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Indications for isospin impurities in the 2_1^+ excitations of the $A=30$ $T=1$ isobaric multiplet

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Indications for isospin impurity in the transition from the ground state to the first 2^+ states of ^{30}S and ^{30}Si mirror nuclei are given, using electromagnetic and proton scattering probes. The ^{30}S neutron and proton transition matrix elements are compared to the corresponding experimental mirror quantities in the ^{30}Si nucleus, indicating a possible charge independence violation. The experimental ^{30}Si neutron transition density deduced from previous (p,p') scattering is found larger than the ^{30}S proton transition density. Electromagnetic data on ^{30}P are also incompatible with charge independence in the $T=1$(^{30}Si, ^{30}P, ^{30}S) isobaric multiplet.

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Isospin symmetry is a much applied concept in nuclear physics [1], but is only an approximate symmetry, partly due to the charge dependence of the nuclear force [2]. Isospin impurities have already been observed in the $N=Z$ ^{64}Ge [3], ^{46}V [4], and ^{54}Co [5] nuclei using β decay measurements. They can also be traced through detailed studies of transition rates between ground and excited states. Electromagnetic probes such as lifetime measurements and Coulomb excitation experiments allow to directly measure the proton contribution to the excitation [6]. Inelastic hadron scattering such as (p,p') is a complementary tool for measuring the neutron contribution. Namely, the proton and neutron transition matrix elements are defined from the transition densities $\delta\rho$,

$$M_{p,n} = \int \delta\rho_{p,n}(r) r^4 dr \tag{1}$$

in the case of a transition from the 0^+ ground state (g.s.) to the first 2^+ state. The M_p factor is directly related to the $B(EL)$ transition strength value obtained by Coulex experiment. In the following we adopt the convention

$$B(E2, J_i \to J_f)_{p,n} = \frac{(2J_f+1)}{(2J_i+1)} |M_{p,n}|^2. \tag{2}$$

Equation (1) shows that the transition matrix element mainly reflects the transition strength at the nuclear surface. Since direct reactions are surface peaked [7], they are well adapted to provide M_n values. Therefore the combination of electromagnetic and hadronic probes allows the extraction of the M_p and M_n values. Isospin symmetry in a given T multiplet imposes [8]

$$M_p(T_Z) = M_n(-T_Z). \tag{3}$$

In stable light nuclei, the symmetry breaking effect due to the Coulomb force is small [2], thus the direct comparison of the measurements of the neutron and proton observables provides a check for this symmetry. Bernstein *et al.* used this argument to investigate the $T=1$ isobaric multiplets for $A \leqslant 42$ nuclei [8], assuming charge independence of nuclear forces. They proposed a method to check if the symmetry is verified within the $T=1$ multiplets [8]. The charge independence entails that the isoscalar multipole matrix element is independent of T_z,

$$M_0 = M_0(T_Z) = M_p(T_Z) + M_n(T_Z). \tag{4}$$

Under this assumption the analog low-lying states of $T=1$ multiplets were analyzed and a disagreement for M_0 was found for the 2^+ towards 0^+ transitions of the (^{30}Si, ^{30}P, ^{30}S) multiplet. The authors concluded to the necessity of checking the experimental data, especially for the ^{30}S and ^{30}P unstable nuclei. For these nuclei our knowledge has now dramatically increased due to the development of radioactive beam facilities in the last decade. With these techniques, isospin purity has been recently investigated in $A=18$ [9], $A=26$ [10], and $A=38$ [11] $T=1$ multiplets. The synthesis of all the results in the $A=4n+2$ multiplets shows that the isospin symmetry is surprisingly broken for the $A=34,38,42$ systems [11].

Recently the isospin symmetry was also investigated for the $T=2$ ^{32}Ar and ^{32}Si mirror nuclei [12]. A Coulomb excitation measurement was performed for the first 2^+ state of ^{32}Ar, leading to its M_p value, whereas inelastic proton scattering provided the M_n value of the first 2^+ state of ^{32}Si. The agreement of the M_p value of ^{32}Ar with the M_n value of its $T=2$ mirror counterpart was observed within experimental uncertainty. However, the main concern is that a simple macroscopic model was assumed in Ref. [12] to extract the M_n value and the result should be cross-checked by measuring ^{32}Ar(p,p').

In this Rapid Communication we report on indications for isospin impurity for the first 2^+ state of the ^{30}S and ^{30}Si mirror nuclei. Since the ^{30}S nucleus is unstable, accurate data have only recently become available [13]. The M_p values are obtained by electromagnetic measurements, and the M_n values are extracted from (p,p') data. Due to the expected weakness of the charge symmetry breaking, it is necessary to test it through the comparison of several independent observables.

First we discuss the available data on ^{30}Si proton and neutron transition matrix elements. The $B(E2)$ value for the stable ^{30}Si nuclei was obtained from five different lifetime measurements [14]. They yield $B(E2)_{exp}=205\pm 11 e^2$ fm^4, for

TABLE I. Proton, neutron transition and deduced isoscalar matrix elements M_0 for 0^+ towards 2^+ transition in the $T=1$, $A=30$ isobaric multiplet, in fm^2. Values for ^{30}Si are from Refs. [14,15]. The M_p values for ^{30}P and ^{30}S are from Ref. [14] and the M_n value for ^{30}S is given in this work.

	^{30}Si	^{30}P	^{30}S
M_p exp	6.40 ± 0.17	7.05 ± 0.27	7.80 ± 0.36
M_n exp	8.92 ± 0.57	$M_n=M_p$	5.75 ± 0.95
M_0 exp	15.32 ± 0.59	14.10 ± 0.54	14.04 ± 1.01

the transition from the g.s. to the first 2^+ state [14]. The method employed to extract the M_n value of ^{30}Si is described in Ref. [15]. First the charge transition density for the 2_1^+ state is fitted to the available electron scattering data [16], and the proton transition density is obtained by unfolding the nucleon form factor. The proton transition density is then held fixed and the neutron transition density is extracted from the proton scattering data measured using 180 MeV protons. A linear expansion of the proton-nucleus interaction is performed, the fitted parameters are obtained with errors reflecting the uncertainties due to the normalization of the data, statistics, and systematic errors due to the fitting procedure. The values obtained for M_p [14] and M_n [15] for ^{30}Si are given in Table I. Since ^{30}S is unstable, (e,e') measurements are not feasible. However, lifetime measurements provide the value of the reduced transition probability $B(E2)$. The experiments [17,18] yield $B(E2)_{exp}=304\pm28e^2$ fm^4. The $B(E2)_{exp}$ value of ^{30}S is at variance with the previous $B(E2)_n=398\pm51e^2$ fm^4 measurement of ^{30}Si, deduced from the M_n value of ^{30}Si.

To investigate further the possible isospin impurity for the g.s. towards the 2_1^+ state transition we need to cross-check this result by using the neutron and proton matrix elements in ^{30}S and ^{30}Si, respectively. The 2_1^+ inelastic angular distribution of the ^{30}S(p,p') reaction has been recently measured at 53 MeV/nucleon in inverse kinematics at the GANIL facility [13]. The g.s. and transition densities of ^{30}S are required in order to perform a microscopic analysis of the angular distribution. The g.s. densities are calculated by the Hartree-Fock+BCS (HF+BCS) model, with the SGII Skyrme force [19]. The transition densities from the g.s. to the 2_1^+ state are given by quasiparticle random phase approximation (QRPA) calculations [20]. It should be noted that the QRPA residual interaction is determined self-consistently from the interaction which generated the mean field in the HF+BCS calculation. The accuracy of the QRPA model can be tested for stable nuclei by comparison with proton transition densities deduced from inelastic electron scattering [6]. The QRPA ^{32,34}S proton transition densities were found in perfect agreement [13] with the measured densities obtained by (e,e') scattering [21,22], indicating an accurate QRPA description of the proton contribution to the excitation in the sulfur isotopes. This shows that the profile of the proton transition density is well reproduced by the QRPA calculations, giving confidence in the use of the QRPA density. For the other even sulfur isotopes, from ^{30}S to ^{40}S, it was shown in Ref. [13] that the QRPA transition densities could reproduce well the evolution of $B(E2)$ with the neutron number. In the case of ^{30}S, the QRPA prediction, $B(E2)_{\mathrm{QRPA}}=328e^2$ fm^4, is in good agreement with the experimental data. The QRPA proton transition density of ^{30}S is also validated by the results mentioned above.

As a first analysis we use directly the QRPA to predict the ^{30}S M_n value since the QRPA calculations were proven to provide a consistent description along the sulfur isotopic chain of both $B(E2)$ values and (p,p') scattering. The M_n value predicted by the QRPA neutron transition density is $M_n=7.45$ fm^2, which shows a strong variance with the measured M_p value for ^{30}Si:$M_p=6.40\pm0.17$ fm^2 (Table I). It should be noted that the ^{30}S and ^{30}Si neutron transition matrix elements are both found $\sim$13 % larger than the ^{30}Si and ^{30}S proton transition matrix elements, respectively. In order to evaluate the contribution of the Coulomb potential to this isospin violation, QRPA calculations for the first 2^+ state of the ^{30}Si nucleus are performed. In the QRPA model the Hamiltonian preserves the isospin symmetry except for the Coulomb term. We get $M_p=7.52$ fm^2 and $M_n=7.76$ fm^2, which shows a variation of 7 % and 4 % with the respective QRPA M_n and M_p values of ^{30}S. This represents the approximate contribution of the Coulomb term to the isospin impurity, which remains much lower that the observed variation.

The ^{30}S(p,p') data may allow to investigate further on this result. The inelastic angular distribution corresponding to transition to the first 2^+ state has been analyzed by two independent sets of microscopic optical and transition potentials, namely, the Jeukenne, Lejeune, and Mahaux (JLM) parametrization [23] and the folding model [24]. In a first analysis [13] of the ^{30}S(p,p') angular distributions, the JLM parametrization is used [23] to generate the optical potential. This potential is derived from nuclear matter calculations, built on the Reid hard-core nucleon-nucleon (NN) interaction, using the Brueckner-Hartree-Fock (BHF) approximation. An improved local density approximation (LDA) is applied to derive the potential in the case of a finite nucleus. The resulting JLM potential is a microscopic, complex, and local nucleon-nucleus potential depending only on incident energy E and on the neutron and proton densities ρ_p, ρ_n of the nucleus. The inelastic (p,p') angular distributions are obtained through distorted wave born approximation (DWBA) calculations [7] including the JLM potential. They are performed with the TAMURA code [25]. The entrance, transition, and exit channel potentials are defined with the g.s. and transition densities.

In Ref. [13], these calculations were performed for sulfur isotopes and it was shown that the 2_1^+ inelastic angular distribution is very well reproduced. In order to test the sensitivity of the predicted angular distribution to the optical model potential, the densities previously used in the JLM potential are folded with a density-dependent effective interaction, based on the G-matrix elements of the Paris potential [24]. The real nuclear, the Coulomb, and spin-orbit potentials are calculated by the folding approach. The imaginary part of the optical and transition potentials is generated using the CH89 [26] parametrization. The angular distributions are calculated using the DWBA formalism. The 2_1^+ angular distribution of ^{30}S is well reproduced [24]. The difference be-

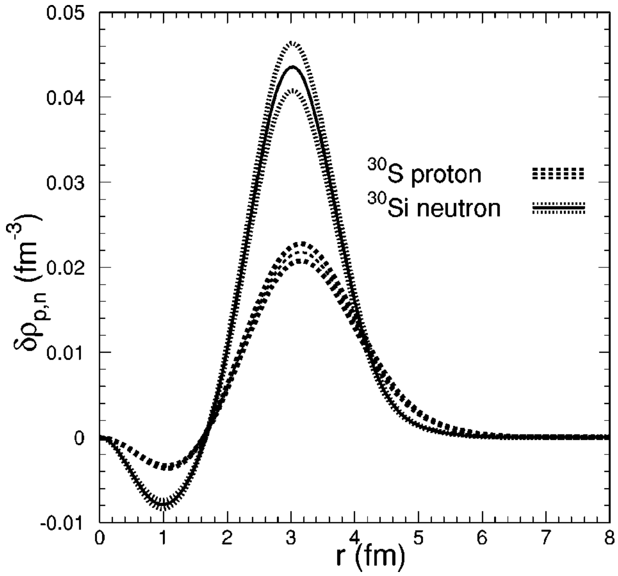

FIG. 1. Comparison of the ^{30}S proton to the ^{30}Si neutron transition density, as described in the text.

tween the JLM and the folding approaches should be emphasized: the JLM parametrization relies on BHF calculations in infinite matter and on the LDA, whereas the folding model is directly a calculation in a finite system. Since the contribution of the protons to the 2^+ excitation of ^{30}S is well described by the QRPA results, the good reproduction of the (p,p') angular distribution by the calculation is a strong test of the QRPA prediction for the neutron contribution. The $B(E2)_n=5|M_n|^2$ QRPA value is $278e^2$ fm^4. The determination of the experimental value of the M_n moment is operated by using the QRPA transition densities, by renormalizing the QRPA proton transition density to the experimental $B(E2)$ value according to Eq. (2) and by renormalizing the neutron one, checking the interval allowed by the variation of the M_n value on the (p,p') data. The deduced experimental value, written in Table I, is $M_n=5.75\pm0.95$ fm^2 at one σ. This last value, obtained with large uncertainties, is compatible with the experimental value of M_p for ^{30}Si (Table I) and is therefore *a priori* consistent with isospin purity.

It is, however, of interest to illustrate the possible isospin impurity situation by comparing the QRPA ^{30}S proton transition density to the experimental ^{30}Si neutron transition density. Figure 1 presents the transition densities for these mirror nuclei as a function of the radius. Their moments correspond to the definition of Eq. (1) and the values are given in Table I. In Fig. 1 the QRPA proton transition density for ^{30}S renormalized to the experimental value $M_p=7.80\pm0.36$ fm^2 is plotted. It is compared to the Si neutron density extracted from (p,p') analysis and given in Ref. [15]. The band delimited with dotted lines for Si corresponds to the overall error given in Ref. [15] and for ^{30}S, to the experimental error of the M_p measurement. As stated before, the transition densities' magnitudes are different. The shapes exhibit also a difference: the proton transition density for ^{30}S is narrower and peaked slightly more inside of the nucleus than the neutron ^{30}Si transition density.

To further test the transition densities given in Fig. 1 we

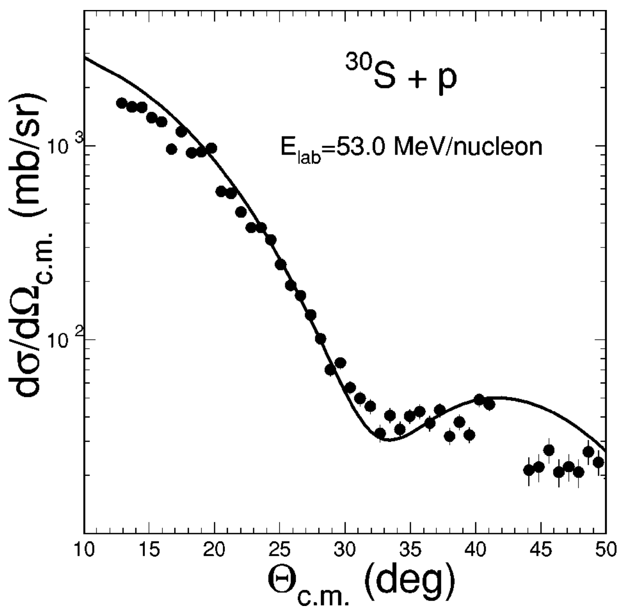

FIG. 2. Elastic scattering data for ^{30}S on proton at 53 MeV/nucleon in comparison with the results given by the JLM potential including mirror g.s. densities for the ^{30}S nucleus.

present in Figs. 2 and 3 the JLM calculations for the elastic and inelastic ^{30}S(p,p') cross sections at 53 MeV/nucleon. $\lambda_V=1$ and $\lambda_W=0.9$ are the normalization factors of the real and imaginary parts of the JLM potential which give good agreement with the elastic scattering data (Fig. 2). We assume the mirror symmetry: for the g.s. densities ^{30}S proton

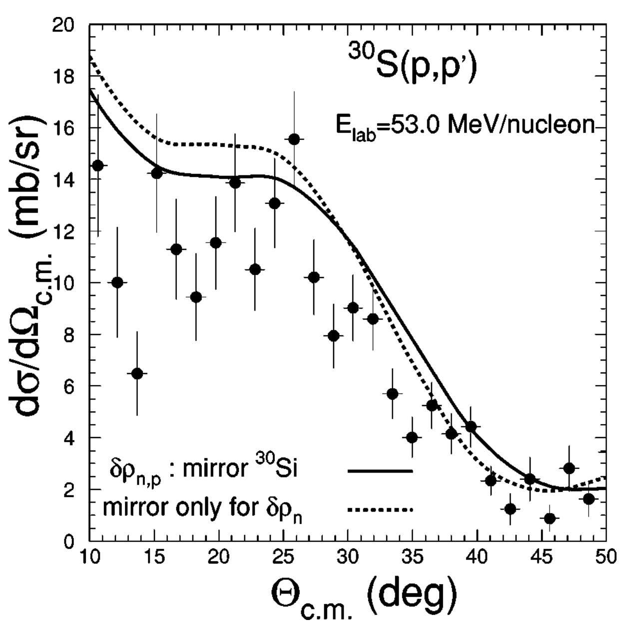

FIG. 3. Inelastic scattering data for ^{30}S(p,p') at 53 MeV/nucleon in comparison with the results given by the JLM potential including mirror g.s. and transition densities for the ^{30}S nucleus. The solid curve is obtained by applying the mirror symmetry to both ^{30}S proton and neutron transition densities while only neutron ^{30}S density is taken equal to the proton ^{30}Si one for the dashed line.

and neutron densities are from neutron and proton ^{30}Si BCS calculations (their shape is close to the profile of the experimentally deduced densities reported in Ref. [27] and obtained by electron scattering), for the transition densities, we test two assumptions. First, showed by the solid curve, mirror symmetry is assumed both for neutron and protons taking mirror ^{30}Si densities, taken with the parametrizations extracted from experimental (e,e') and (p,p') data in Ref. [15]. Second, the dashed curve shows the QRPA proton transition density renormalized to the experimental M_p value, and the neutron transition density taken from the mirror ^{30}Si proton transition density of Ref. [15]. In both cases the data are slightly overestimated by calculations which assume mirror symmetry, implying a possible isospin impurity.

^{30}P is the third element of the $T=1$ isobaric multiplet and provides complementary information to the isospin violation situation. We can therefore compare the three values of M_0 obtained using Eq. (4) for each nucleus of the $A=30$ multiplet. In the case of the $N=Z$ ^{30}P nuclei, charge independence states that $M_p=M_n$. Since the M_p value has been measured with lifetime method [14] one gets $M_0=2M_p$. The resulting M_0 values for the multiplet are given in Table I. A discrepancy of 8% is observed between ^{30}Si and ^{30}P M_0 values, still implying the violation of the charge independence. The M_0 value calculated assuming Eq. (3) for ^{30}Si and ^{30}S is $M_0=M_p(^{30}\text{S})+M_p(^{30}\text{Si})=14.10\pm0.46$ fm^2. This result is at variance from the result of Bernstein *et al.* [8], because of the low quality of the data on the unstable ^{30}S nucleus at that time. It is now in agreement with the M_0 value of ^{30}P (see Table I), as previously mentioned in Ref. [11].

To summarize, indications for isospin impurity are observed in the transition from the g.s. to the first 2^+ state of the ^{30}S and ^{30}Si nuclei. The two M_p values are directly obtained by several electromagnetic probes. The two M_n values are obtained by (p,p') scattering using reliable methods. The two (M_n,M_p) comparisons in mirror nuclei both lead to isospin impurity conclusion and are in quantitative agreement. The charge independence using the ^{30}Si and the M_p ^{30}P data is also not verified. Therefore the combination of the electromagnetic and the hadronic probes provides a quantitative test of the charge dependence violation. Complementary ways to measure the neutron contribution are called for in order to confirm this result. It should be noted that each $T=1$ isobaric multiplet with $A\leqslant42$ includes at least one unstable nucleus. The use of the most recent electromagnetic and hadronic data should provide a test of charge independence in these multiplets.

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