ISOSPIN MIXING: RECENT RESULTS AND FUTURE PLANS*

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The value of isospin mixing at zero temperature was recently deduced in the mass region of $60 \leq A \leq 80$. The measured values have been obtained using both fusion–evaporation reactions and exploiting the selection rules for the emission of electric dipole radiation in $N = Z$ nuclei. The strength of the γ-decay of the IVGDR provides the starting point for the determination of the value of the isospin mixing probability α^2. This quantity is expected to decrease when the excitation energy increases. In this contribution, the phenomenon of isospin mixing will be discussed, the measurements of isospin mixing in ^{80}Zr and ^{60}Zn, using the IVGDR technique, will be summarized, some very preliminary data on ^{72}Kr will be presented, and some perspectives will be given.

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1. Introduction

The neutron and proton almost identical mass values (their mass is different by less than 0.2%), the charge symmetry, and the charge independence of the strong nuclear force field suggested a symmetry between protons and neutrons. In other words, proton and neutron equal mass and their identical behaviour in the strong nuclear field suggested, almost one century ago, to consider them as two quantum states of the same particle called a nucleon. A 'new' quantum number, the "isotopic spin" or "isospin", was, therefore, defined. In analogy with the spin quantum number, the isospin of the nucleon should be 1/2, while its third component is $-1/2$ for the proton and $+1/2$ for the neutron.

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In this approach, all isobars should be degenerate in energy. The Coulomb interaction, however, breaks this symmetry in the atomic nucleus and, consequently, breaks the energy degeneracy of the isobars. As isospin is not anymore a good quantum number, the wave function of a generic nuclear state does not have a fixed value of isospin. It is instead perfectly defined, for a specific nucleus, the third component of the isospin quantum number as $(N-Z)/2$, where N indicates the number of neutrons and Z the number of protons. The evidence of the very similar nuclear level scheme in mirror nuclei, the evidence that $N = Z$ nuclei are not stable for a mass number larger than 50 and the I.M.M.E. relation [1] show that: *(i)* the Coulomb interaction breaks this symmetry, *(ii)* the Coulomb interaction cannot be neglected, *(iii)* the Coulomb interaction is much weaker than the nuclear one, and that *(iv)* the Coulomb interaction can be treated using a perturbation approach.

In figure 1, the term α_c indicates the calculated degree of mixing ($\alpha_\mathrm{c} = 0$ means no mixing). As its value mainly depends on the 'strength' of the Coulomb interaction, α_c is expected to increase with the atomic number (namely the number of protons) of a nucleus [2]. In the past years, several calculations of isospin mixing using different approaches have been performed. The predicted values for mass $A \simeq 80$ moved from a value of approximately 1% (at the end of the sixties) up to 4.5% [2]. In general, as the percentage of the mixing in $N = Z$ nuclei is expected to be always smaller than a few %, a main isospin value can be, therefore, assigned to every nuclear state (one has to remember, however, that some mixing could always be possible).

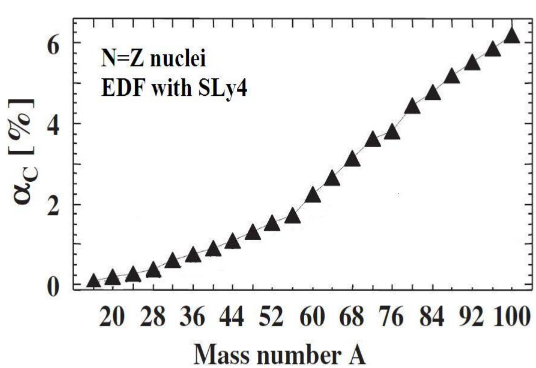

Fig. 1. The expected mixing values in $N = Z$ nuclei at zero nuclear temperature. The plot is taken from Ref. [2].

2. Isospin mixing and nuclear temperature

The behaviour of the isospin mixing with the nuclear temperature was studied in Ref. [3]. In that reference, the authors predict that, as the nuclear temperature starts to increase, the degree of mixing weakly increases (due to the increase in the level density). Starting from a nuclear temperature of approximately 1.0–1.5 MeV, the importance of the mixing strongly diminishes. For an even higher nuclear temperature ($T > 3$ MeV), it should be possible to observe a gradual restoration of the isospin symmetry. This is due to the fact that, at high excitation energy, the nuclear decay width overwhelms the Coulomb interaction width. The excited nucleus, therefore, decays before the states with different isospin start to mix. This does not mean that, at high nuclear temperature, isospin mixing does not act but that it does not have enough time to act. It is a dynamical symmetry restoration due to the competition between the nuclear lifetime and the Coulomb interaction time scale. This scenario was first depicted several years ago by Wilkinson [4] and Morinaga [5]. The relation proposed by Sagawa *et al.* in [3] is

$$\left(\alpha^{T_0+1}\right)^2 = \frac{1}{T_0+1}\frac{\Gamma_{\rm IAS}(E^*)}{\Gamma_{\rm CN}(E^*)+\Gamma_{\rm M}(E^*)}\,,$$

where $\Gamma_{\rm IAS}(E^*)$ is the Coulomb spreading width, $\Gamma_{\rm CN}(E^*)$ is the Compound spreading width, and $\Gamma_{\rm M}(E^*)$ indicates the width of the Isovector monopole resonance (IMR) in the case IMR has the same energy of the IAS. Practically, $\Gamma_{\rm M}(E^*)$ can be considered a free parameter which in Ref. [3] was fixed at 200 keV.

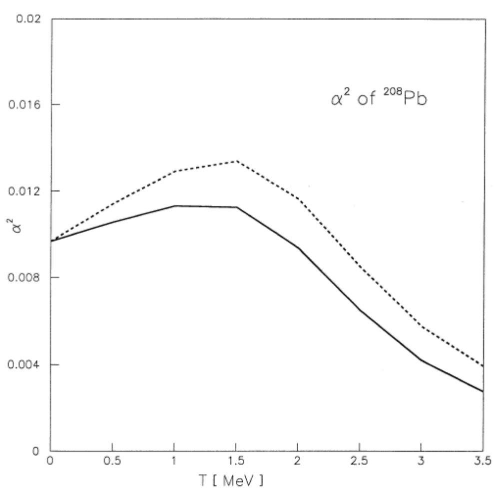

Fig. 2. The calculated nuclear temperature dependence of isospin mixing in ^{208}Pb as reported in [3]. The solid and dashed lines indicate a linear nuclear temperature dependence for $\Gamma_{\rm M}$ and $\Gamma_{\rm IAS}$. The slope parameter is 0.025 and 0.05 respectively.

Figure 2 and the previous formula show that it is possible to estimate the zero temperature value of isospin mixing if, in the same compound nucleus, at least two measurements at two different temperatures are performed. In fact, even though the Compound width $\mathit{\Gamma}_{\mathrm{CN}}(E^*)$ can be calculated, $\mathit{\Gamma}_{\mathrm{IAS}}(E^*)$ and $\mathit{\Gamma}_{\mathrm{M}}(E^*)$ should be extracted from the data.

3. Measurement of isospin mixing

As isospin cannot be directly measured, one should rely on the theory and/or on the consequences that the isospin symmetry breaking induces. For example, the isospin conservation selection rules predict a reduction in the amount of E1 emission in self-conjugated nuclei for a system in an isospin zero channel. As the γ-decay of the IVGDR is constituted by E1 radiation, such a selection rule could be used to measure the amount of isospin mixing.

The IVGDR built on a Compound Nucleus (CN) can be populated with a fusion–evaporation reaction. Using a combination of $N = Z$ projectile and target, it is possible to produce a CN in the zero isospin channel. Due to the selection rules, the E1 γ-decay from an isospin zero state to another isospin zero state is forbidden and only E1 decay to states with isospin one is possible. The presence of isospin mixing makes the initial state a superposition of isospin zero and isospin one and, therefore, makes the E1 γ-decay to isospin zero states possible. In the first step of the decay of the $N = Z$ compound nucleus in a zero isospin state, the amount of high-energy γ-rays emitted in the decay of the IVGDR provides a measurement of the amount of isospin mixing.

The idea of using the γ-decay of the IVGDR to measure isospin mixing was first applied, several years ago, by Harakeh *et al.* and published in [6]. In this work, the authors compare the γ-emission of the ^{28}Si compound produced in a zero isospin channel (using, as projectile and target, $N = Z$ nuclei) with the γ-emission of the same CN but in a non-zero isospin channel (see figure 3). Theoretically, as the gamma decay of the compound nucleus does not depend on the way the CN is formed, the two measured spectra should be identical. However, the authors measured very different high-energy γ-rays spectra (see figure 3). The spectra clearly show that the excited ^{28}Si does not behave as if isospin is fully mixed but, on the contrary, shows a very small value of isospin mixing. The very first measurement, using the IVGDR technique, focused on the extraction of the zero temperature value of isospin mixing, was published in 2011 for the ^{80}Zr nucleus [7] (see figure 4). Five years later, in 2015, the results on the same compound nucleus, ^{80}Zr, but at a different nuclear temperature were published in [8] (see figure 5). In 2021, the analysis of ^{60}Zn at two different nuclear temperatures was published [9]. Measurements on ^{72}Kr were performed this winter and the data are still being analysed. A very preliminary plot is shown in figure 6.

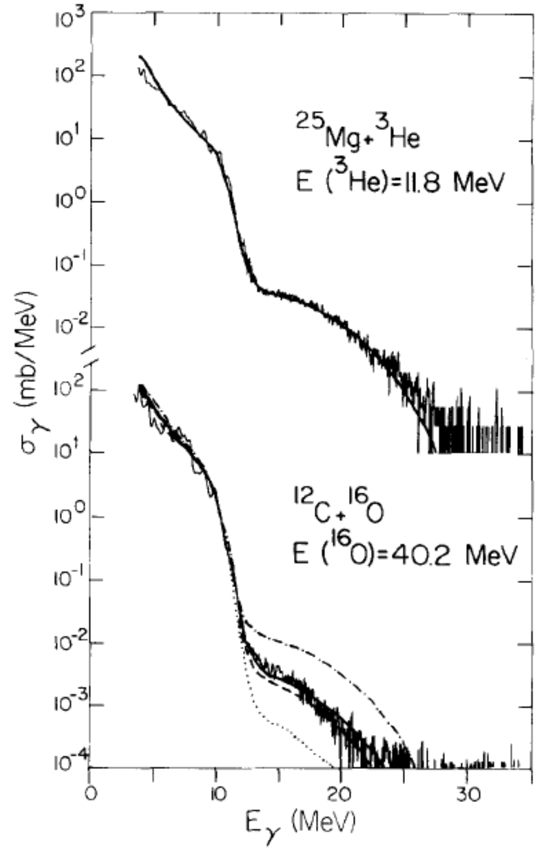

Fig. 3. The measured spectra of the IVGDR decay in the ^{28}Si compound nucleus. The nucleus was created in an isospin zero channel (bottom plot) and a non-isospin zero channel (top plot). The dot-dashed line in the bottom plot indicates the expected γ-emission in the case of fully mixed states, while the dashed line indicates the expected γ-emission in the case of no mixing. The plot is taken from Ref. [6].

The procedure used by all these works follows closely the one of Ref. [6]. It is based on the production of two very similar (in mass, nuclear temperature, angular momentum, *etc.*) compound nuclei. One is produced in a zero isospin channel and the other in a non-zero isospin channel. As the selection rules for E1 radiation are valid only in the former case, the comparison between the amount of IVGDR E1 γ-transitions between the CN produced in the two reactions provide a direct measurement of isospin mixing. Practically, the statistical model analysis of the γ-decay of the CN produced in a non-zero isospin channel provides the IVGDR and statistical model param-

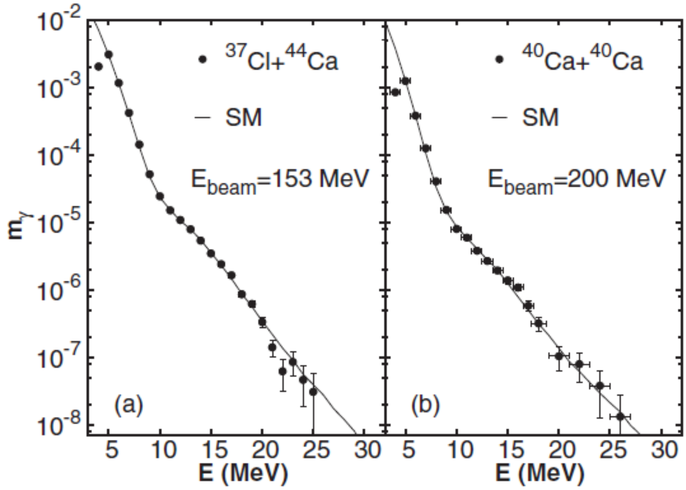

Fig. 4. The high-energy γ-rays spectra measured for the ^{37}Cl+^{44}Ca and ^{40}Ca+^{40}Ca reactions are indicated with filled points. The statistical model calculations are indicated with the continuous line. The plot is taken from [7].

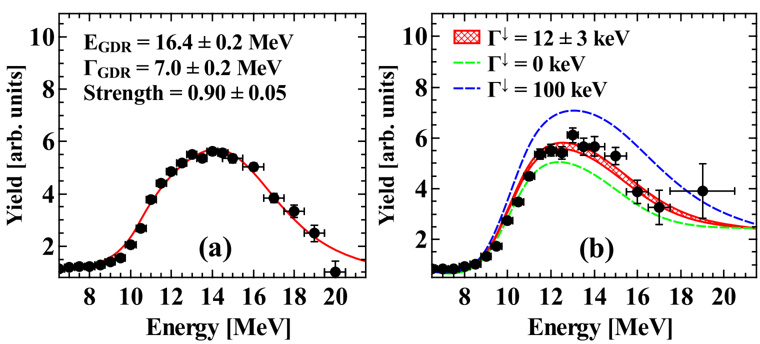

Fig. 5. The linearized γ-rays spectra measured for the ^{37}Cl + ^{44}Ca and ^{40}Ca + ^{40}Ca reactions. The statistical model calculations are indicated with the dashed and continuous lines (see legend). The plots were taken from [8].

eters, which will be then used in the analysis of the CN produced in the zero isospin channel. In this way, only the amount of isospin mixing is left as a free parameter. In these works, the Coulomb spreading width was found, as expected, to be either constant or with a very weak dependence on the nuclear temperature, while the isospin mixing was found to decrease with the nuclear temperature. The extracted zero temperature values were found to be in agreement with the predictions of Ref. [2].

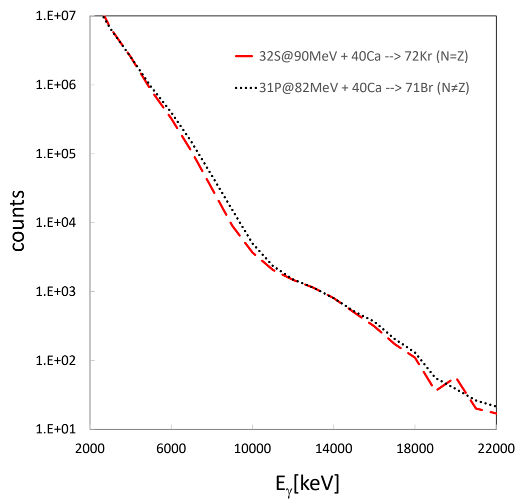

Fig. 6. (Colour on-line) The very preliminary high-energy γ-rays spectra measured for the ^{31}P + ^{40}Ca (black dotted line) and ^{32}S + ^{40}Ca reactions (red dashed line.)

The correction due to the isospin symmetry breaking (usually indicated with δ_c) for the first term (V_{ud}) of the CKM matrix was deduced from the extracted zero temperature value of the measured isospin mixing following the prescription of Ref. [10] (see Eq. (26)). The extracted experimental data are in agreement with the theoretical predictions as shown in the inset of figure 4 in Ref. [9].

4. Perspectives

It is important to remember that, using the IVGDR technique, it is not possible to measure the value of the mixing in $N = Z$ nuclei heavier than mass 108 [11] (^{100}Sn is one the heaviest bound $N = Z$ nucleus). In addition, in the case of nuclei with a mass number lower than 50, more precise data which uses alternative techniques (like for example the superallowed β decay) are available. Future efforts should go in the direction of: *(i)* increasing the CN nuclear temperature (to observe the dynamical restoration of isospin symmetry), *(ii)* decreasing the CN nuclear temperature (to observe the predicted small increase of the mixing), *(iii)* studying CN around the heaviest possible mass, namely near ^{100}Sn. Unfortunately, measurements *(i)* and *(ii)*, namely the measurement of isospin mixing in CN at very low $0 < T < 1$ MeV or at very high $T > 3$ MeV nuclear temperatures are extremely difficult. In fact, fusion–evaporation reactions with slow or very fast beams have very low cross sections and, in addition, practically only the first step γ-decay of the CN can be used to extract a value for isospin mixing. Therefore, one can expect low statistics and, consequently, large error bars.

It is instead possible, to use radioactive beams (as, for example, ^{56}Ni or ^{60}Zn) and stable targets (as, for example, ^{40}Ca), to produce a self-conjugated CN in the proximity of ^{100}Sn. The ^{56}Ni nucleus is only two mass units away from the stable ^{58}Ni and its lifetime is several days. Using a beam energy of the order of 190 MeV, one can have a fusion cross section of approximately 200 mb. More difficult could be the use of a ^{60}Zn radioactive beam as this nucleus is four mass units away from the stable ^{64}Zn and its lifetime is only a few minutes.

Such a type of measurements requires a detectors' array with a large efficiency for high-energy γ-rays, with excellent time resolution (for the discrimination between γ-rays and neutrons), and with a high granularity for the measurement of the γ-multiplicity.

A possible array, which could be used in this type of experiments, would be the PARIS array. In fact, PARIS is composed of several, large volume, fast phoswich detectors. It has a frontal part of $2'' \times 2'' \times 2''$ composed of $LaBr_3$ or $CeBr_3$ scintillators coupled to $2'' \times 2'' \times 6''$ NaI scintillators, both read by one PMT. The detectors can be either arranged in clusters of 9 phoswiches each or in other geometries (for example, a wall geometry was used in Orsay). The total energy deposited in one phoswich is obtained by an off-line add-back procedure applied to the energies deposited in the two parts of the phoswich. The energy deposited in the whole cluster is obtained by summing the energy deposited within each phoswich.

The very important feature of the PARIS array is its efficiency for high-energy γ-rays and its excellent time resolution (it was measured to be smaller than 1 ns). Figure 7 shows the simulated efficiency of PARIS for different

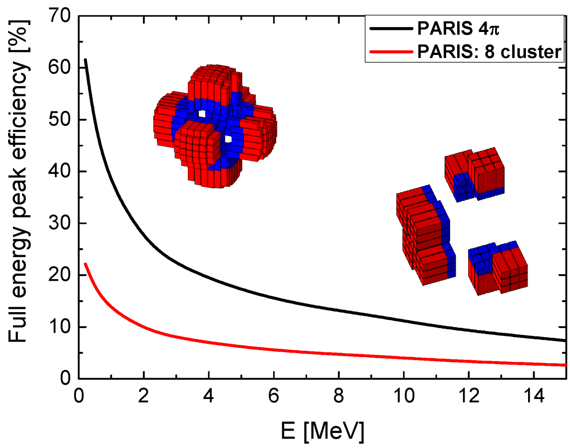

Fig. 7. The simulated efficiency for different configurations for the PARIS array. The plot was taken from the PARIS White Book [12].

configurations. A second important characteristic of the PARIS array consists in its high granularity. In fact, the frontal $2'' \times 2'' \times 2''$ $LaBr_3/CeBr_3$ scintillator can stop with high-efficiency low-energy gamma rays. Therefore, these frontal crystals (the PARIS array consists of more than 8 clusters, namely of more than 72 phoswiches) can act as a very efficient and granular multiplicity filter to measure the coincidence fold. Starting from the measured coincidence fold, it is possible to extract the multiplicity of the γ-rays and the angular momentum of the compound nucleus.

5. Conclusion

The phenomenon of isospin mixing at zero nuclear temperature can be deduced in the mass range of $50 \leq A \leq 110$ using the γ-decay of the IVGDR. This technique exploits the selection rules associated with the isospin symmetry, namely that the E1 transition in $N = Z$ nuclei in zero isospin channel must link states with $\Delta I = 1$ not $\Delta I = 0$ isospin. It is then possible (using the IVGDR γ-decay) to measure the amount of isospin impurity in the nuclear wave function. This is not a direct measurement and the results are somehow dependent on the used IVGDR parameters and the parameters of the statistical model. In addition, at least two measurements of the same compound are necessary to extract the zero temperature values of the isospin mixing. This technique can be applied only for self-conjugated CN in a zero isospin channel and in the $50 \leq A \leq 110$ mass region. The 'Holy Graal' for such a type of measurement is the use of the proton-rich radioactive beam to measure isospin mixing around ^{100}Sn. For larger values of mass ($A > 110$), other techniques (different from the IVGDR and β decay) should be developed.

REFERENCES

[1] S. Lenzi, M. Bentley, in: J. Al-Khalili, E. Roeckl (Eds.) «The Euroschool Lectures on Physics with Exotic Beams, Vol. III» Lecture Notes in Physics Vol. 764, *Springer*, Berlin, Heidelberg 2009, pp. 57–98.

[2] W. Satuła *et al.*, *Phys. Rev. Lett.* **103**, 012502 (2009).

[3] H. Sagawa *et al.*, *Phys. Lett. B* **444**, 1 (1998).

[4] D.H. Wilkinson, *Philos. Mag.* **1**, 379 (1956).

[5] H. Morinaga, *Phys. Rev.* **97**, 444 (1955).

[6] M. Harakeh *et al.*, *Phys. Lett. B* **176**, 297 (1986).

[7] A. Corsi *et al.*, *Phys. Rev. C* **84**, 041304(R) (2011).

[8] S. Ceruti *et al.*, *Phys. Rev. Lett.* **115**, 222502 (2015).

[9] G. Gosta *et al.*, *Phys. Rev. C* **103**, L041302 (2021).

[10] N. Auerbach *et al.*, *Phys. Rev. C* **79**, 035502 (2009).

[11] K. Auranen *et al.*, *Phys. Rev. Lett.* **121**, 182501 (2018).

[12] F. Camera, A. Maj, «PARIS White Book», *H. Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences*, Kraków 2021. Available at: `http://rifj.ifj.edu.pl/handle/item/333`