Parities of bound dipole states in ^{40}Ar

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(Received 17 January 1986)

Nuclear resonance fluorescence experiments with linearly polarized bremsstrahlung were performed to determine parities of strong dipole transitions in ^{40}Ar. A total of 14 transitions—ten of them previously unknown—in the energy range from 4.7 to 10.2 MeV could be identified. From this experiment it is evident that the main dipole strength to bound states is due to $E1$ excitations. An upper limit of $B(M1)\uparrow < 0.5\ \mu_N^2$ was found for individual magnetic dipole excitations in ^{40}Ar in the energy region below neutron threshold.

I. INTRODUCTION

Observation of an unexpectedly strong isovector $M1$ transition in the spin saturated nucleus ^{40}Ca (Refs. 1—3), which was explained by intense ground-state correlations, caused us to search for $M1$ transitions in the neighboring nucleus ^{40}Ar with the help of nuclear resonance fluorescence (NRF) experiments. This isospin $T=2$ nucleus has the interesting feature that two pure isoscalar spin-flip $M1$ excitations are expected in the simple shell model: Firstly, a proton spin-flip transition from the fully occupied $d_{5/2}$ orbit into the half empty proton $d_{3/2}$ orbit, and secondly, a neutron spin-flip transition from the $f_{7/2}$ orbit into its $f_{5/2}$ counterpart. A systematic investigation of spin-flip $M1$ transitions in $T=1$ sd-shell nuclei with the help of nuclear resonance fluorescence[4] had shown that this method is well suited to determine $M1$ and $E1$ transitions model independently and that the experimental centroid energy of the $T_<$ component of the $M1$ resonance is located at 9.2 MeV, with deviations falling within a 1 MeV spread. No information about levels in this energy region has been published so far[5] for ^{40}Ar. The study of the β^- decay of ^{40}Cl (Refs. 6 and 7) yielded precise level energies, γ-ray branchings, and some spin and parity assignments for levels in ^{40}Ar below 7 MeV. An ^{38}Ar(t,p) experiment by Flynn *et al.*[8] extended the range of known states in ^{40}Ar up to 8 MeV, but yielded no information about dipole excitations, and the energy determination was only within errors of ± 15 keV. Beyond the aforementioned gap around 9 MeV, where no levels were known, 27 unbound states were identified in the ^{40}Ar(γ,n$_0$) reaction between 10.4 and 12.5 MeV excitation energy.[9]

In the present paper the method to determine parities model independently in a photon scattering experiment is briefly explained. Then we describe the ^{40}Ar($\vec{\gamma}$,γ) experiment and discuss transitions observed in the energy range from 4.7 to 10.2 MeV.

II. METHOD

Excitation of magnetic and electric dipole states in a nuclear resonance fluorescence experiment with linearly polarized photons yields different azimuthal scattering asymmetries

$$\epsilon=\frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} \tag{1}$$

for magnetic and electric transitions, where $N_\perp$ and $N_\parallel$ are the numbers of photons recorded perpendicular to and parallel to the polarization plane of the bremsstrahlung beam.[10] The polarization plane is defined by the direction of the electric field vector of the incoming linearly polarized bremsstrahlung beam. The measured asymmetry depends on the degree of bremsstrahlung polarization $P_\gamma(E_\gamma)$ and the analyzing power $\Sigma(\theta)$ of the ($\vec{\gamma}$,γ) reaction

$$\epsilon=P_\gamma(E_\gamma)\Sigma(\theta) \ . \tag{2}$$

Bremsstrahlung polarization was measured employing the ^{2}H($\vec{\gamma}$,p) reaction. The analyzing power $\Sigma(\theta)$ at a scattering angle of $\theta=90°$ for a ($\vec{\gamma}$,γ) reaction involving a spin $J_0=0$ ground state nucleus and a $J=1$ excited state equals $\Sigma(90°)_m=-1$ for magnetic and $\Sigma(90°)_{el}=+1$ for electric transitions. Therefore, excitation of a magnetic dipole transition and an electric dipole transition will yield a negative and positive photon scattering asymmetry, respectively, allowing an unambiguous distinction between the two different types of dipole excitations.

In a NRF experiment only dipole and, to a lesser degree, electric quadrupole transitions are excited. The analyzing powers $\Sigma(\theta=90°)$ for $E2$ and $M1$ transitions in a ground state $J_0=0$ nucleus are the same.

III. EXPERIMENT

The NRF search for strong magnetic transitions in ^{40}Ar was performed at the linearly polarized bremsstrahlung beam facility at the University of Giessen 65 MeV electron linear accelerator. High resolution Ge(Li) detectors were used to record the scattered photons.

The principle of the experimental arrangement is shown in Fig. 1. The electron beam from the linac was energy analyzed by a 90° Brown magnet system. Linearly polar-

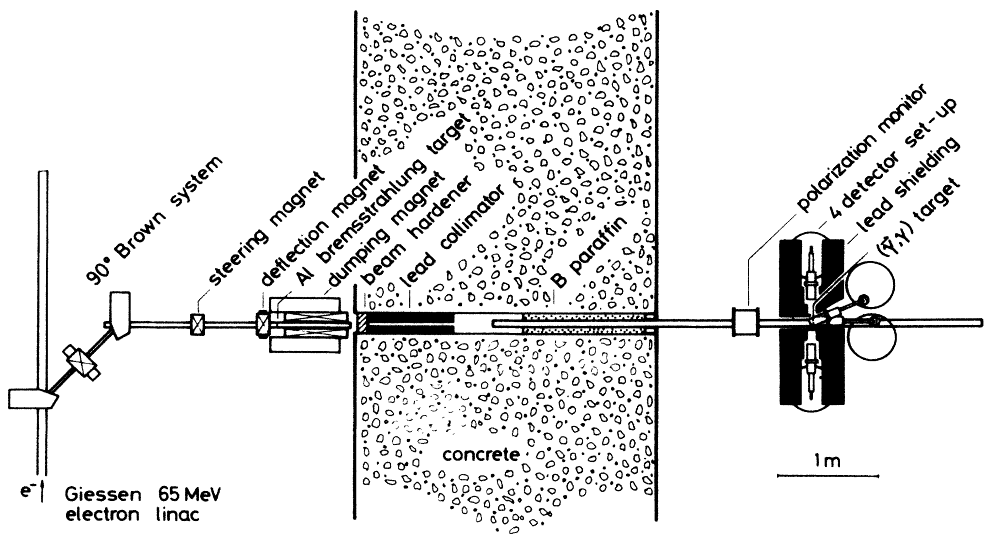

FIG. 1. Experimental arrangement of the nuclear resonance fluorescence facility using linearly polarized bremsstrahlung at the Giessen electron linear accelerator.

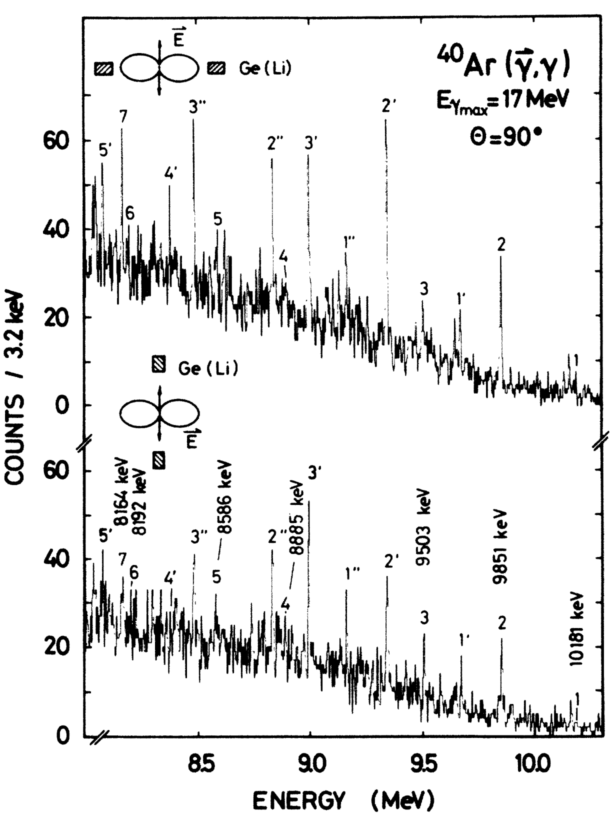

FIG. 2. Sum of all ^{40}Ar($\vec{\gamma}$,γ) spectra recorded with the Ge(Li) detectors perpendicular to (upper spectrum) and parallel (lower spectrum) to the polarization plane. Transitions are labeled by numbers and excitation energies. Single and double escape peaks are marked by one or two primes, respectively. The inserts show the expected azimuthal angular distribution for scattering of 100% linearly polarized photons from an electric dipole state. The position of the Ge(Li) detectors relative to the polarization plane is indicated.

ized photons were obtained by selecting an off-axis part of the bremsstrahlung beam produced in a thin (25 μm Al) bremsstrahlung target. For this reason the electron beam was slightly deflected by a magnet 14 cm in front of the bremsstrahlung target in horizontal and vertical directions. Maximum polarization is obtained at an angle of $\theta_0 = m_0c^2/E_0$ (m_0c^2 is the electron rest mass energy and E_0 the kinetic energy of the electrons). A steering magnet compensated for the displacement of the electron beam on the bremsstrahlung target. In order to avoid production

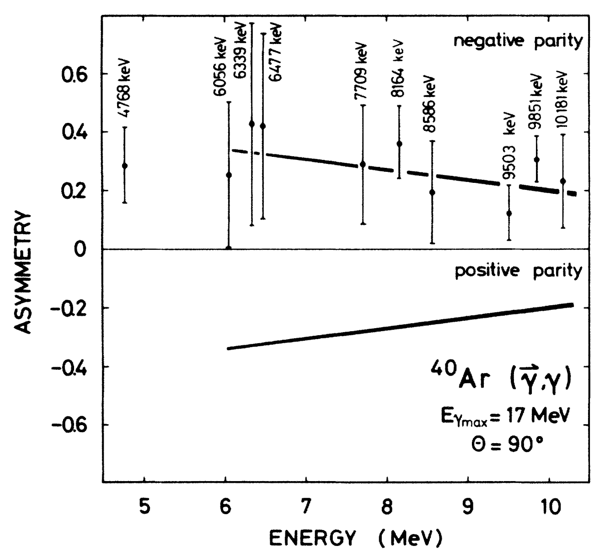

FIG. 3. Asymmetries for scattering of linearly polarized bremsstrahlung photons on ^{40}Ar. The measured asymmetries are labeled by the energies of the states excited. The bold lines show the asymmetries, which are expected from the measurement with the ^{2}H($\vec{\gamma}$,p) polarization monitor.

of unpolarized photons behind the bremsstrahlung target, the electrons were deflected into the ground by a dumping magnet.

The area of bremsstrahlung production was well shielded from the experimental area by a 3 m thick concrete wall. A lead collimator limited the photon beam to a spot of about 2 cm diameter at the (γ,γ) target. The argon gas target consisted of a steel cylinder with an inner diameter of 7.0 cm, closed by 190 μm thick plastic entrance and exit foils. The gas pressure amounted to 7.0×10^5 Pa ($\hat{=}5.3\times10^3$ Torr).

Nuclear resonance fluorescence photons were detected by four Ge(Li) detectors placed vertically and horizontally around the ^{40}Ar target in order to simultaneously measure the photon scattering intensities perpendicular to and parallel to the polarization plane. The azimuthal photon scattering asymmetries were then used to determine the parities of the excited states in a model-independent way.[10]

We employed 6129.270 ± 0.050 keV photons[11] from a ^{13}C$(\alpha,n\gamma)^{16}$O source and performed a ^{28}Si(γ,γ') experiment right after the ^{40}Ar$(\vec{\gamma},\gamma)$ run in order to calibrate energies of the γ-ray transitions observed in ^{40}Ar. The level at $11\,446.2\pm0.5$ keV in ^{28}Si (Refs. 4 and 5) is strongly excited in NRF and is, therefore, well suited for calibration of high excitation energies.

IV. RESULTS AND DISCUSSION

The ^{40}Ar$(\vec{\gamma},\gamma)$ experiment was performed with bremsstrahlung of 17 MeV end point energy. The high energy part of the recorded spectra is shown in Fig. 2. The spectrum in the upper half is the sum of spectra recorded by Ge(Li) detectors perpendicular to the polarization plane while the sum spectrum in the lower half was obtained by detectors parallel to the polarization plane, as indicated in the insert. It is obvious that peaks are larger in the upper spectrum, revealing that $E1$ transitions are excited.

Figure 3 represents the results of a quantitative analysis of the measured photon scattering asymmetries. The asymmetries of transitions exhibiting a good peak to background ratio (4768, 8164, 9503, and 9851 keV) were obtained from the single spectra, whereas weaker transitions could only be analyzed in the sum spectra. The error bars represent the standard deviations of the asymmetry distributions obtained from the analysis of full energy, single, and double escape peaks in the diverse $(\vec{\gamma},\gamma)$ spectra.

To give a survey about the relative magnitudes of γ-ray transitions observed below 8 MeV the spectra recorded parallel to and perpendicular to the scattering plane were summed up. This spectrum is plotted in Fig. 4. Only those peaks were identified to be due to a real transition in ^{40}Ar where in the sum spectrum a triplet of full energy, single- and double-escape peaks occurred in a distance of 511 keV. The states observed at 7993, 8192, and 8885 keV are close to the detection limit of this measurement with polarized photons and, therefore, only a tentative assignment is given in Table I.

Transitions with γ-ray energies $E_\gamma>7$ MeV can be attributed unambiguously to excitations in ^{40}Ar because of the Q values of possible ^{40}Ar$(\gamma,p\gamma)$, ^{40}Ar$(\gamma,n\gamma)$, and ^{40}Ar$(\gamma,\alpha\gamma)$ reactions. The bremsstrahlung end point energy amounted to 17 MeV and the Q values for particle emission of the reactions mentioned above are $Q_{\gamma,p}=-12.5$ MeV, $Q_{\gamma,n}=-9.9$ MeV, and $Q_{\gamma,\alpha}=-6.8$ MeV. In addition, the Coulomb wall has to be taken into account for charged particle emission. Furthermore, peaks from $(\gamma,x\gamma')$ reactions are broadened due to Doppler recoil of the ejected particle. The transitions do not appear Doppler broadened, and, on the other hand, the states with $E_\gamma<7$ MeV were already known from the ^{40}Cl(β^-) measurement[7] (see Table I).

A summary of the ^{40}Ar$(\vec{\gamma},\gamma)$ results is given in Table I. A total of 14 transitions could be identified. Ten of them in the energy region from 7.7 to 10.2 MeV correspond to levels in ^{40}Ar not published so far (see Table I). From the asymmetry plot in Fig. 3 it is obvious that the states at 4768, 8164, and 9851 keV are due to $E1$ excitations. Only a tentative spin-parity assignment of $J^\pi=(1^-)$ is given for the strong 9503 keV transition, because the measured asymmetry value is somewhat low and less than two standard deviations away from the region of positive parity states. The photon scattering asymmetries for the transitions at 6056, 6339, 6477, 7709, 8586, and 10 181 keV are close to the expected values for negative parity excitations, but a clear parity determination seems

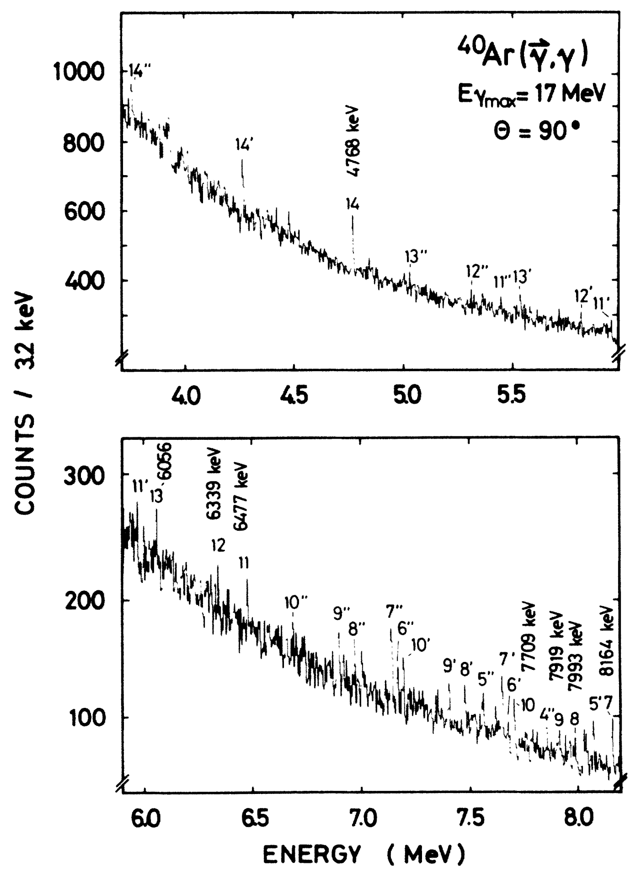

FIG. 4. Sum of all spectra obtained with the four Ge(Li) detectors during the ^{40}Ar$(\vec{\gamma},\gamma)$ experiment in the energy range from 3.7 to 8.2 MeV.

TABLE I. Excitation energies, spins, and parities from the ^{40}Ar($\vec{\gamma},\gamma$) experiment. Data from this work are compared with results from the β^- decay studies of ^{40}Cl (Ref. 7).

This experiment E_x (keV)	J^π	^{40}Cl(β^-)[a] E_x (keV)	Ground state branching (%)
4768±1	1^-	4769.0±0.3	100
6056±2	$1,2^+$	6053.6±0.8	100
6339±2	$1,2^+$	6339.0±0.8	100
6477±3	$1,2^+$	6476.0±0.8	100
7709±3	$1,2^+$		
7919±2	$1,2^+$		
7993±3[b]	$1,2^+$		
8164±2	1^-		
8192±4[b]	$1,2^+$		
8586±3	$1,2^+$		
8885±3[b]	$1,2^+$		
9503±2	(1^-)		
9851±2	1^-		
10 181±2	$1,2^+$		

[a]Reference 7.
[b]Tentative.

not to be statistically safe due to the weakness of these excitations (see Figs. 2 and 4). Spins and parities of levels, for which parities could not be determined unambiguously, can nevertheless be limited to $J^\pi=1,2^+$, because the states were excited by photons.

Recently, a NRF experiment on ^{40}Ar with unpolarized photons, but with very good statistics, was performed at the University of Illinois at Urbana-Champaign[12] with bremsstrahlung end point energies of 8.5, 10.3, and 11.8 MeV. The same ^{40}Ar levels as listed in Table I (and many more weaker transitions[12]) were observed at Urbana-Champaign, and the agreement of excitation energies of states observed in both measurements is very good.

The four states in ^{40}Ar at excitation energies of 4768, 6056, 6339, and 6477 keV were known from β^- decay measurements of ^{40}Cl (Refs. 6 and 7). The excitation energies of ^{40}Ar levels populated through the β^- decay of ^{40}Cl are in good agreement with the results of our experiment as shown in Table I. It should be noted that all corresponding levels show a 100% γ-ray branching to the ground state in the ^{40}Cl(β^-) experiment. Since peaks from elastic and inelastic scattering occur simultaneously in a NRF spectrum, the levels observed have been checked carefully for possible non-ground-state transitions. The NRF experiments in the *sd* shell[4] showed that ground state decay of the levels excited is the strongest. If γ-ray decay to excited states was present, it occurred in general to the first 2^+ state. This state is at 1460.81 keV in ^{40}Ar (Ref. 5). None of the energy differences in Table I is close to 1461 keV. Therefore, we conclude that all transitions listed in Table I are due to ground state transitions.

From β^- decay measurements of ^{40}Cl no definite spin and parity assignments were published for the levels mentioned above. The NRF experiment with linearly polarized photons yielded $J^\pi=1^-$ for the state at 4768 keV.

Kern *et al.*[6] found a negative parity for possible $J=1$ states at 6335±3 keV excitation energy in ^{40}Cl(β^-). This state was observed later in the same reaction by Klotz *et al.* at 6339±0.8 keV as listed in Table I. If we take the parity from the β^- decay studies and the asymmetry for the 6339 keV transition from Fig. 3, a $J^\pi=1^-$ assignment for the 6339 keV state becomes very probable.

The ^{40}Ar($\vec{\gamma},\gamma$) experiment discovered ten states above the level of highest excitation energy populated in the β^- decay of ^{40}Cl. An ^{38}Ar(t,p) experiment[8] covered the energy region up to 8 MeV, but the only states from the stripping reaction for which at least marginal agreement of excitation energies exists are at 6470±15 and 7980±15 keV. Flynn assumed that a possible $J^\pi=(2^+)$ state at 6470±15 keV is identical to the 6476.0±0.8 keV level reported by Klotz *et al.*[7] The ^{40}Ar($\vec{\gamma},\gamma$) measurement, however, indicates that the state at 6477 keV has a negative parity rather than a positive one (see Fig. 3).

It was pointed out in the Introduction that strong magnetic spin-flip transitions were expected in ^{40}Ar in the energy region around 9 MeV. The ^{40}Ar($\vec{\gamma},\gamma$) experiment, however, demonstrates that the strongest dipole transitions to bound and quasibound states are due to $E1$ excitations. A rough estimate of reduced transition probabilities, obtained by a comparison with a ^{20}Ne(γ,γ) measurement, yields an upper limit of $B(M1)\uparrow<0.5\ \mu_N^2$ for individual excitations in ^{40}Ar.

It shall be mentioned at this point that shell model calculations performed by Wildenthal and Chung[13] predict a strong $M1$ excitation of $B(M1)\uparrow=4.1\ \mu_N^2$ in ^{38}Ar. If this proton spin-flip transition should "survive" with the same strength after adding two neutrons into the $f_{7/2}$ orbit it should have been sticking out in the ^{40}Ar($\vec{\gamma},\gamma$) experiment or it must be located above the neutron threshold. Inelastic electron scattering experiments performed at the Darmstadt linac, however, yielded that also in the region of unbound states no strong $M1$ transitions occur.[14] Therefore, the strongest transitions in the energy region $E_x=10.4-12.5$ MeV observed by Lokan *et al.*[9] should be due to $E1$ excitations too.

In summary, 14 ground state excitations have been detected in the $^{40}Ar(\vec{\gamma},\gamma)$ experiment using polarized bremsstrahlung as γ-ray source. The four states identified with excitation energies below 7 MeV could be compared with results from previous work.[7] Excitation energies of ten further states in ^{40}Ar with $E_x > 7$ MeV are published in this paper for the first time. Photon scattering limits the multipole order and parity of the excitations to $J^{\pi}=1^{\pm},2^{+}$. Employing polarized photons, it becomes clear that the strongest transitions to bound states are due to electric dipole transitions. In the energy region of bound states an upper limit of $B(M1)\uparrow < 0.5\ \mu_N^2$ was found for magnetic dipole excitations. However, no definite $M1$ excitation has been identified in ^{40}Ar so far, leaving open the question about the total $M1$ strength in ^{40}Ar and its fragmentation.

ACKNOWLEDGMENTS

We would like to thank Professor W. C. Sellyey for making available for us the $^{40}Ar(\gamma,\gamma')$ results performed at MUSL-2 prior to publication. We also appreciate the help of Professor A. Richter for sending the results of the (e,e′) measurements. The authors are grateful to W. Arnold and his staff for providing an excellent running linac. This work was supported by the Deutsche Forschungsgemeinschaft.

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