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A SOURCE OF POLARIZED ELECTRONS

G. BAUM and U. KOCH

Physikalisches Institut der Universität Bonn

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Investigations on a source of polarized electrons intended for use in an accelerator are reported. An intense potassium atomic beam is polarized to a degree of 0.8 by a magnetic six-pole field. The valence electrons are set free by ultraviolet light of a Xe flash tube. The polarization P of the photoelectrons is measured by Mott scattering at 120 keV. We obtain $P = 0.55 \pm 0.05$. The intensity of the source is 10^7 electrons/pulse with a pulse length of 20 μsec. The maximum possible repetition rate is 50 Hz and will result in 5×10^8 electrons/sec. With a Li atomic beam and improved lamp operation an intensity increase by a factor of 50 is expected.

1. Introduction

A source of polarized electrons would be useful in elementary particle physics for obtaining a more thorough understanding of fundamental interaction processes. For performing experiments at high energies, a source with sufficient degree of polarization ($P > 30\%$) and above all high intensity (minimum 10^{10} electrons/sec) is required. This paper reports on the present stage of development of a polarized electron source intended for use with the 2.5-GeV synchrotron of the University of Bonn.

Photoionization of a polarized atomic beam was chosen from the various methods for producing polarized electrons[1]). This method has the advantage of giving nearly complete polarization and high electron intensity, especially under pulsed operation. The method was suggested by Fues and Hellmann[2]). A first experimental attempt was made by Friedmann[3]), but his data could not be confirmed[4]). During the course of our work, results have been reported by Hughes et al.[5]) (10^8 electrons/μsec, 10 Hz, $P = 0.75$) and Coiffet[6]) (10^{-12} A, $P = 0.9$).

2. Experimental method

The alkali atomic beam is polarized by a strong magnetic six-pole field. Additionally to the separation of the two electronic spin states, the field focuses one of the states[7]) thus giving high intensity. The polarized atoms then pass adiabatically into the ionization region, where the spin of the valence electrons is oriented parallel to the propagation axis by a longitudinal homogenous magnetic field. The field is strong enough to decouple the nuclear moment from the electron moment. This is necessary for maintaining the high electronic beam polarization.

Photoionization is an electric dipole transition, and hence the orientation of the electron spin is unaltered by this process[8]). The ionization efficiency depends on the choice of alkali atom, light source and focusing mirrors.

Among the alkalis high photoionization cross section at high threshold wavelength would be best. The magnitude of the hfs-interaction energy however must also be considered. A high decoupling magnetic field means an enlarged technical effort. In spite of its particularly low cross section, we chose potassium for our first experiment as a compromise between the decoupling field strength (330 G) and the threshold wavelength of the ionization (2855 Å).

Designing the ionization region, care must be taken to suppress unpolarized electrons. As all part of the apparatus in the ionization region are unavoidably covered with potassium, they yield considerably more photoelectrons than the atomic beam itself. For directing the ionizing light into the beam, we use an elliptical cylinder as mirror with the atomic beam in one focal line and the light source in the other. This arrangement provides sufficient clearence between beam and apparatus parts, necessary for an easy suppresion of electrons which would otherwise mask the polarization completely.

A flash tube is used as light source because of its high photon flux. The flash duration can be matched to the injection time of a high energy accelerator.

A longitudinal electric field of 100 V/cm extracts an estimated 99% of the photoelectrons. The electrons are then accelerated to 120 keV for polarization analysis by Mott scattering. As the electrons leave the ionization region with longitudinal spin direction, they pass a "Wien filter" arrangement[9]) which turns the spin perpendicular to the scattering plane. The left-right asymmetry A in scattering is recorded by two semiconductor detectors placed symmetrically to the scattering foil. Their counting rate ratio r is connected to the beam polarization P by $A = (1-r)/(1+r) =$

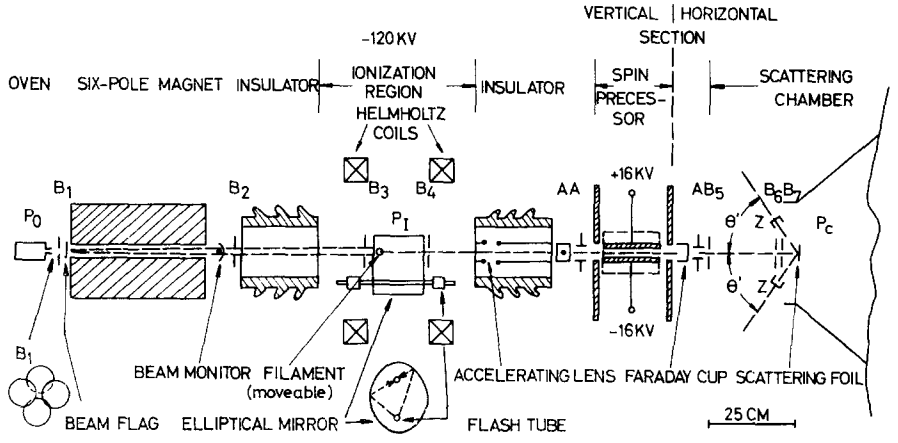

Fig. 1. Sectional view of the whole apparatus, semi schematical (details near the axis not to scale); A: Deflecting plates; B_n: Collimators; Z: Electron detector; Pressure in the vacuum tanks: $p_0 = 5 \times 10^{-6}$, $p_I = 2 \times 10^{-6}$, $p_C = 5 \times 10^{-6}$ Torr.

$= P \cdot S$. The analyzing power S is high for gold foils and shows low angular dependence at the used scattering angle of 125°.

3. Experimental apparatus

3.1. Source of polarized atoms

The oven has a Laval nozzle operating in the region of hydrodynamic flow. Alkali-Laval beams have been shown[10]) to yield at high vapour pressures up to 100 times more intensity, combined with a 30% higher mean velocity, and 2.5 times less velocity spread than conventional beams with Knudsen flow. The basic oven design of ref.[10]) has been modified. The nozzle of 9 mm o. d. is connected by a thin tube, 3 mm long, to the oven. The nozzle is heated separately by a coil of Thermocoax isolated heating wire (Philips) to a temperature of about 100 °C higher than the oven. This is important for forming a good Laval beam. The oven has a capacity for 10 g potassium and is emptied in 5 h through the orifice of 0.2 mm dia. at an operating temperature of 500 °C (vapour pressure 30 Torr).

The beam defining collimator is nitrogen cooled and consists of four overlapping rotating disks, leaving an aperture of 1.5×1 mm^2 in the centre (B_1 in fig. 1)[11]). Scrapers keep the disk edges clean, to avoid plugging of the collimator. Through the efficient condensation of unwanted beam parts, the background of potassium atoms is kept low in spite of the high intensity. Thus beam attenuation by scattering in the oven chamber is minimized.

The six-pole magnet (32 cm field length) provides parallel exit of the focused beam component. The gap diameter is $2\,r_0 = 10$ mm and matches the beam diameter to the diameter of the light source image. Fig. 2 shows the layout of the magnet designed to give a high peak field H_0 at the pole faces, necessary for focusing a large solid angle. At 200 A coil current the magnet is saturated. The radial dependence of the magnetic field was measured with a rotating coil (0.5 mm diameter) and agreement with $H \propto r^2$ was shown within 5%. Extrapolation of the measured field to r_0 yields $H_0 = 12$ kG.

The magnet accepts atoms of velocity 10^5 cm/sec within a solid angle of 1 msr. The defocused atoms are condensed on nitrogen cooled collimators at the magnet exit (B_2) and the ionization region entrance (B_3). A fraction of 1/10 of the defocused atoms stays in the beam, as is estimated from the six-pole data. Thus a theoretical atomic beam polarization of 0.9 is given.

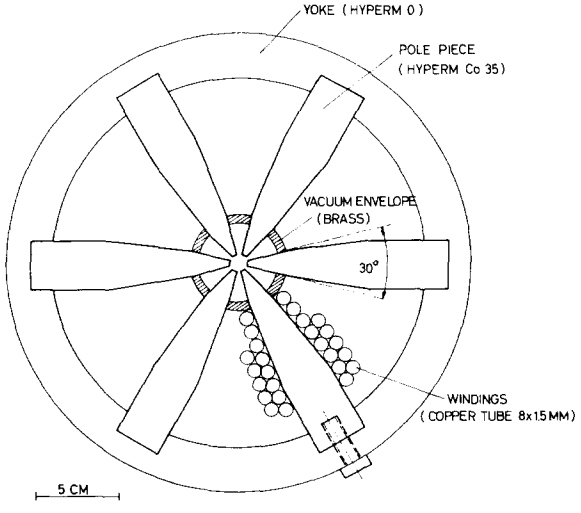

Fig. 2. Cross section of the six-pole magnet.

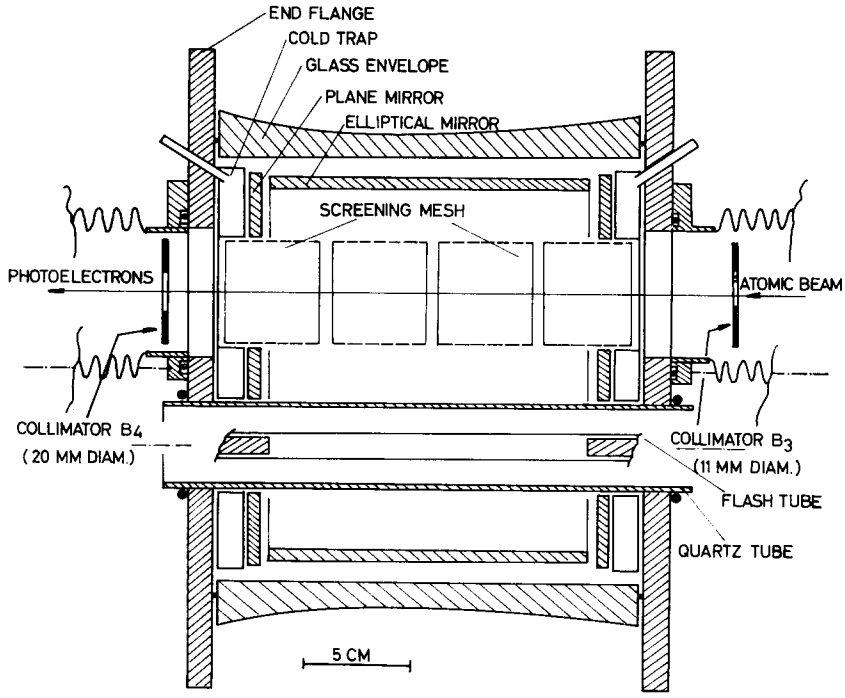

Fig. 3. Longitudinal section of the ionization region.

With a removable Langmuir-Taylor detector, the intensity is monitored at the six-pole exit. We measured a polarized beam current of 3.5×10^{14} at/sec · cm^2 through the ionization region at the typical oven temperature of 500 °C, corresponding to a density $\rho = 3.7 \times 10^9$ at/cm^3. This is 20 times more than obtainable with a standard beam assuming equal deflecting conditions in the six-pole magnet.

3.2. Ionization region

The ionization region (fig. 3) has a potential of −120 kV against ground to provide suitable energy for Mott scattering or injection of the electrons into a linear accelerator. Through a ceramic insulating tube, the polarized atomic beam reaches the ionization region, where it is surrounded by a cylindrical stainless steel mesh (80% transparency) for screening from electrical stray fields. A total potential of 2 kV is divided onto the mesh sections and produces an axial electric field of 100 V/cm for extracting the photoelectrons from the interaction region. An electron lens, mounted in the second ceramic insulating tube, then accelerates the polarized electrons to ground potential. Two Helmholtz coils produce the homogenous axial decoupling field of 500 G. The field guides and focuses the photoelectrons. Together with the exit collimator (B_4 in fig. 1), it discriminates effectively against electrons not coming from the atomic beam.

The focusing mirror is a glass cylinder 150 mm long with elliptical cross section. The distance of the focal lines is 72 mm, the maximum diameter is 167 mm. The inner surface is covered with dielectric multilayers, having their reflection maximum at 2600 Å with a half-width of 600 Å (fig. 5b). Transparency to visible and near infrared avoids heating up. The mirror was manufactured by Schott & Gen., Mainz. From the focusing geometry it follows[12]), that the image of the light source has a 40% larger diameter than the light source itself.

The light source is a linear xenon flash tube (Edgerton, G. & G. type FX-65A) with an arc of 15 cm length and 7 mm diameter. It discharges a 80 μF capacitor resonantly recharged to 2 kV. Power supply and lamp water cooling allow a repetition rate of max. 50 Hz. For the present measurement it was run with 5 Hz. The spectral intensity distribution (fig. 5a) was measured with a Zeiss double monochromator and a Na-photocell, calibrated absolutely with a Philips UV-standard lamp. The light pulse length shows a spectral dependence: it rises from 15 μsec at 2600 Å to 40 μsec at 2750 Å.

The discharge current is returned coaxially by four

copper bars, placed symmetrically around the lamp axis, thus avoiding a disturbance of the decoupling field. The flash tube is separated from vacuum by a quartz tube (suprasil). The space in between can be filled with filtering liquids. For testing purposes, it is possible to replace the flash tube by a cw-operated lamp.

The power for the flash lamp and the Helmholtz coils is provided by a generator driven with an insulating belt; cooling is provided by a closed circuit distilled water system.

3.3. Detector section

The spin precessor consists of crossed homogenous electric and magnetic fields, both oriented perpendicular to the electron velocity. The magnetic field is provided by a C-magnet with pole piece cross section 176×145 mm^2. Two iron end plates, of 30 cm dia. with holes for beam passage, give a steep field decrease at both ends of the magnet to guarantee nonadiabatic transition of the electron spin. The effective field length was measured to be 186 mm. The condensor plates (size: 200×40 mm^2) for the electric field are mounted inside the 65 mm gap of the magnet. They are spaced 14 mm apart; over 25 mm on both ends the gap distance increases smoothly to max. 26 mm to match the magnetic field decrease. A high voltage of 32 kV, applied symmetrically to the plates, and a magnetic field of 128 G are needed to rotate the spin of 120 keV-electrons by 90° from longitudinal to transversal direction.

The scattering chamber for polarization measurement is 70 cm long and has a maximum dia. of 85 cm. The unscattered beam part is stopped 90 cm away from the electron detectors. Metal parts visible to the detectors are covered with plastic painted with hydrocollag. The large size of the chamber and its walls with low backscattering coefficient are necessary for reducing the number of background electrons which can present a major source of error in Mott scattering. As the analyzing power of the Mott detector is diminished considerably by multiple scattering in the foil, we calibrated it using the method of extrapolation to zero foil thickness[13]). The three exchangeable, self-supporting gold foils (0.17, 0.28, 0.55 mg/cm^2) of 13 mm dia. are oriented perpendicular to the beam axis. The two surface barrier detectors (Ortec, type SBEE 025-300), with a utilized sensitive area of 3 mm dia., accept scattering angles of 127°. The solid angle of 1 msr definitely avoids overloading of the counting electronics in every operating condition.

The electron beam enters the scattering chamber through an aperture of 3 mm dia. (B_5 in fig. 1), located 25 cm before the foil. Two vertical slits, 3.5×7 (B_6) and 3×6 mm^2 (B_7), 6 cm respectively 4 cm before the foil, further fix the scattering geometry. As checked experimentally, changes of the counting rate ratio due to beam shifting or inclination thus stay below 1%. The stray field of the Helmholtz coils is shielded with iron and permalloy sheets. A compensating coil additionally diminishes the field in the scattering region to less than 0.3 G.

The two identical branches of the conventional counting electronics have a maximum counting rate of 100 kHz. A special device directly displays the counting rate ratio. The energy resolution of the detecting system is $\Delta E/E = 16\%$, and the spectrum is checked frequently during measurements with a multichannel analyzer.

3.4. Adjustments

All adjustable parts of the apparatus as oven nozzle, atomic beam collimators, focal line of the mirror, accelerating lens, condenser plates of the spin precessor, scattering collimators, foil changer, and electron detectors were aligned to the axis of the six-pole magnet with a telescope. For adjusting the decoupling field axis, and for setting the magnetic field of the spin precessor perpendicular to its electric field, we used an electron beam from a filament in the ionization region, watched on a screen at the foil changer. This beam was also used to find the magnetic field corresponding to the electric field in the spin precessor. Beam losses were minimized, for any combination of spin precessor and decoupling field directions, with three pairs of deflecting plates (A in fig. 1), mounted at entrance and exit of the spin precessor. The counting electronics was also adjusted and checked with the thermal electron beam.

4. Polarization measurements

For obtaining one polarization value, the counting rate ratio r – resulting from 2000 counts – is measured repeatedly and in alternating order in six different field settings, which arise from the combinations of the two decoupling field directions with the spin directions turned "up" (↑), "down" (↓) or unchanged (0). Thus one gets twice the rates $r(\uparrow)$, $r(\downarrow)$, r_0. The values for r_0, which give the instrumental asymmetry, are consistent within the measurement accuracy with the calculated

$$\{r(\uparrow) \cdot r(\downarrow)\}^{\frac{1}{2}}$$

values and with the instrumental asymmetry measured before with the filament electron beam. For data evaluation we average over all experimental r and the final

$$r_t = \{r_{av.}(\uparrow)/r_{av.}(\downarrow)\}^{\frac{1}{2}}$$

is independent of instrumental asymmetries.

The correction for multiple scattering of 120 keV electrons in the foil of 0.17 mg/cm^2 amounts to a relative reduction of the analyzing power S by $\Delta S/S = 0.2 \pm 0.05$. This was found experimentally[13]) and checked by calculations[14]). Together with the theoretical value[15]) we have an effective $S = 0.32 \pm 0.02$.

4.1. Effects reducing polarization

The first experiments performed with the continuous lamp showed an electron beam polarization of $P = 0.3$. This was considerably below the expected value of $P = 0.9$. We investigated three processes which can diminish the electron polarization:

1. Ionization of the potassium atoms out of a level already exited by a light quantum (two-step process). The orientation of the electron spin is disturbed in the exited level by fine structure interaction;
2. Ionization of K_2-molecules. The molecules are not separated in the six-pole magnet and even small fractions reduce the polarization considerably since the K_2 ionization cross section is about 1000 times higher than for potassium atoms[16]);
3. Reduced atomic beam polarization by insufficient separation in the six-pole magnet.

Long et al.[17]) have first pointed to the influence of effects 1. and 2.

4.1.1. *Two-step ionization process*

By filtering the light of the cw-lamp with a nickel sulfate solution[18]), which absorbs the visible and infrared light and reduces therefore the two-step ionization, we raised the polarization from 0.3 to 0.45 (thickness of the filter layer $D = 5$ mm, concentration $C = 450$ g $NiSO_4 \cdot 7\ H_2O$/1000 cm^3 H_2O).

First measurements with the flash tube and unfiltered light showed no polarization. The light intensity of the flash tube is substantially higher than that of the cw-lamp (approx. 3 MW pulse-power compared with 3 kW cw-power). The number of electrons which are ionized by the two-step process raises with the square of the light quanta density, whereas the number of electrons ionized by one photon only increases linearly. Therefore the polarization by the electron beam produced with unfiltered flash light is completely masked.

Filtering the flash light with $NiSO_4$-solution (fig. 5b) we obtained a beam polarization $P = 0.55$ ($D = 11$ mm, $C = 850$ g/1000 cm^3 H_2O). This filter seems to be strong enough to suppress the two-step processes. There is no further rise of the polarization if we use a filter which absorbs the disturbing light even stronger[18]) ($D = 11$ mm, $C = 680$ g $NiSO_4 \cdot 7\ H_2O + 160$ g $CoSO_4 \cdot 7\ H_2O$/1000 cm^3 H_2O).

4.1.2. K_2-*molecules*

The K_2 content in the beam can be influenced by the nozzle temperature of the oven, on which the molecules thermally dissociate at higher temperatures. An increase of the nozzle temperature from 600 °C up to 700 °C only raised the polarization by a factor of 1.2 ± 0.15. It is estimated that the content of K_2 in the beam is less than 3 ‰.

4.1.3. *Atomic beam polarization*

The atomic beam polarization was investigated with a central obstacle of 1 mm dia. at the six-pole entrance. This obstacle reduces the intensity by 30% and stops besides others those atoms which are not strongly enough defocused in the magnet and which therefore are not separated. Bringing the obstacle on the axis yielded an increase of the electron polarization by a factor 1.25 (cw-lamp measurements). From this polarization increase one can conclude that the atomic beam polarization without central obstacle is $P_A \leqq 0.8$ and that the separation of the six-pole magnet is not as good as was expected from the magnet data.

An explanation for this may be that the source of the atomic beam is a relatively large "luminous area" (Mach disc)[19]). From the outlines of condensed

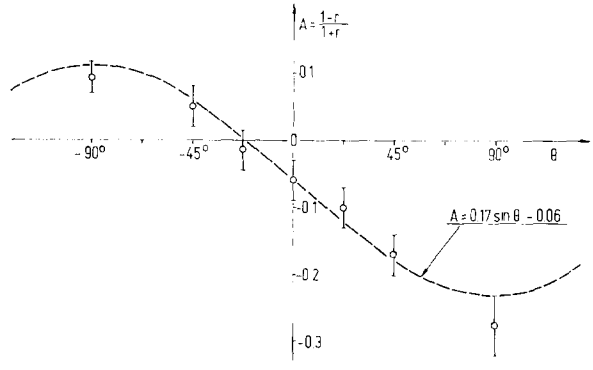

Fig. 4. Polarization asymmetry A recorded by transferring the electron spin direction in steps from +90° (up) to −90° (down).

potassium on the six-pole entrance diaphragm, we estimated the dia. of this disc to be 1.2 mm. Of course with such a large source area the fraction of the not separated atoms can be considerably larger than with a point like source.

4.2. Results

The result of the polarization measurement on the electron beam by ionizing the atomic beam with the flash tube and filtering the light with the $NiSO_4$-solution is

$$P = 0.55 \pm 0.05.$$

This value is an average over all measurements at 120 keV electron energy, 127° scattering angle, 0.17 mg/cm² foil thickness, and the typical temperatures 500 °C oven and 600 °C nozzle. Fig. 4 gives an example of a special measurement to show the polarization asymmetry involved in Mott scattering of our beam.

The total error of $\Delta P/P \approx 10\%$ results from: 4% statistical counting error, 3% error due to uncertainty of the scattering geometry, and 6% error in analyzing power. The background of unpolarized electrons was measured frequently by stopping the atomic beam with a beam flag near the six-pole entrance. It never exceeded 5%. Together with an atomic beam polarization of $P_A = 0.8$, one expects theoretically an electron polarization of 0.75. The discrepancy is not yet understood.

5. Intensity

The intensity of the pulsed electron beam with the polarization $P = 0.55$ is measured with a Faraday cup, located between spin precessor and Mott chamber. The diameter of the beam at this place is estimated to be 10 mm. The cup has a removable bottom, so that intensity and polarization can be obtained without breaking the vacuum. The resulting voltage pulse was observed with an oscilloscope. At the typical oven conditions we measured an intensity of

$$I = 10^7 \text{ electrons/pulse}.$$

This corresponds to a pulse current of about 8×10^{-8} A. Comparing it with the atomic beam density $\rho = 3.7 \times 10^9$ at/cm³, one sees that a fraction $w = 2 \times 10^{-4}$ of the atoms in the interaction volume $V = 15$ cm³ is ionized by one flash: $I = w\rho V$.

This measured w was checked by calculation:

$$w = f(d/V) \int_0^{\lambda_{\text{thres.}}} J(\lambda) \cdot T(\lambda) \cdot R(\lambda) \cdot \sigma(\lambda) \, d\lambda,$$

in which $d = 0.75$ cm is the average photon-atom interaction length and f the fraction of the flash tube radiation reaching the interaction region. The spectral dependence of w is shown in fig. 5d, obtained by using the values of $J(\lambda)$ from fig. 5a, $T(\lambda)$ and $R(\lambda)$ from fig. 5b, and $\sigma(\lambda)$[16]) from fig. 5c. A great uncertainty

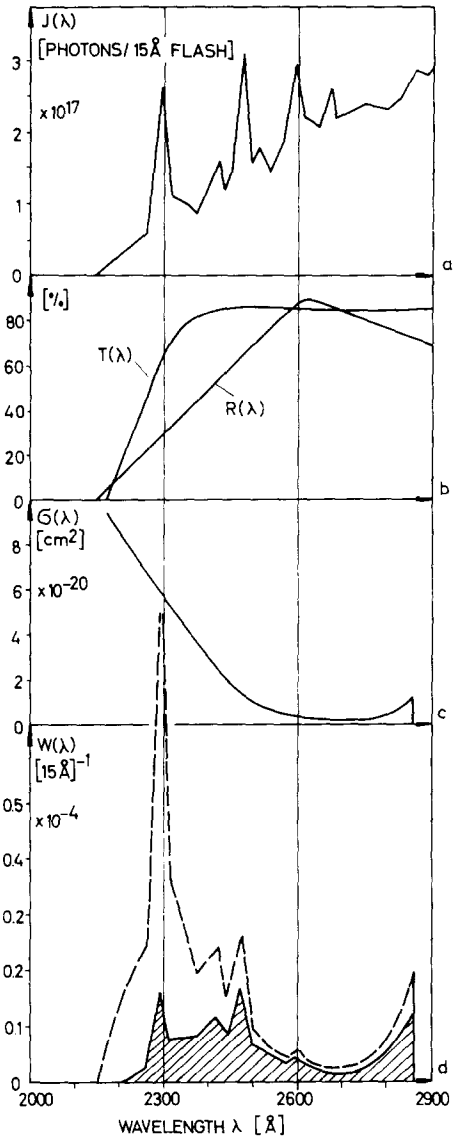

Fig. 5. Determination of the ionization probability.
a. Photon number $J(\lambda)$ radiated per 15 Å and pulse by the flash tube;
b. Reflection coefficient $R(\lambda)$ of the elliptical mirror and transparency $T(\lambda)$ of the nickel sulfate filter solution;
c. Photoionization cross section $\sigma(\lambda)$ of potassium;
d. Spectral dependence of the ionization probability w with (——) and without (– – –) regard to losses by mirror and filter solution.

comes from the estimation of f. From the relative spectral dependence of w it is seen that dominantly the region about 2400 Å contributes to the intensity. The mirror reflection coefficient here is already below 0.5, so that we only have to account for quanta which reach the interaction region by one reflection. This gives a used solid angle of the flash tube radiation of 1.75 sr. Considering further absorbtion by the stainless steel mesh (20%) and by the current return bars (10%) we have $f = 0.13$. The evaluation of fig. 5d gives $w = 3 \times 10^{-4}$, a satisfying agreement with the measured value.

Using lithium with its high photoionization cross section (about 2 Megabarn) and moderate decoupling field strength (^{7}Li: 575 G), but low ionization threshold (2300 Å)[20]), the polarized electron intensity can be increased as has been shown by Hughes et al.[5]). In our set-up the following modifications will be made for ionizing lithium. The mirror will be coated with layers reflecting below 2300 Å. The lamp will be operated with a higher voltage in the double pulsing technique[21]), giving more efficiency in the UV and shorter pulse lengths (approx. 1 μsec). We expect to achieve a ionization probability of 10^{-2} corresponding to 5×10^8 electrons/pulse.

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References

1) For a review on this subject see, e.g. P. S. Farago, *Advances in electronics and electron physics* **21** (ed. L. Marton; Academic Press, New York, 1965) p. 1.

2) E. Fues and H. Hellmann, Physik. Z. **31** (1930) 465.

3) H. Friedmann, Sitzber. Bayr. Akad. Wiss. (München, 1961) 13.

4) F. Bopp, D. Maison, G. Regenfus and H. Chr. Siegmann, Z. Physik **185** (1965) 48.

5) V. W. Hughes, M. S. Lubell, M. Posner and W. Raith, Proc. 6th Intern. Conf. *High Energy Accelerators*, Sept. 1967, Cambridge (Cambridge, 1967) p. A-144.

6) P. Coiffet, CR Acad. Sci. B **264** (1967) 454.

7) H. Friedburg and W. Paul, Naturw. **38** (1951) 159.

8) N. F. Mott and H. S. W. Massey, *The theory of atomic collisions*, 2nd ed. (Clarendon Press, Oxford, 1949) p. 65.

9) H. Frauenfelder and A. Rossi, in *Methods of experimental physics* **5B** (ed. L. Marton; Academic Press, New York, 1963) p. 214.

10) E. Hundhausen and H. Pauly, Z. Naturf. **20a** (1965) 625.

11) A similar arrangement is described by E. Hundhausen and H. Harrison, Rev. Sci. Instr. **38** (1967) 131.

12) S. B. Schuldt and R L. Aagard, Appl. Optics **2** (1963) 509.

13) A. R. Brosi, A. I. Galonsky, B. H. Ketelle and H. B. Willard, Nuclear Physics **33** (1962) 353.

14) H. Wegener, Z. Physik **151** (1958) 252.

15) G. Holzwarth and H. J. Meister, Nuclear Physics **59** (1964) 56; and *Tables of asymmetry for Mott scattering of electrons by screened gold nuclei* (Univ. München, March 1964).

16) R. D. Hudson and V. L. Carter, Phys. Rev. **139** A (1965) 1426.

17) R. L. Long, W. Raith and V. W. Hughes, Phys. Rev. Letters **15** (1965) 1.

18) H. Meyer and E. O. Seitz, *Ultraviolette Strahlen*, 2nd ed. (W. de Gruyter, Berlin, 1949) p. 140; and M. Kasha, J. Opt. Soc. Am. **38** (1948) 929.

19) K. Bier and O. Hagena, Proc. 3rd Intern. Symp. *Rarefield gas dynamics* **1** (ed. J. A. Laurmann; Academic Press, New York, 1963) p. 478.

20) For alkali photoionization data see, e.g. J. A. R. Samson, *Adv. atomic molecular physics* **2** (1966) 240.

21) J. L. Emmet and A. L. Schawlow, Appl. Phys. Letters **2** (1963) 204.