Large Resonance Effect in K-Shell Ionization Probability in Elastic Proton Backscattering on ^{138}Ba

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We have measured the K-shell ionization probability P_K at 172° across the 10.00-MeV isobaric analog resonance in the reaction $^{138}Ba(p,p)^{138}Ba$. An excursion of more than 200% from the off-resonance P_K value permits a sensitive comparison with recently calculated atomic-ionization amplitudes. The effects of nonresonant background nuclear scattering and compound-elastic nuclear scattering are considered. The experimental results are found to be consistent with a negligible compound-elastic contribution.

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The first observation of a nuclear-reaction effect on K-shell ionization was reported by Blair *et al.*[1] using an $s_{1/2}$ nuclear resonance in the elastic scattering of protons from ^{58}Ni. A subsequent theoretical treatment by Blair and Anholt[2] has been successful in reproducing these ionization-probability (P_K) data as well as those of others.[3-5] However, all experimental studies have suffered from large uncertainties in the measurement of a relatively small ($\approx 20\%-40\%$) effect, and analysis of the data has made limited use of the quantitative merit of the theoretical framework.

Amundsen and Aashamar[6] have recently published the most detailed calculations of P_K during nuclear-resonance scattering available to date. Based on the full Blair-Anholt theory, without approximations such as the neglect of nuclear recoil, and using relativistic electron wave functions, their numerical results were compared with the entire body of P_K data. They concluded that while the improved calculations were valuable in identifying the nuclear-recoil term as nonnegligible in some cases, the inaccuracy of the experiments prevented more subtle tests of the theory.

In this work, we have measured the K-shell ionization probability over the $f_{7/2}$ isobaric analog resonance in proton elastic backscattering from ^{138}Ba at 10.00 MeV. For this resonance, the width (≈ 68 keV) is comparable to the K-electron binding energy (≈ 37 keV), so that a maximal resonance effect is expected.[1] The size of the measured effect in P_K is far greater than any observed up to now ($> 200\%$) and the data set represents the largest number of measurements reported for a single resonance and scattering angle. Consequently, the data provide an attractive basis for comparison of theory and experiment.

Our experiment measured the K-shell ionization probability by means of the x-ray–particle coincidence method with one important modification: The detector resolution was improved by cooling of the silicon surface-barrier detector to $-30\,°C$ with a solid-state heat pump so that we could gate on only those particle events which had produced a K vacancy. In this way, the number of accidental coincidences was reduced drastically, compared to the usual gating over the entire elastic peak. A conceptually similar method had been employed by Clark *et al.*[7] using magnetic separation of K-vacancy–producing protons (with a rather small solid angle, though).

The experimental arrangement is shown in Fig. 1. The 10-MeV proton beam from the Stanford FN tandem Van de Graaff accelerator was collimated upstream of the scattering chamber by an elaborate system of tantalum apertures with lead and cadmium gamma-ray shields. Targets of 90-μg/cm^2 $BaCO_3$, enriched to 99.8% in ^{138}Ba, were mounted on 20-μg/cm^2 C foils at 45° to the beam. A 200-mm^2-annular (4-mm-diam. hole), 1-mm-thick, surface-barrier detector subtended the angular range from $\theta = 168°$ to 176° with respect to the incident beam direction. A 1.5-m-long Faraday cup fitted with a graphite end plate was used to minimize the number of gamma rays and backscattered particles reaching the detectors.

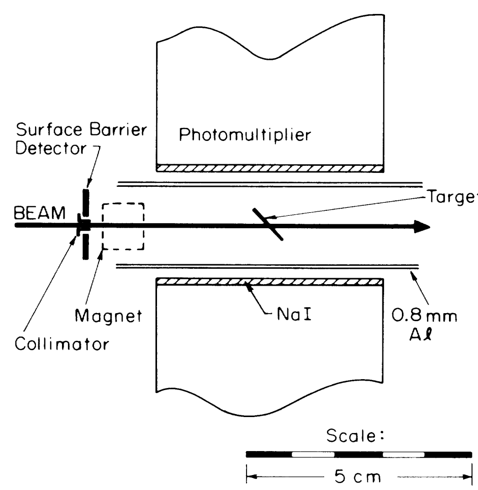

FIG. 1. Experimental arrangement. The surface-barrier detector is protected from direct exposure to the beam by a graphite tube surrounded by a thin brass sleeve.

The 32.0-keV Ba K x rays were detected by two 2-mm-thick, 5-cm-diam NaI scintillators mounted outside the vacuum chamber at 90° with respect to the beam. Aluminum windows, 0.8 mm thick, eliminated Ba L x rays but hardly attenuated the K x rays. The efficiency and solid angles were calibrated with ^{133}Ba.

A set of rare-earth cobalt magnets mounted in front of the target was used to divert delta electrons emanating from the target away from the particle detector. Without this protection, the detector resolution deteriorated even at subnanoampere beam currents because of saturation effects. The proton-energy resolution was typically 20 keV FWHM with the detector cold. Beam currents were about 5 nA.

Standard electronics with event-mode aquisition were used to process the detector signals. The coincidence-timing resolution was 9 nsec FWHM. The Ba K x-ray peak was the only visible structure in the x-ray spectrum. In the particle spectrum, the peak due to elastic scattering from Ba was well separated from other scattering processes.

The ionization probability was measured at twenty different energies in the range of interest. Periodic scans of the elastic cross section provided a convenient energy calibration of the proton beam. At two energies, the measurement of P_K was repeated to ensure reproducibility of the data. The ratio of true to random coincidences was almost 3:1 in favorable cases and never less than 1:1, with an average accumulation time of 30 h per point.

Figure 2 shows computer-sorted elastic proton spectra from ^{138}Ba obtained by our requiring a particle–Ba-K-x-ray coincidence. The full histogram is generated by the setting of a gate on the time-to-amplitude converter (TAC) peak and represents the number of coincidences, both true and random, as a function of particle energy. The dashed histogram is gated off the TAC peak and is a spectrum of accidental coincidences. The peak due to protons responsible for K-shell ionization is clearly evident, with its maximum displaced from the elastic peak by approximately the binding energy U_K, which for Ba is 37.4 keV. The peak shape agrees with that calculated from the energy distribution of the delta electrons,[8] folded with the experimental energy resolution. To evaluate P_K, the number of coincidences was found by integration of the difference of the on-TAC and off-TAC proton spectra between the limits $E_p - U_K$ and $E_p - 3U_K$ (indicated on Fig. 2), where E_p is the incident beam energy. The number of coincidences divided by the total number of elastically scattered particles, the fluorescence yield, the x-ray efficiency (including solid angle), and the cal-

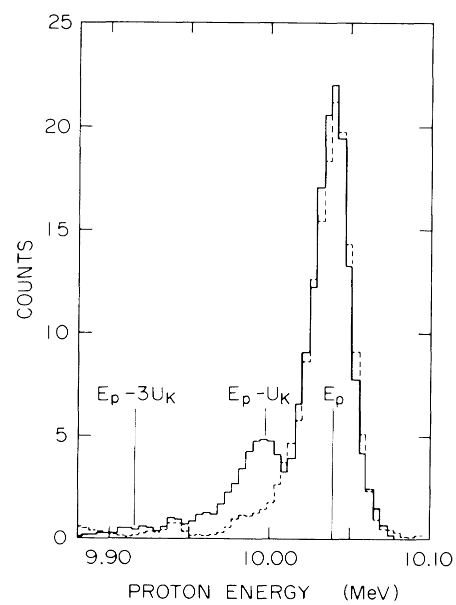

FIG. 2. Sorted proton spectra. Full histogram gated on TAC peak, dashed histogram gated off TAC peak, as discussed in text.

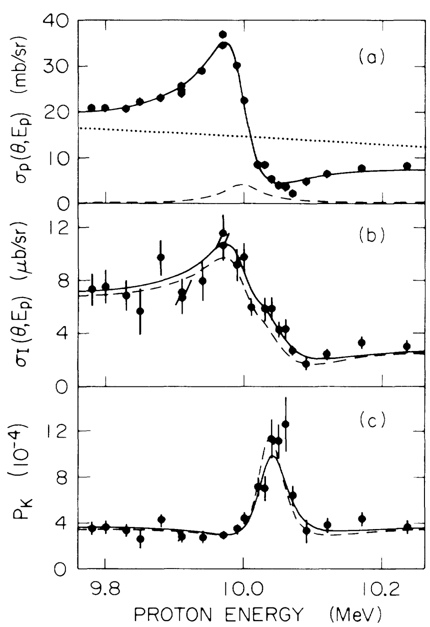

FIG. 3. (a) Elastic scattering cross section $\sigma_p(\theta,E_p)$ at $\theta = 172°$, as a function of proton energy E_p. Full curve shows best fit with or without compound-elastic (CE) scattering (Table I, fits A–D). Dashed curve is upper limit to CE contribution ($\sigma_0 = 4.0$ mb; Table I, fits C and D). Dotted curve is elastic background scattering ρ^2. (b) Differential ionization cross section $\sigma_I(\theta,E_p)$. Full curve, fit to data using scaled Reb_l and Imb_L values (Table I, fit B). The unscaled amplitudes would give a curve lying approximately 10% lower. Dashed curve, calculation including CE effects, but using unscaled atomic ionization amplitudes b_l of Amundsen and Aashamar (Ref. 6) (Table I, fit C). (c) Ionization probability P_K. Full curve is for Table I, fit B; dashed curve, for fit C. The $\chi^2(P_K)$ value is best for fit B (see Table I).

culated fraction of inelastically scattered projectiles with energies between $E_p - U_K$ and $E_p - 3U_K$ gives the measured ionization probability P_K.

In Fig. 3, we display (a) the measured differential elastic scattering cross section $\sigma_p(\theta,E_p)$, (b) the differential ionization cross section $\sigma_I(\theta,E_p)$, and (c) P_K, which by definition is equal to σ_I/σ_p. The error bars reflect statistical uncertainty for the ionization data and uncertainty in target thickness for the cross sections. In the analysis of the data, the nuclear parameters are determined first by a least-squares fitting[9] with $\sigma_p = |f|^2$ using the elastic scattering amplitude f of Seitz *et al.*[10], including their definition of the background phase α. The nuclear resonance parameters Γ, Γ_p, E_R, and $\rho^2(E_p) = a_0 + a_1/E_p^2$ describing the total and elastic proton widths, resonance energy, and elastic background scattering cross section (consisting of Coulomb and nonresonant elastic scattering), respectively, as well as α, were varied. The results are indicated in Table I (fits A and B) and Fig. 3(a) (solid curve), and are close to those of Seitz *et al.*[10] The presence of additional resonances in the vicinity of the $f_{7/2}$ resonance was taken into account by use of the parameters given in Seitz *et al.*[10] without modification. We neglect the small spin-flip contribution, as in the analysis of Dost *et al.*[5]

It is best to determine atomic parameters by fitting the directly measured σ_I, rather than P_K, because the latter is affected by errors in σ_p and σ_I [note that $\chi^2(\sigma_I) < \chi^2(P_K)$ in Table I]. Here,

$$\sigma_I(\theta,E_p) = \int_0^\infty d\varepsilon \sum_l \{(|f|^2 + |f'|^2)[(\mathrm{Re}b_l)^2 + (\mathrm{Im}b_l)^2] + (-1)^l \times 2\,\mathrm{Re}[ff'^*(b_l)^2]P_l(\cos\theta)\} \quad (1)$$

which derives from Amundsen and Aashamar[6] if we explicitly define the atomic-ionization amplitudes by $b_l = \mathrm{Re}b_l + i\,\mathrm{Im}b_l$. In Eq. (1), f is the elastic scattering amplitude $f(\theta,E_p)$ evaluated at the incident beam energy E_p, and f' is the same function evaluated at the reduced proton energy $E_p - (U_K + \varepsilon)$, where ε is the kinetic energy of the ejected electron. The sum over the final electron orbital angular momenta is truncated to include only $l=0$ and $l=1$, as in previous analyses.[5,6] We found that the variation of $\sigma_I(\theta,E_p)$ with θ at far backward angles simply changes the magnitude of the peak excursion of P_K from its off-resonance value without severely affecting its shape, so that evaluation of the theoretical values of σ_I at the mean observation angle of the small detector acceptance is justified. The values for $\mathrm{Re}b_l$ and $\mathrm{Im}b_l$ are taken from Amundsen and Aashamar,[6] and the integration over ε is carried out from $\varepsilon=0$ to $\varepsilon=2U_K$ in steps of $0.04U_K$. A generally good fit results (Table I, fit A).

In an effort to test the sensitivity of σ_I to the atomic amplitudes, a new fit to the data was made by scaling of the calculated values[6] of $\mathrm{Re}b_l(\varepsilon)$ and $\mathrm{Im}b_l(\varepsilon)$ by constant factors A_l and B_l, respectively. This procedure gives an improved $\chi^2(\sigma_I)$ [Table I, fit B and solid line in Fig. 3(b)], which is significant because $\Delta\chi^2$ is greater than 1/(number of degrees of freedom) ≈ 0.06. Some modifications occur in the values of the amplitudes; but unfortunately the imaginary parts cannot be determined accurately.

As shown by Anholt, Chemin, and Amundsen,[11] compound-elastic (CE) nuclear scattering (caused by the fine structure of the isobaric analog resonance) can have an important effect on P_K at large scattering angles. Because of the low (p,n) threshold for ^{138}Ba (2.58 MeV), the amount of CE scattering is expected to be small at 10.00 MeV.[5] To investigate this question quantitatively, we use the formulation of Anholt, Chemin, and Amundsen[11] to evaluate P_K. The total elastic cross section is written as the sum of the compound-elastic cross section (σ_{CE}) and the direct-elastic cross section (σ_{DE}). With use of Eq. (11) of Ref. 11, σ_{CE} is readily evaluated, and σ_{DE} is again computed with the help of the Seitz formulation.[10] The measured elastic scattering cross section σ_p is now fitted by use of the peak value σ_0 of σ_{CE} as an additional free parameter. The results are displayed in Table I (fits C and D) and plotted in Fig. 3(a), where the solid curve is the total elastic cross sec-

TABLE I. Results of fits to elastic-scattering and ionization cross-section data.[a]

Fit	Nuclear parameters Γ (keV)	Γ_p (keV)	E_R (MeV)	α (rad)	σ_0 (mb)	$\chi^2(\sigma_p)$	Atomic parameters A_0	A_1	B_0	B_1	$\chi^2(\sigma_I)$	$\chi^2(P_K)$
A	68.4	14.9	9.995	3.19	0.0	1.59[b]	1.00	1.00	1.00	1.00	1.37	1.58
B	68.4	14.9	9.995	3.19	0.0	1.59[b]	1.07[c]	0.85	1.00	1.95	1.01	1.33
C	68.0	15.3	9.996	3.38	4.0	1.70	1.00	1.00	1.00	1.00	1.84	1.97
D	68.0	15.3	9.996	3.38	4.0	1.70	1.05[c]	1.04	−2.88	−1.16	1.07	1.65

[a] In the background term $\rho^2 = a_0 + a_1/E_p^2$, the optimal value for a_0 was −30.5 mb for fits A and B, and −29.9 for fits C and D, and for a_1, 4.48 b·MeV^2 for fits A and B, and 4.43 b·MeV^2 for fits C and D. The fits are explained in the text.

[b] The values for χ^2 are per degree of freedom. In the fits varying the nuclear parameters, the number of degrees of freedom is 15 for fits A and B and 14 for fits C and D. There are 18 degrees of freedom for all fits varying the atomic parameters.

[c] In fits B and D, typical errors on the A's are ±0.05, and on the B's, ±1.00.

tion (indistinguishable from fits A and B), and the dashed curve is the CE contribution only ($\sigma_0=4.0$ mb). Although the $\chi^2(\sigma_p)$ value favors the fits with or without CE scattering equally, the fit to the ionization cross section is not as good when CE effects are included (Table I, fit C). If the atomic amplitudes are once more varied for an optimal fit (Table I, fit D), the $\chi^2(\sigma_I)$ value is not quite as good as for fit B. Furthermore, the large negative amplitude factor B_0 does not agree with the off-resonance anisotropy of P_K measured by Wietstruck *et al.*[12] We conclude that $\sigma_0=4.0$ mb represents an upper limit to the CE cross section.

The effect of the nuclear background scattering on P_K in the reaction $p+{}^{138}\mathrm{Ba}$ is discussed by Amundsen and Aashamar[6] in connection with the work of Dost *et al.*,[5] in which ionization probabilities were measured at mean angles of 63° and 117°. Their calculations of P_K with and without nonresonant background scattering are indistinguishable at the forward angle, and only a slight difference in the two cases is seen at the backward angle. At 172°, we find that if nonresonant nuclear scattering is neglected, i.e., ρ^2 is represented by pure Coulomb scattering, the peak value of P_K decreases by 50%.

The data presented here offer an opportunity for the first detailed exploration of atomic-ionization amplitudes.[6] It is in good agreement with calculations including the nuclear background scattering,[13] and is the first experimental work of this type to discriminate cleanly between various contributions to the elastic scattering.

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