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INFLUENCE OF NUCLEAR RESONANCE ^{56}Fe(p,p)^{56}Fe ON K–SHELL IONIZATION PROBABILITY*

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ABSTRACT

The K–shell ionization probability P_K was measured as a function of E_p across the strong resonance ^{56}Fe(p,p)^{56}Fe at 2.522 MeV and about 50 % variation was observed. For a large ratio of the K–shell binding energy to the total width of the nuclear resonance, $U_K/\Gamma \geqslant 5$, the present experimental result is still in good agreement with theoretical calculation based on Blair and Anholt's formula.

Keywords: ^{56}Fe(p,p)^{56}Fe elastic scattering K–shell ionization probability Nuclear resonance

1 INTRODUCTION

In recent years, increasing attention has been paid to the interplay between atomic and nuclear processes[1]. One of the effects studied is the variation of the K–shell ionization probability P_K caused by a non–negligible nuclear reaction time[2]. In 1978 Blair *et al.*[3], for the first time, observed this phenomenon in the proton elastic scattering from ^{58}Ni. It was interpreted in terms of interference of the K–shell electron ionization amplitudes between on the way into and out of the nucleus. This time delay effect can be quantatively described in terms of ratio U_K/Γ, where U_K is the K–shell binding energy and Γ is the total width of the nuclear resonance[4]. A significant variation of P_K may occur at any nuclear resonance provided that $U_K/\Gamma \geqslant 1$. In other words, the time delay ($\sim 1/\Gamma$) should be in the order of or greater than the K–shell orbiting period($\sim 1/U_K$).

Both theory and experiments confirmed that there are no variations in P_K for $U_K/\Gamma \ll 1$. The previous experiments[3, 7] were performed in the range of $0.01 < U_K/\Gamma < 3.5$ and the results are generally in agreement with the theory of Blair and Anholt[8]. However, there is no experiment yet to investigate the case of large ratio U_K/Γ. The present study concerns the K–shell ionization probability in the vicinity of a strong $p_{1/2}$ resonance in ^{56}Fe(p,p) at $E_p = 2.534 \pm 0.003$ MeV. This resonance was

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chosen because of its long nuclear delay time. The resonance width is $\Gamma = 1350 \pm 120$ eV[9] and $U_K = 7.2$ keV, thus $U_K/\Gamma \geqslant 5$.

In some theoretical calculations of the time delay effect, the phase shift of the monopole ($\lambda = 0$) ionization amplitude was considered as an adjustable parameter. Such as, a detailed experiment was performed by Chemin *et al.*[10] on ^{86}Sr(p,p) resonance at $E_p = 5.06$ MeV. In the calculations, they found that $R_o < -1$ has a good agreement between the measured and the calculated P_K, where $R_o = \mathrm{Im}(b_o)/\mathrm{Re}(b_o)$ is the ratio of the imaginary part to the real part of monopole ionization amplitude. More detailed measurements of P_K across the $f_{7/2}$ isobaric–analog resonance at $E_p = 10.003$ MeV in the ^{138}Ba(p,p) reaction were carried out by Dost *et al.*[6] and by D.W.Spooner *et al.*[7]. They obtained $R_o = -0.3$ for the best fitting of the experiment results. Another quite different value $R_o = 1.8$ has been used in a preliminary analysis of the present ^{56}Fe(p,p) experiment[11]. Thus, the R_o values derived by different authors vary considerably. This fact suggests that it may not be correct to consider R_o as a constant independent of ε_f, where ε_f is the kinetic energy of ionized electron.

In this paper we report the experimental measurement of P_K at ^{56}Fe(p,p)^{56}Fe resonance. The experimental procedures and results are detailed in Sec.2. Following Blair & Anholt's theory, we obtained an ε_f–dependent ionization amplitude without any adjustable parameters. These analyses and discussions are given in Sec.3.

2 EXPERIMENTAL RESULTS

The experiment was performed with a 2× 3 MV tandem pelletron accelerator (9SDH–2, NEC). Relative P_K–values were determined by measuring, with the standard fast–slow coincidence technique, the ratio of K X–ray–proton coincidence events to the total number of elastically scattered protons. The proton beam has a day–long stability of 1.2 keV with an energy resolution of 1 keV. This is important since it takes about 24 h to obtain a single data point due to the very small K–shell ionization probability. With our system the ^{56}Fe(p,p) resonance was found at $E_p(\mathrm{lab}) = 2.522 \pm 0.010$ MeV and it is consistent with the value of 2.534 ± 0.003 MeV reported in Ref.[9] in the error range. The experimental setup is shown in Fig.1. Two NaI(Tl) detectors, both 1 mm thick and 50 mm in diameter, placed outside the scattering chamber perpendicular to the incident beam, subtended a total solid angle of 0.29 sr. Two thin polypropylene foils were used as windows of the chamber. Including attenuation of the K X–rays in various absorbers, the detection efficiency of the NaI(Tl) detectors was estimated to be $19 \pm 1\,\%$ at 5.9 keV. A 20 mm in diameter annular surface barrier detector was placed with an angle interval from 150° to 170° with respect to the beam incidence. The scattering chamber was maintained to a vacuum of 2.7×10^{-5} Pa. The alignment of the chamber was assured by passing the beam through two tantalum apertures, 1 mm and

2 mm in series and 20 mm apart, at the entrance of the scattering chamber (see Fig.1).

The target was prepared by evaporating a metal iron (99.9 % of ^{56}Fe) layer of 15 μg/cm^2 onto a carbon foil of 7 μg/cm^2. The target holder was fixed at 45° with respect to the beam. The proton beam were dumped to a Faraday cup and integrated with an accuracy of 0.1 %.

The proton signal acted as the start signal of the time to amplitude converter (TAC) and the two K X-ray signals coupled in parallel as the stop signal. For each coincidence event, the time difference between the proton and K X-ray signals was converted by the TAC and stored in a multiple channel buffer (ORTEC 918) which was connected to a microcomputer. Finally, the data of the coincidence events were reconstructed and a typical TAC spectrum was generated with a time resolution (FWHM) of 10 ns which is shown in Fig.2. The ratio of true to random coincidences in a 20 ns window was 0.3. The beam current was kept at 0.6 nA and the projectile energy was checked every five hours.

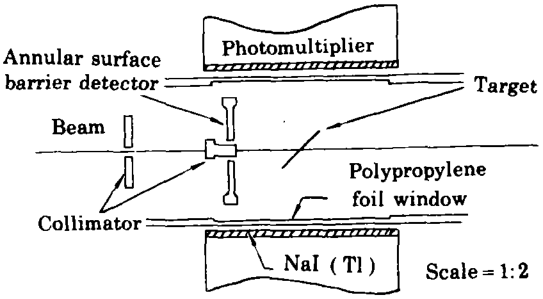

Fig.1 Experimental set-up (top view)

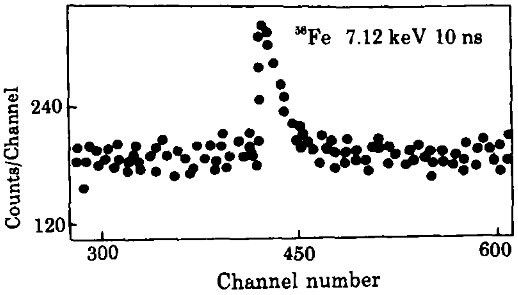

Fig.2 Typical time-amplitude-converter (TAC) spectrum showing FWHM 10 ns

The experimental results are given in Fig.3. We measured the relative differential cross section for $E_p = 2.45$—2.60 MeV in steps of 1 keV. Fig.3(a) shows the data for $E_p = 2.50$—2.54 MeV, since there is no structure of present interest outside this energy range. The relative K-shell ionization probability P_K in the resonance region is shown in Fig.3(b). Experimentally, P_K is the ratio of counts of true coincidences to that of the elastically scattered protons. Each data point was normalized to the average off-resonance value. In the vicinity of the resonance, the measured ionization probability P_K exhibited a resonance peak with a maximum variation of (53 ± 24) %. The theoretical curves shown in Fig.3(b) will be accounted for in Sec.3.

3 ANALYSIS

Following the framework of Blair and Anholt[7], the ionization probability of a K-shell electron by proton with center-of-mass energy E and scattering angle θ is given by

$$P_K(\theta, E) = \int_0^\infty d\varepsilon_f \Sigma_{\lambda\mu} \mid D^\lambda{}_{\mu 0}(\theta)\, b_\lambda + (-1)\delta_{\mu 0}[f(\theta, E-\triangle E)/f(\theta, E)\, b^*{}_\lambda \mid^2 \quad (1)$$

where the b_λ is the ionization probability amplitude and the $f(\theta, E)$ is the nuclear scattering amplitude, the λ is the orbital angular momentum of the ionized electron, the ε_f is the kinetic energy of the electron, the μ runs from $-\lambda$ to $+\lambda$. The asterisk represents the complex conjugate. The rotation matrix element $D^\lambda{}_{\mu 0}(\theta) = D^\lambda{}_{\mu 0}(\theta, \theta, 0)$ takes account of the direction of the projectile on its way out. If the ionization occurs on the way into the atomic nucleus, the amplitude for emission of an electron from the K-shell into a continuum state (ε_f, λ, μ) is denoted by $b^*{}_\lambda$ and only $\mu = 0$ electronic states has the contribution. The amplitude b_λ is for the ionization on the way out. The expressions for $b^*{}_\lambda$ and b_λ are given in Ref.[8]. The $\triangle E = U_K + \varepsilon_f$ is the energy loss of the projectile in the ionization of the K-shell. As a good approximation, it is sufficient to take only $\lambda = 0$ and $\lambda = 1$ into account, because the contribution of $\lambda = 1$ is at least one order of magnitude smaller than that of $\lambda = 0$ and two orders of magnitude larger than that of $\lambda \geqslant 2$. Thus Eq.(1) can be written in two terms:

$$P_K(\theta, E) = P_K{}^{\lambda=0}(E) + P_K{}^{\lambda=1}(\theta, E) \quad (2)$$

Following the discussion given in Ref.[7], the total elastic scattering amplitude from Coulomb and resonance scattering is then given by

$$f(\theta, E) = f_c(\theta, E) + f_R(\theta, E)$$

$$= f_c(\theta, E) + (1/2K)(J + 1/2)\exp(2i\sigma_l) \times \Gamma_p/[(E_R - E) - i\Gamma/2] \times P_l(\cos\theta) \quad (3)$$

where the K is the wave number of the relative nuclear motion, the Γ and Γ_p are total width and the elastic proton width, respectively, for the resonance investigated

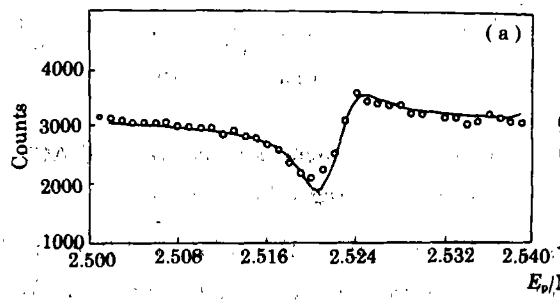

Fig.3(a) Measured relative differential cross sections for ^{58}Fe(p,p)

The solid-line shows the calculated differential cross section in which the beam energy and detector solid angles are taken into account

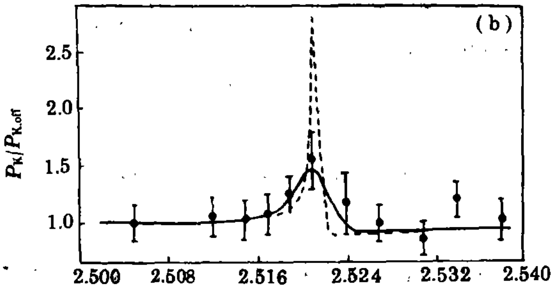

Fig.3(b) Measured values of the ratios $P_K/P_{K,\mathrm{off}}$ in ^{56}Fe(p,p)^{56}Fe

The dash-line represents the calculated ratios $P_K/P_{K,\mathrm{off}}$. The solid-line shows the theoretical values of the ratios $P_K/P_{K,\mathrm{off}}$ with energy and angle averages here, one has $\Gamma_p = \Gamma = 1350 \pm 120$ eV, $J = 1/2$ and $l = 1$. The Legendre polynomial $P_l = P_1$ and the Coulomb phase shift $\sigma_l = \sigma_1$.

It should be noted that there is no adjustable parameter in our calculation. From Eq.(1), the dependence of P_K on the incident proton energy can be obtained, which is shown as the dashed curve in Fig.3(b). For comparison with the measured values, both the proton beam energy resolution and stability and the angular range of the detectors have to be taken into consideration. A Gaussian distribution of the proton energy dispersion was assumed in our calculation. The final results are shown as solid line in Fig.3(b). By using the nuclear amplitude of Eq.(3), the proton elastic scattering differential cross sections were obtained and shown as solid line in Fig.3(a). These calculated results are in good agreement with experiment. The present work indicates that the theory of Blair and Anholt is still valid for the case of the large value of U_K/Γ, and it shows that the variation of P_K across the resonance peak is reasonable.

4 CONCLUSION

We have observed the variation of P_K across a ^{56}Fe(p,p) resonance which has a long nuclear delay time. Under the present experimental conditions, a maximum deviation of $53 \pm 24\%$ was measured over the 2.522 MeV resonance. We have calculated the variation of P_K without any adjustable parameters. Taken into account the finite beam energy resolution, long-term stability and the solid angle of the detectors, the agreement between the experimental data and the calculation is satisfactory.

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