proton transfer charge exchange. Even in the region of E = 70 MeV/nucleon, the two-step processes are non-negligible especially for higher multipolarities where the direct charge exchange strength is becoming suppressed. This suppression was found to be a quite general property of the higher multipoles of meson exchange interactions. Only in the GT-channel they found a clear dominance of direct charge exchange.

From the above work, a total DCX cross section of the order of 10 μb can be expected [27]. This is pretty close to what could be expected from transfer CX, i.e., the exchange of a proton pair from one nucleus and a neutron pair from the other, at these incident energies. If the two processes interfere destructively a cross section close to zero might be obtained. The rather flat shape of the angular distributions could be due to such an effect.

The importance of transfer CX might be tested experimentally by measuring 2p and 2n transfer exit channels separately in reactions like (^{18}O,^{20}O) and (^{18}O,^{20}Ne). An ambitious investigation of the physics issues discussed above could be to compare the DCX reaction with the two SCX reactions related to it. This could provide an estimate of the total DCX strength, provided interference effects among the amplitudes leading through different intermediate states are not too strong. A possible case might be the ^{48}Ti(^{18}O,^{18}Ne)^{48}Ca DCX reaction, and the ^{48}Ti(^{18}O,^{18}F)^{48}Sc and ^{48}Ca(^{18}Ne,^{18}F)^{48}Sc SCX reactions.

The authors wish to thank the staff at the NSCL-MSU and GANIL facilities. This work was financially supported by the foundation Blanceflor Boncompagni-Ludovisi, née Bildt, the Swedish Natural Science Research Council, and the U.S. National Science Foundation.

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