Observation of parity nonconservation in the integrated γ spectrum from (n,γ) reactions in Cl, Br, Cd, Sn, and La nuclei

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A P-odd asymmetry has been observed in the emission of γ rays upon the capture of polarized thermal neutrons by Cl, Br, and La nuclei. A circular polarization of the γ rays has been observed during the capture of unpolarized neutrons by Cl, Br, Sn, and La nuclei.

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Effects of parity violation in the (n, γ) reaction were observed in the 1960s and 1970s for certain γ transitions[1–3] in which the dynamic enhancement was supplemented with a so-called kinematic enhancement,[4] which stemmed from a relative increase in the amplitude of the $E1$-transition admixture in comparison with the amplitude of the fundamental $M1$ transition. Observations of P-parity violation in neutron optics have recently been published.[5–7] Sushkov and Flambaum[8] have offered a theoretical interpretation of these observations based on the idea that the P-parity nonconservation effects are intensified near a p-wave resonance.

We have now studied parity-violation effects in the integrated spectrum of γ rays from the (n, γ) reaction in nuclei of chlorine, bromine, cadmium, tin, and lanthanum. We measured effects of two types: (1) an asymmetry in the γ-ray emission in the direction of the neutron spin and in the opposite direction during the capture of polarized thermal neutrons and (2) the circular polarization of γ rays during the capture of ploarized thermal neutrons and (2) the circular polarization of γ rays during the capture of unpolarized neutrons. The experiments were carried out at the VVR-M reactor of the B. P. Konstantinov Leningrad Institute of Nuclear Physics.

The apparatus for measuring the asymmetry and the experimental procedure have been described elsewhere.[6] A beam of transverse-polarized neutrons with a wavelength $\lambda_{\rm av} \cong 2.7$ Å passes through a sample surrounded by ^{6}LiF shielding. The γ detectors are scintillation counters, placed on both sides of the sample. The asymmetry is sought in the form $W \sim (1 + a_\gamma \vec{\sigma} \cdot \mathbf{n}_\gamma)$, where a_γ is the asymmetry factor, and $\vec{\sigma}$ and $\mathbf{n}_\gamma$ are unit vectors along the direction of the neutron spin and along the momentum of the γ ray, respectively. We measure the quantity $\delta' = (I^+ - I^-)/(I^+ + I^-)$, where I^+ are the intensities of the γ rays detected for opposite directions of the neutron spin. The polarization of the neutron beam is rotated once every 2 s by an rf adiabatic flipper. We use an integrated method for detecting the γ rays. The experimental results are summarized in Table I (columns 2 and 3).

The asymmetry factor a_γ is calculated with a correction for the background (4–10%), $\overline{\cos\theta}$, and the beam polarization (95%). The contribution of hard γ rays to the effect was checked in La and Sn with auxiliary lead filters 4 and 8 mm thick in front of

TABLE I.

Target		$\delta'_{\rm expt}$ 10^6	a_γ 10^6	$\delta''_{\rm expt}$ 10^6	$P_\gamma \cdot 10^5$
Cl		−24,5 ±4,3	−27.8 ±4,9 2)	2,8 ±0,2	6,4 ±0,5
Br		−17.2 ±1.4	−19.5 ±1,6	1.31 ±0.05	3,1 ±0,2
Cd		−1.1 ±1.2	−1.3 ±1.4	0,09 ±0,035	$\leqslant$0,3
Sn (natural)		—	–	0,46 ±0,065	1,9 ±0,5
^{117}Sn	No filter	2,1 ±1.4	2,4 ±1.6	–	–
	8-mm filter	0,3 ±1,7	0,3 ±1.9	–	–
La	No filter	−15.7 ±1,9	−17.8 ±2,2	−5.3 ±0,3	−16,0 ±2,5 .
	4-mm filter	−20.7 ±2,2	−23.5 ±2,5	–	–

the detectors. This test revealed no substantial enchancement of the effect, as can be seen from Table I.

The circular polarization of the rays is measured by an apparatus similar to that described in Ref. 9 for studying the reaction $np \rightarrow d\gamma$. A detailed description of this apparatus will be published separately.

The Cl, Br, Sn, and La targets are mixtures of the corresponding compounds (NaCl, NaBr, tin metal, and La_2O_3) with graphite powder, packed in a hermetically sealed zirconium container. The cadmium target consists of two Cd sheets 0.5 mm thick between graphite blocks in a zirconium jacket. The targets are placed in a water-filled cavity (120 mm in diameter) in the reactor core. The cavity is surrounded with three layers of lead with a total thickness of 90 mm to shield against the γ radiation of the core. The γ's from the target propagate through a 4-m collimating channel to a "transmission" polarimeter with an absorber 70 mm thick. This polarimeter consists of two halves which are magnetized in opposite directions. The γ rays which pass through each half are detected by separate scintillation detectors operating in the integrating mode. Fluctuations in the reactor power are eliminated by taking the difference between the signals from the two detectors (the signal of interest is doubled in the process). The experimental effect is determined as $\delta'' = 2(I^+ - I^-):(I^+ + I^-)$, where $I^\pm$ are the intensities of the γ rays which have passed through the absorber for opposite magnetization directions of the absorber; this direction was changed every second. The circular polarization of the γ rays is found from $P_\gamma = \delta''/\epsilon$, where ϵ, the the polarization efficiency, is $\approx 5\%$.

The contribution to the measured effect of the γ rays from the reactor core was checked in measurements with two graphite targets in the cavity, from which some of the water is displaced. The effect of the γ rays from the (n, γ) reaction in the structural materials of the cavity and the targets and in the remaining water was checked in separate experiments with corresponding targets. All these control experiments showed that there was no such effect within $\delta'' \leqslant 0.5 \times 10^{-7}$.

The experimental results are shown in columns 4 and 5 in Table I. The error shown in column 4 is purely statistical. The circular polarization (column 5) were calculated with allowance for the background (different for the different targets) from γ rays from the water remaining in the cavity (that which had not been displaced by the targets) and from the (n, γ) reaction in the structural materials. It is difficult to evaluate this background precisely in the absence of reliable data on the spectra of the (n, γ) reactions. The estimated uncertainty lies within the cited error. For cadmium we give only an upper limit on the polarization, since the measured effect does not substantially exceed the error, when a possible systematic error is taken into account.

The observed polarization could not be caused by bremsstrahlung from the β decay of isotopes formed in the (n, γ) reaction. The sign of the effect in the cases of Cl, Br, and Sn is opposite that in the case of a bremsstrahlung effect. In the case of La, the effect was observed reliably during the first 30 min after the reactor was brought up to power, before the 40-h β activity had had a chance to build up. Furthermore, in all cases we carried out measurements immediately after the reactor was shut down, when there was no γ rays from the (n, γ) reaction and when the bremsstrahlung effect should have been relatively intensified. In these measurements we found no effect above the errors.

The integrated spectrum of γ rays from the (n, γ) reaction thus reveals both an asymmetry in theemission and a circular polarization of the γ rays from the Cl, Br, and La nuclei (natural isotopic mixtures). For ^{117}Sn, for which Forte *et al.*[5] have observed a rotation of the neutron polarization plane, we do not see an symmetry at theaccuracy of these measurements, and the circular polarization for the natural isotopic mixture is at the level of 10^{-5}. If we assume that the entire effect is due to the isotope ^{117}Sn, the corresponding polarization would be on the order of 10^{-4}. It must be noted that a direct comparison of the values found for a_γ and p_γ requires taking into account the differences in the neutron spectra from the polarizing neutron duct and in the water-filled cavity of the reactor core.

In general, it is difficult ot interpret these effects at present because of insufficient data on the characteristics of the γ transitions from the (n, γ) reactions in these nuclei [the spectra of the (n, γ) reactions of these nuclei are extremely complicated]. In principle, the effects for γ transitions from a capture state to states with different spins should have different signs and should largely cancel each other out, greatly reducing the resultant effect in the integrated spectrum; this cancellation apparently does not occur to its full extent. Another interesting observation is that the effects are large for La and Br, for which most of the hardest γ transitions have the $E1$ multipolarity, i.e., a kinematic enhancement factor $\sim 10^{-1}$. We should point out that no p-wave resonance is known in the neutron capture by ^{35}Cl near the thermal region.

The existing ideas regarding the mechanism for the enhancement of parity-nonconservation effects in (n, γ) reactions and regarding the mechanism for the mixing of highly excited states apparently require further study.

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