Ground state $M1$ transition strength of the 1.115 MeV level in ^{65}Cu

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In inelastic electron scattering, form factors are measured for the 1.115 MeV level ($J^\pi=\frac{5}{2}^-$) in ^{65}Cu. This transition from the ground state ($J^\pi=\frac{3}{2}^-$) is predominantly longitudinal, with $B(E2,k)\uparrow=290\pm20$ e^2fm^4. In the framework of a model calculation, the $M1$ strength is deduced to be $B(M1,k)\uparrow=0.12$ $\pm0.03\mu_N^2$ [$\Gamma_\gamma(M1)=1.3\pm0.4$ meV].

In ^{65}Cu, the $E2/M1$ mixing ratio for the 1.115 MeV ($J^\pi=\frac{5}{2}^-$)$\rightarrow$ground state ($J^\pi=\frac{3}{2}^-$) transition has been the subject of several investigations.[1] Earlier, this quantity was of interest for refining the weak coupling model calculations. Lately, the $M1$ component of this transition is required as an input parameter in the search for axions.[2] In the literature, two types of measurements, viz., Coulomb excitation and resonance fluorescence experiments have been used (see Ref. 1), in attempts to determine the $M1$ strength. The results are conflicting as to the mixing ratio and hence for the $M1$ strength. Perhaps, in view of this ambiguity, Lehmann *et al.*,[2] in their search for axions, employed the single proton transition strength as the $M1$ component. This assumption did not influence their final conclusion very much, as their results were only order of magnitude estimates. However, for future axion searches in ^{65}Cu, a better estimate of the $M1$ strength is a prerequisite.

In the presence of a strong $E2$ component, as is the case for the transition of our interest, it is rather difficult to determine the $M1$ strength in a model independent way. Recently, shell model calculations, employing somewhat different configuration spaces have become available from two authors.[3,4] Müller and Metsch[3] performed adjusted surface delta interaction (ASDI) calculations with $1f\frac{5}{2}$, $2p\frac{3}{2}$, and $2p\frac{1}{2}$ as the active shells. Haxton,[4] in addition, allows for a single nucleon hole in the $1f\frac{7}{2}$ shell. It was considered possible to extract the $M1$ and $E2$ strengths by analyzing high-precision low-momentum-transfer (q) electron scattering data with these models. Also, high q data were taken to test the validity of these models.

The measurements spanned the momentum transfers $0.25<q<1.0$ fm^{-1} with incident electron energies of $24.6<E_0<140$ MeV. The experiments at the low q, $0.25<q<0.5$ fm^{-1}, were carried out at the Darmstadt linear accelerator (DALINAC) facility. Isotopically enriched ^{65}Cu ($>99\%$) targets of thickness 10 mg/cm^2 were employed and a total of ten spectra were recorded, including two q-matching measurements to determine the longitudinal and transverse components. The overall energy resolution full width at half maximum (FWHM) was 30 keV. Figure 1 shows the set of the three matching $q=0.4$ fm^{-1} spectra over the excitation region of 0.6–1.6 MeV. It is apparent that the transition to the 1.115 MeV level is predominantly longitudinal. The higher q measurements were carried out at the Saskatchewan Accelerator Laboratory. The targets were enriched ^{65}Cu foils of 30 mg/cm^2 thickness. The energy resolution varied between 100–150 keV (FWHM). The low resolution at Saskatoon was not a limitation as the neighboring levels were separated by about 300 keV from the level of interest.

The inelastic cross sections were measured relative to the elastic ones. The elastic cross sections were calculated with a phase shift analysis code in a two parameter Fermi model,[5] with $c=4.271$ fm and $t=2.549$ fm. Table I

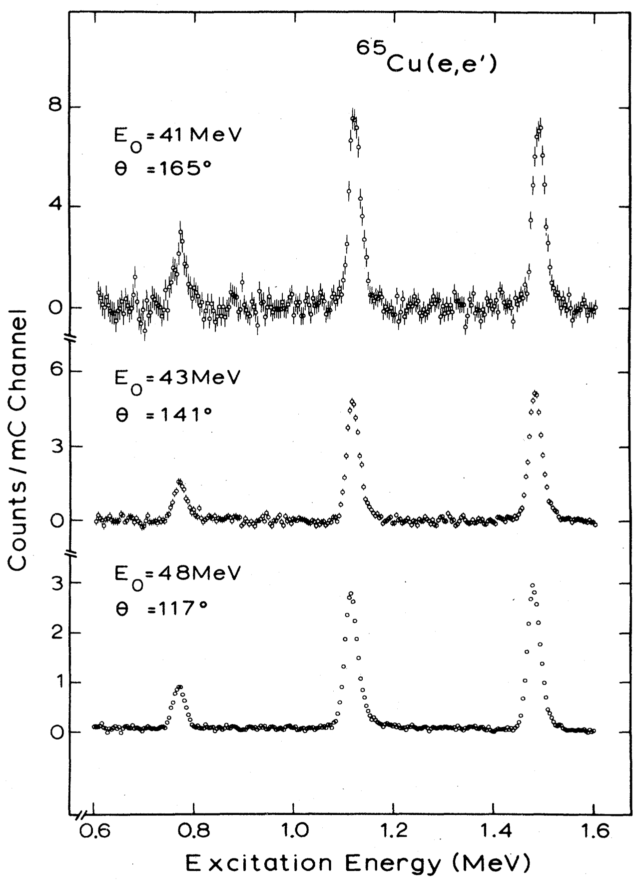

FIG. 1. Three matching q spectra ($q=0.4$ fm^{-1}) of the ^{65}Cu (e,e′) reaction for the excitation region 0.6–1.6 MeV.

TABLE I. Kinematic conditions and the measured cross sections and the form factors for ^{65}Cu (e,e′) populating the 1.115 MeV level.

Nr.	E_0 (MeV)	Θ (deg)	q (fm^{-1})	$10^5(d\sigma/d\Omega)_{in}$ (fm^2/sr)	$10^4F^2(q)$	Error (%)
Darmstadt						
1	24.6	165	0.247	0.124	0.975	28
2	29.6	165	0.297	0.157	1.788	11
3	29.8	165	0.298	0.173	1.998	5
4	31.4	141	0.298	0.958	1.537	3
5	34.7	117	0.298	2.93	1.567	1
6	41.5	165	0.413	0.21	4.693	2
7	43.6	141	0.413	1.366	4.217	2
8	48.2	117	0.413	3.763	3.877	1
9	48.2	141	0.455	1.224	4.618	1
10	49.1	165	0.483	0.177	5.552	3
Saskatoon						
11	74.2	123	0.66	2.042	5.8	5
12	107.0	80	0.7	6.86	5.24	3
13	107.0	99	0.83	1.8	3.94	3
14	109.0	120	0.954	0.186	1.14	5
15	140.0	90	1.02	0.779	1.75	4

presents the details of the measurements and the deduced cross sections.

Rosenbluth plots for matching q at two low-momentum transfers and one high q value, showed the transition to be predominantly longitudinal with a small admixture of transverse components. This feature made it impossible to extract the $M1$ strength in a model independent way. Under the assumption that the transition is purely $E2$, we obtain a value of $B(E2,k)\uparrow = 290 \pm 20$ e^2fm^4, which is consistent with and more precise than the weighted mean value of $B(E2,k)\uparrow = 306 \pm 80$ e^2fm^4, deduced by us from the resonance fluorescence measurements. All the real-photon experiments yield the $M1$ component to be nonzero, though there is a discrepancy about the magnitude. From our Rosenbluth plots, the $M1$ component cannot be separately determined from the transverse $E2$ part. In the following, we compare our results with the model calculations of Müller and Metsch[3] and Haxton.[4]

The two different calculations result in the same value for $B(E2,k)\uparrow = 175$ e^2fm^4, which is about 60% of the experimental value. This agreement indicates that a single hole in the $1f\frac{7}{2}$ shell does not significantly influence the $E2$ strength. It is apparent that a much larger configuration space or, as an alternative, effective charges have to be introduced to account for the experimental $B(E2)$ values. For the $M1$ strength, Haxton[4] predicts $B(M1,k)\uparrow = 0.12$ μ_N^2, while Müller and Metsch[3] obtain a value $0.06\mu_N^2$. The mixing ratios deduced from these calculated $M1$ strengths, $\delta = [\Gamma_\gamma(E2)/\Gamma_\gamma(M1)]^{1/2} = 0.355$ and 0.525, respectively, correspond to the two extreme values of the mixing ratios deduced from the resonance fluorescence measurements.[1]

In order to constrain the models further, we evaluated the form factors using a distorted wave program[6] based on DUELS. The transition amplitudes calculated by Haxton,[4] with an effective charge of $1.3e$, reproduce the experimental $B(E2)$ value. Also, the mixing ratio, with bare nucleon g factors, is found to be $\delta = 0.46$, in excellent agreement with the adopted value[1] of $\delta = 0.44 \pm 0.02$. The same approach to Müller's model yields $\delta = 0.62$, about 50% higher than the adopted value. Clearly, this weakness of the model cannot be remedied within the configuration space employed, as any attempt with effective g factors would result in larger mixing ratios. Figure 2 shows the plot of the measured form factor as a function of q_{eff}, along with the one calculat-

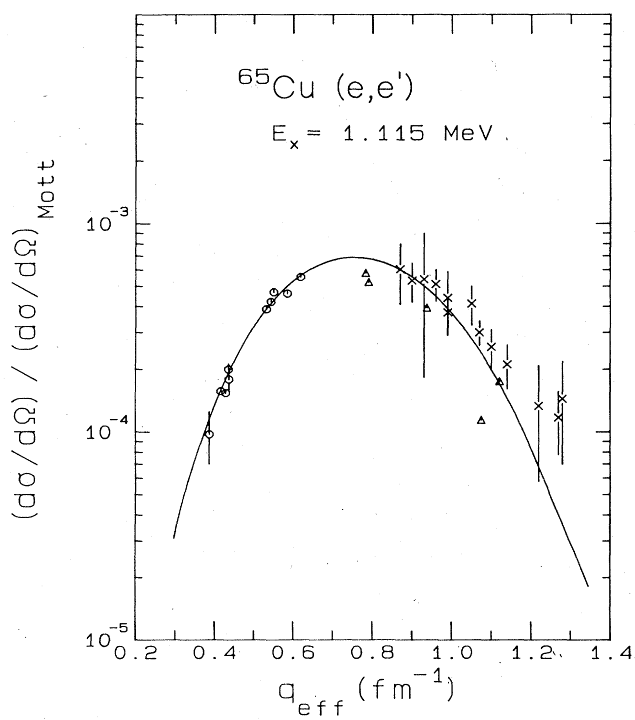

FIG. 2. Plot of the form factor $F^2(q)$ vs q_{eff} for the inelastic electron scattering to the 1.115 MeV level in ^{65}Cu. Full circles are the data taken at Darmstadt, triangles are the measurements at Saskatoon. The data from Polishchuk *et al.* (Ref. 7) are shown as crosses. The curve is the model prediction of Haxton, with effective charge $1.3e$ (see text for details).

ed using Haxton's transition densities and the effective charges. Also shown are the data of Polishchuk *et al.*[7] As can be seen, our results are in fair agreement with the latter data and are of higher precision and the model accounts for the form factor over the entire measured region. We estimate the error in $M1$ component to be about 20%, which yields $B(M1,k)\uparrow = 0.12 \pm 0.03\mu_N^2$. In view of the constraint placed on this model, this estimate should be more reliable than earlier evaluations.

It is of interest to note that the assumption of Lehmann *et al.*,[2] that the $M1$ transition is a single proton transition, overestimates the $M1$ width by an order of magnitude. This implies that they underestimated $R_{\gamma\gamma} = \Gamma_{\text{axion}}/\Gamma_\gamma\ (M1)$ by a factor of 10. If this factor is taken into account, the upper limit of 1 MeV for the axion mass is barely satisfied. Any future experiment on the axion search in this nucleus would have to incorporate this correction.

In summary, we have deduced the $M1$ strength for the 1.115 MeV → ground state transition to be $B(M1,k)\uparrow\lambda = 0.12 \pm 0.03\mu_N^2$ or $\Gamma_\gamma(M1) = 1.3 \pm 0.4$ meV. It is a more reliable estimate than the results available before the present work, in view of the constraints placed on the model to account for a large set of data. More precise determinations would have to wait for the experiments of the type (e,e′γ) or electron scattering with a polarized ^{65}Cu target.

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