

Energy separation of the $1^+/1^-$ parity doublet in ^{20}Ne

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Abstract. The parity doublet of $1^+/1^-$ states of Ne-20 at 11.26 MeV excitation energy is one of the best known test cases to study the weak part of the nuclear Hamiltonian. The feasibility of parity violation experiments depend on the effective nuclear enhancement factor ($R_N/|E(1^+) - E(1^-)|$) which amplifies the impact of the matrix element of the weak interaction on observables indicating parity mixing. An extreme large value of $R_N/|E(1^+) - E(1^-)| = (670 \pm 7000) \text{ MeV}^{-1}$ was reported for the doublet in ^{20}Ne . The large uncertainty depends amongst others on the large uncertainty of $|E(1^+) - E(1^-)| = 7.7 \pm 5.5 \text{ keV}$ of the parity doublet. Nuclear resonance fluorescence (NRF) experiments with linearly and circularly polarized photon beams were performed at the High Intensity Gamma-Ray Source at Duke University, Durham, NC, USA, to determine the energy difference of the parity doublet with higher precision. The different angular distributions for $0^+ \rightarrow 1^- \rightarrow 0^+$ and $0^+ \rightarrow 1^+ \rightarrow 0^+$ NRF cascades in polarized γ -ray beams were used to determine the energy difference of the parity doublet to 2.9(13) keV.

1. Introduction

Since 1956, when Lee and Yang postulated a mirror symmetry violation in β -decays [1] and 1957 when Wu experimentally verified the symmetry violation effect [2] parity non-conservation is well known. It has fundamental importance for studies of the impact of the weak interaction on nuclear structure. Hence, various theoretical and experimental approaches have been done to investigate parity violation (details are reviewed in [3, 4]). However, the weak meson-nucleon coupling constants deduced from various experiments are not consistent. Consequently a further investigation of parity violation is desirable.

The parity doublet of $1^+/1^-$ levels of ^{20}Ne at 11.26 MeV excitation energy has been suggested as one of the best cases to study parity violation of isolated nuclear eigenstates. The parity doublet in ^{20}Ne offers one of the very rare cases, where the effects of weak interaction can be studied for nuclear states with comparatively simple wave functions. The effect of parity violation in elementary quantum systems is known to result from contributions of the weak interaction [2]. Usually, contributions of the weak part to the nuclear effective Hamiltonian are not well

known, small, and neglected.

The $T = 1$, $1^+/1^-$ parity doublet represents the isospin analogue structure of the lowest-lying 1^+ and 1^- states near 1 MeV excitation energy of the $T = 1$ isobar ^{20}F . The structure of ^{20}F can comparatively easily be calculated in microscopic theoretical approaches such as the nuclear shell model. Therefore, this doublet allows to test the effect of weak interaction on nuclear two-particle states whose structure can be calculated quite reliable in the nuclear shell model. Recently, scattering off circularly polarized photons on strongly excited parity doublets has been proposed [5] as a promising tool for such studies. Despite that the degree of the expected parity violation is small, in the order of 10^{-7} , dynamical and kinematical nuclear enhancements are expected to make its observation possible. However, as the large error demonstrates, the effective nuclear enhancement factor $|R_N/\Delta E| = (670 \pm 7000)$ as given by [5] is so far not known to a sufficient precision for making quantitative proposals for such investigations. The major contribution to the large uncertainty of the nuclear enhancement factor is due to the excitation energy difference of the parity doublet, which is only measured to an accuracy of (7.7 ± 5.5) keV. In order to improve this value, a combination of circular and linear polarized photons was used to increase the accuracy of the excitation energy difference of the parity doublet.

2. Experiment

The linearly and circularly polarized photons were provided by the High Intensity γ -Ray Source (HI γ S). The deexciting transitions of ^{20}Ne were studied with the NRF setup consisting of four HPGe detectors surrounding the target. Each of the detectors has an efficiency of 60 % relative to a 3 inch by 3 inch NaI detector.

The angular distribution function for a $0^+ \xrightarrow{\tilde{\gamma}} 1^\pm \xrightarrow{\gamma} 0^+$ NRF cascade as it occurs when ^{20}Ne is excited from its $J_0^\pi = 0^+$ ground state to a $J^\pi = 1^\pm$ level by linearly polarized photons and the subsequent decay back into the ground state is given by [6]

$$W(\vartheta, \varphi) = 1 + \frac{1}{2} \left[P_2(\cos \vartheta) + \frac{1}{2} \pi \cdot \cos(2\varphi) \cdot P_2^{(2)}(\cos \vartheta) \right], \quad (1)$$

with π being the parity of the excited state and ϑ and φ being the polar and azimuthal angle, respectively. The terms P_2 and $P_2^{(2)}$ denote the second order ordinary and unnormalized associated Legendre polynomial. Figure 1a illustrates the relevant angles. The angular distribution function for E1 ($\pi = -$) and M1 ($\pi = +$) transitions as given in Eq. (1) together with a schematic plot of the detector setup is shown in Fig. 1b.

Photons emitted in the $0^+ \xrightarrow{\tilde{\gamma}} 1^+ \xrightarrow{\gamma} 0^+$ cascade are preferentially detected within the polarization plane. While the decay photons of a $0^+ \xrightarrow{\tilde{\gamma}} 1^- \xrightarrow{\gamma} 0^+$ cascade are preferentially emitted in the plane perpendicular to the polarization plane. Thus, by measuring the NRF intensities in both planes it is possible to separate $J^\pi = 1^\pm$ states with respect to their parity. Since the states of the parity doublet have different parities they can be separated by this method. Due to the finite target and detector sizes, the separation will, of course, not be 100%. The analysing power of the setup has been reported to be 0.9 in previous experiments (see e.g. [7]). Thus, the peak of the $0^+ \rightarrow 1^+ \rightarrow 0^+$ ($0^+ \rightarrow 1^- \rightarrow 0^+$) transition will be suppressed by a factor of ten in the vertical (horizontal) spectrum. Therefore, even though the $0^+ \rightarrow 1^+ \rightarrow 0^+$ transition is expected to be about a factor 30 stronger [8], a clear identification of the peak corresponding to the $0^+ \rightarrow 1^- \rightarrow 0^+$ transition is possible. The transition strength of the two states to the ground state were measured with $^{16}\text{O}(\alpha, \gamma)$ and $^{16}\text{O}(\alpha, \alpha)$ reactions before. During the experiment two measurements were performed on ^{20}Ne at a γ -beam energy of 11.26 MeV and a spectral width of 3%. A ^{28}Si target was placed together with the ^{20}Ne gas target in the beam. ^{28}Si has a 1^+ state at 11.45 MeV [9] which is used to extract the analysing power of the setup. In addition the ^{28}Si state together with its single escape peak

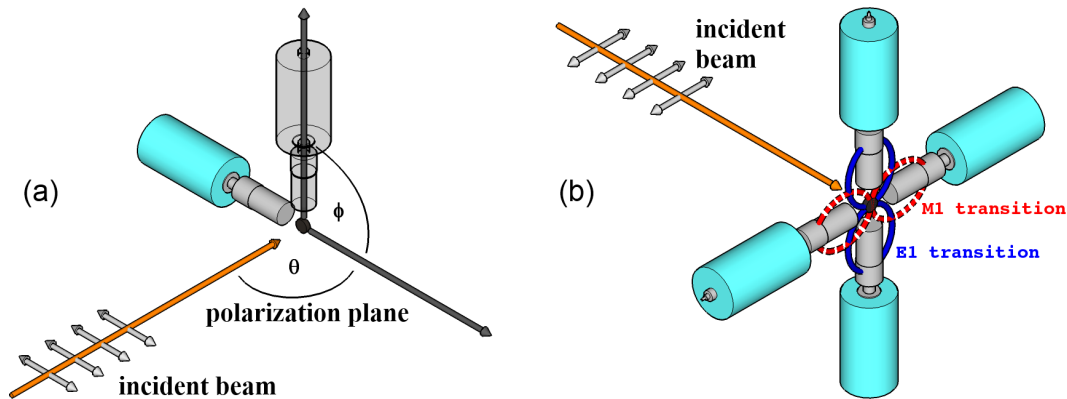


Figure 1. (a) Definition of the polar angle ϑ measured with respect to the incident horizontally polarized γ -ray-beam and of the azimuthal angle φ . (b) Schematic view of the NRF setup. The incoming beam is horizontally polarized and hits the target in the middle of the detector setup. The dashed curve shows the emission in case of a M1 transition and the solid curve illustrates the emission in case of an E1 transition.

deliver a consistent energy calibration for each detector. In one measurement a linearly polarized photon beam was used to separate the parity doublet. To get a consistent energy calibration for all detectors we performed a second measurement with circularly polarized photon beams. Here, the angular distributions of the scattered γ -rays have no azimuthal dependence and the deexciting transitions of the parity doublet and of the excited states in the calibration target have the same intensities in every detector. The obtained spectra are shown in Fig. 2. The HPGe detectors have an energy resolution of 7.5 keV at 11.4 MeV.

3. Analysis

The parity doublet states are too close in energy to resolve them individually within the detector resolution of 7.5 keV. However, the positions of the centroids of the parity doublet shift when switching from circularly to linearly polarised photon beams because depending on the azimuthal observation angles with respect to the polarization plane of the incident γ -ray beam, the intensities of the $1^\pi \rightarrow 0_1^+$ E1 or M1 transition will be different. Their energy centroids $E_{vertical/horizontal}$ can be expressed with the help of known values and the energies of the doublet states

$$E_{vertical} = \frac{E(1^-) \frac{I(1^-)}{I(1^+)} + E(1^+) \frac{W_{vertical}}{W_{horizontal}}}{\frac{I(1^-)}{I(1^+)} + \frac{W_{vertical}}{W_{horizontal}}} \quad (2)$$

$$E_{horizontal} = \frac{E(1^-) \frac{I(1^-)}{I(1^+)} \cdot \frac{W_{vertical}}{W_{horizontal}} + E(1^+)}{\frac{I(1^-)}{I(1^+)} \cdot \frac{W_{vertical}}{W_{horizontal}} + 1} \quad (3)$$

with $I(1^{+/-})$ being the integrated cross sections of the $1^{+/-}$ levels and $W_{vertical/horizontal}$ representing the angular distributions function for NRF M1 $1^+ \rightarrow 0_1^+$ transitions in vertical and horizontal direction, respectively. We could derive the polarization sensitivity of our setup from the ^{28}Si $1^+ \rightarrow 0_1^+$ transition. The ratio of the integrated cross sections of the parity doublet could be determined to $\frac{I(1^-)}{I(1^+)} = 0.034(14)$ with the help of the peak areas of the parity doublet and the analysing power of the setup which was measured with the calibration target ^{28}Si . Combining this value with equations (2) and (3) we calculate the energy position of the

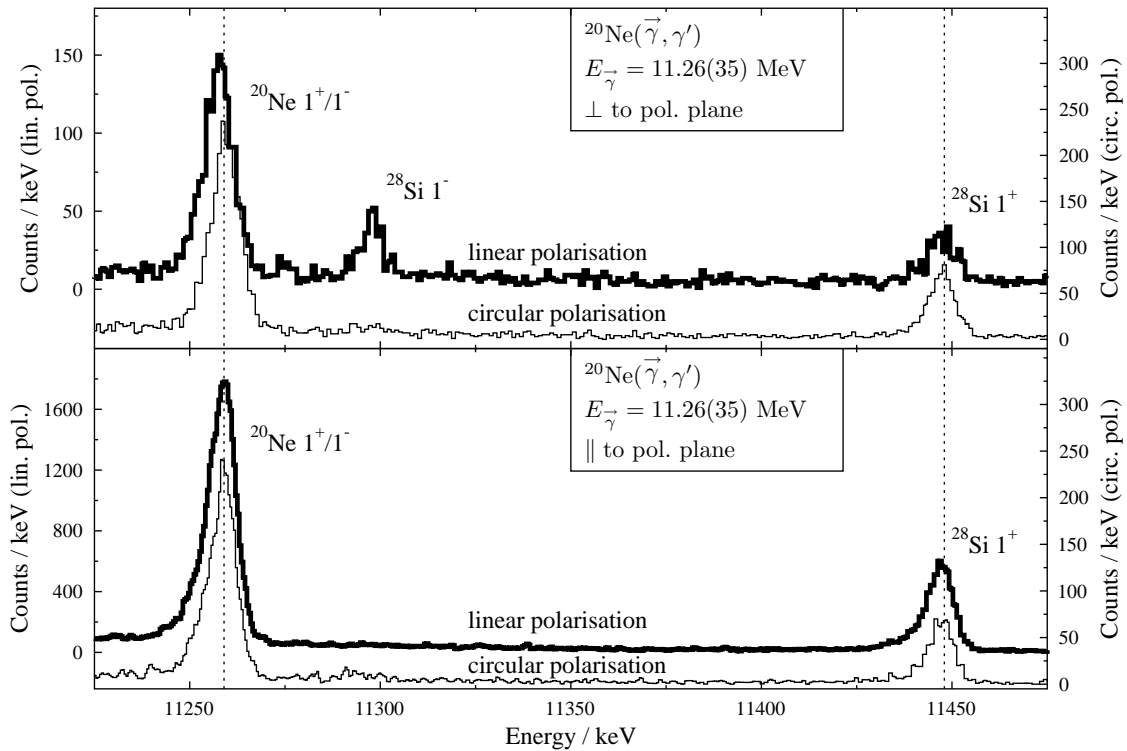


Figure 2. The summed spectra for the vertical (top) and horizontal (bottom) detectors. For a better comparison between spectra obtained either with linear polarization or with circular polarization two different scales are used to account for varying count rates data acquisition time periods. The spectra obtained with an incoming linearly polarized beam (bold) use the left axis, while the spectra obtained with an incoming circularly polarized beam (thin) use the right axis. We determine the energy difference between the ^{20}Ne doublet states from the small energy shift between linear and circular polarisation.

doublet states to:

$$\begin{aligned}
 E(1^+) &= 11257.8(1) \text{ keV} \\
 E(1^-) &= 11254.9(12) \text{ keV} \\
 \Delta E &= 2.9(13) \text{ keV}.
 \end{aligned}
 \tag{4}$$

Despite the fact, that we were able to measure the energy difference of the parity doublet with a higher precision, we also state that the energetic ordering of the two states was wrong. The 1^- state is lower in energy than the 1^+ . This was only possible because we excited both states simultaneously and, therefore, were able to perform a high-precision relative measurement.

4. Summary

We reported on the status of our analysis of the energy separation of the $1^+/1^-$ parity doublet states in ^{20}Ne . Our preliminary value amounts to $|E(1^+) - E(1^-)| = 2.9(13) \text{ keV}$. This leads to a preliminary value for the effective nuclear enhancement factor of $R_N/|E(1^+) - E(1^-)| \approx 1800 \text{ MeV}^{-1}$. In addition, the energetic ordering of the two levels could be corrected. These achievements were only possible with the combination of linearly and circularly polarized photon

beams and the high resolution of HPGe detectors.

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