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Electron Scattering and Photonuclear Reactions at the MIT Bates Linac

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Abstract

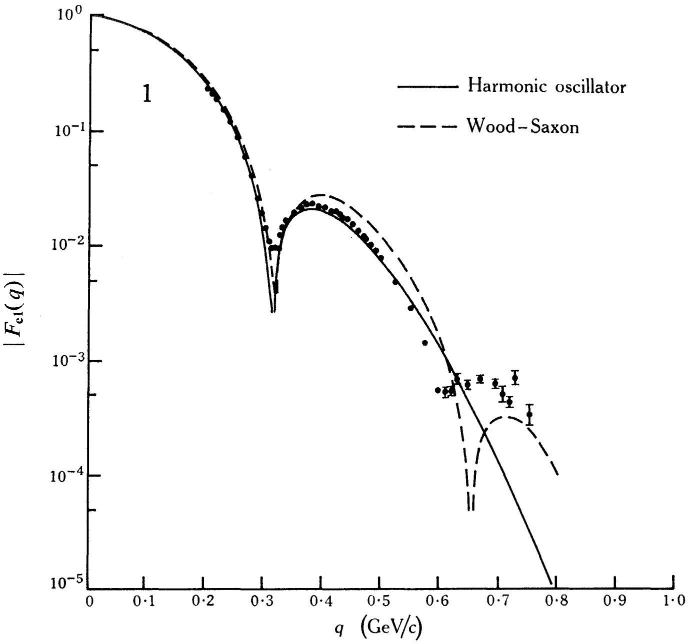
Progress is reported in the development of the Bates Electron Linear Accelerator Facility at MIT. Preliminary data are shown for high resolution electron scattering, and for the high energy photoproton reaction on ^{16}O and the threshold photoproduction of pions on ^{12}C and ^{11}B.

1. Introduction

In this paper I give a progress report on the development of the MIT Bates electron linear accelerator facility, and on the initial research program in electron scattering and high energy photonuclear reactions. This facility has been a long time in coming: the first proposal was submitted to the U.S. Government in 1961; construction on the buildings was started and the first subcontracts for the accelerator hardware were let in late 1967; the first beam was accelerated through the entire accelerator in March 1973, and research on photopion production started that summer; the big (900 MeV/c) spectrometer was assembled by late summer 1974, and the first high resolution data in electron scattering were produced as a mutual Christmas present a few months later. Even though we have yet to operate at full design specifications, as I hope to show you, both the quality and quantity of data which are beginning to emerge indicate that our design specifications will be met, and that the utility of the electromagnetic probe for nuclear structure studies will be realized on a large scale. The present paper is organized around three questions: (1) Why did we build the laboratory? (2) What has been built so far? (3) What is coming out of it?

2. General Objectives

The most general answer to the first question (why did we build the laboratory?) is given in every physics catechism: to study unknown structures, use a probe whose properties are understood and whose interaction with the structure is weak enough for us to use with confidence perturbation theory. The electromagnetic field is the classic example, of course, and there are many articles in the literature in which these arguments are developed in detail with numerous beautiful examples (see e.g. deForest and Walecka 1966; Überall 1971; Donnelly and Walecka 1975, and references therein). Some, if not most, of the benchmarks of nuclear physics are based on the use of the electromagnetic probe. Some examples are: collective degrees of freedom—the E1 and other giant resonances; sizes and shapes of nuclear charge and magnetization distributions—nuclear microscopy.



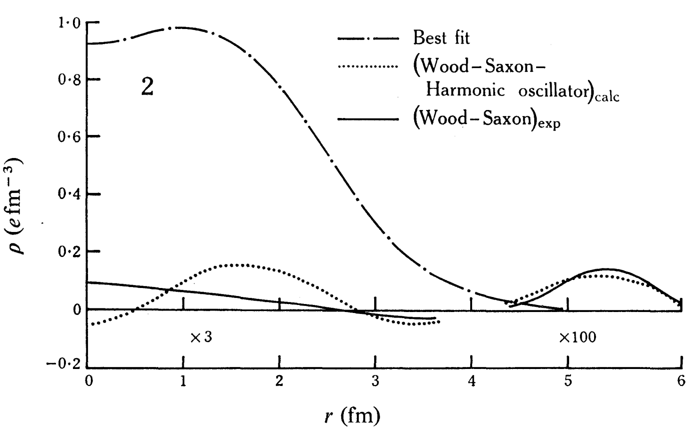


Fig. 1. Elastic charge form factor for ^{16}O, showing theoretical wave functions (Donnelly and Walker 1969) and experimental data (Sick and McCarthy 1970).

Fig. 2. Charge distribution for ^{16}O based on the experimental data of Sick and McCarthy (1970).

Although there is no disagreement on this general proposition, indeed it has attained the status of a cliché, only a small fraction of the community of experimental nuclear physicists (heroes of the republic) has attempted to exploit it. I exclude the legions of classical γ-ray spectroscopists who, with the development of the Ge–Li detector, continue to make interesting systematic contributions. There are many reasons for this lamentable state of affairs, the chief one being the low cross sections, which are of order α^2 compared with hadronic cross sections. What simplifies the theorist's job produces experimental nightmares.

It is instructive to look in some detail at a particularly favourable example: elastic electron scattering from ^{16}O. Here we have $\alpha Z \approx 0{\cdot}06$, so that the first Born approximation is pretty good and, since the ground state of ^{16}O has spin 0, the cross section is determined by the Coulomb monopole and is simply written:

$$d^2\sigma/d\Omega\, dE = \sigma_M\, |F_{el}(q^2)|^2, \tag{1}$$

where the point charge (Mott) cross section σ_M and the elastic form factor F_{el} are

$$\sigma_M \approx \frac{2Z^2}{(E/M)^2}\frac{\cos^2(\frac{1}{2}\theta)}{\sin^4(\frac{1}{2}\theta)} \times 10^{-26}\ \ \mathrm{cm}^2, \qquad F_{el} = \int \left\{\frac{\sin(qr)}{qr}\right\} \rho(r)\, d^3r, \tag{2a, b}$$

with $\boldsymbol{q} = \boldsymbol{k}_1 - \boldsymbol{k}_2$, the momentum transfer, while $\rho(r)$ is the radial distribution of the charge density. Fig. 1 shows the elastic form factor derived from some data for ^{16}O obtained at Stanford by Sick and McCarthy (1970). Also shown in Fig. 1 are form factors calculated by Donnelly and Walker (1969) using harmonic oscillator wave functions, and those derived from a finite-well nuclear potential of the Wood–Saxon type. Fig. 2 shows the charge densities derived from each of these wave functions as well as the best phenomenological fit. The sensitivity of such data to fine details of the wave function is apparent, as is the simplicity of the connection between the wave function and the cross section. There is by now a considerable theoretical literature provoked by these data which I will not review (see Überall 1971).

My purpose in discussing this example is to reveal its implications for experimental facilities attempting to get similar data for an arbitrary nucleus. First, note that the oscillator form factor looks pretty good up to 500 MeV/c and that the higher q data provide important information (the central depression at small r in the phenomenological fit comes from the high q data). Since $q = 2E\sin(\frac{1}{2}\theta)$, it is clear that, to get $q = 800$ MeV/c, one needs at least 400 MeV in the beam if $\theta = 180°$. Here $\sigma_M = 0$, owing to the $\cos(\frac{1}{2}\theta)$ term in the numerator, and the clear requirement is for higher energy since, for a given q, the angular variation is faster than the E^{-2} factor. The situation is more complicated if the target spin is not 0, since higher multipoles can contribute to elastic scattering, but the general conclusion remains unchanged. In the above example, for 570 MeV electrons scattered through 90° ($q = 800$ MeV/c), the cross section is 5×10^{-31} cm^2 from σ_M multiplied by 4×10^{-7} from the form factor, giving a total of 2×10^{-37} cm^2, which approaches neutrino size. Since the first excited state of ^{16}O is at 6 MeV, the elastic cross section can be measured unambiguously if the system resolution is 4 MeV or better. At 570 MeV, this is not much better than 1%, so that most of the electron beam for the Stanford Mark III accelerator could be used; i.e. an average current $\bar{I}$ of about 1 μA. Other sources of energy spread clearly must be kept sufficiently low so as not to compromise this resolution. There is no difficulty in achieving with quite crude magnetic analysers a resolution of a few tenths of a per cent at a solid angle acceptance Ω of 1 msr or somewhat larger. The final source of energy spread is energy-loss straggling in the target, which otherwise should be thick to maximize the counting rate. To keep this source of energy spread below 3 MeV, the target should be less than 12 MeV thick (or 6 g cm^{-2}). Putting all the factors together, we have: $\sigma = 2\times10^{-37}$ cm^2,

$\bar{I} = 6\times10^{12}\ \mathrm{s}^{-1}$ (1 μA), $\Omega = 10^{-3}$ sr and $N \approx 2\times10^{23}$ atoms cm^{-2}. We thus get a counting rate of $2\cdot4\times10^{-4}\ \mathrm{s}^{-1}$, or about 1 per hour, so that if one is confident that the background from the beam dump and other sources is no larger, a day's run yields the highest q point in Fig. 1. I don't claim this to be an accurate account of how those data were obtained. It might have been worse or a little better, but I think the point is clear: the next decade in the form factor of ^{16}O was not available. Then, what about ^{19}F whose first excited state is at 110 keV excitation, or inelastic scattering to the 0^+, 3^- doublet in ^{16}O at about 6 MeV whose separation is 80 keV?

The lesson of the above example, on which the Bates design specifications were based, is that one wants 400 MeV or higher, 100 μA on target at least, and a system resolution of 10^{-4} or better. As I show in Section 4*b* below, similar beam characteristics are desirable for photon induced reactions. In addition, since in detectors the random pile-up is proportional to I^2, where I is the peak beam intensity (whereas the real event rate is linear in I), the signal-to-noise ratio is therefore directly proportional to the beam duty factor in a two-fold coincidence experiment (see e.g. Barber 1962; Bertozzi 1969). For an n-fold coincidence, as in counter telescopes and/or trying to determine the complete kinematics in a many-body final state, the signal-to-noise ratio is a stronger function of the duty factor. The technology for economical high energy, high intensity machines with 100% duty factor is still under development (McAsham *et al.* 1973), but at the time we were planning the Bates laboratory more or less conventional technology was available to produce high power RF at duty factors of a few per cent. This is an improvement of about 100 over the linacs of the 1950s and early 1960s (e.g. at Stanford, Orsay, Mainz, Tohoku) and moves certain experiments from the class of impossible to difficult.

Table 1. Bates accelerator design objectives

Operation at klystron total power	10—40 MW
Beam energy (max. unloaded)	220—440 MeV
Beam energy (10% loaded)	198—396 MeV
Peak beam current (10% loaded)	7—16 mA
Duty ratio	5·8%—1·8%
Pulse length (max.)	15 μs
Repetition rate (max.)	5000 Hz
Energy spread (50% current)	±0·2%

3. Design Specifications and Performance to Date

Detailed descriptions of the Bates accelerator and its French counterpart, its most formidable competitor, have been published (Bertozzi *et al.* 1967*a*; Haimson 1970). Table 1 lists the most important design objectives of the Bates accelerator. The majority of these have been met or exceeded, but we have yet to operate the system at full peak and average power. This is partly because neither the beam switchyard (BSY) nor experimental equipment are yet capable of handling very high average beam power (> 10 kW), but also because prudence has required that a careful eye be kept on the stock of expensive klystrons and switchtubes and the power-demand monitor. One of the main objectives for the coming year [1975] will be to bring the accelerator into operation at full specification.

The first major experimental facility to be constructed is the high resolution spectrometer (Bertozzi *et al.* 1967*b*; Kowalski 1973). This spectrometer and the BSY are designed to operate at a resolution of 10^{-4}, even though the energy spread in the incident beam may be as much as 5×10^{-3}. This is done by matching the dispersion and magnification of the spectrometer to that of the BSY, so that the location of a scattered electron at the focal surface is determined by the energy lost by the scattered electron and not by the energy it had when incident on the target.

Table 2. MIT energy loss spectrometer

Maximum momentum		900 MeV/c
Maximum field		1·45 T
Mean radius		2·23 m
Deflection angle		±45°
Entrance face rotation	D1	13·5°
	D2	3·0°
Exit face rotation	D1	3·0°
	D2	13·5°
Entrance face curvature	D1	−0·727 m
	D2	1·543 m
Exit face curvature	D1	1·543 m
	D2	−1·013 m
Object distance		3·40 m
Image distance		3·40 m
Gap		0·20 m
Field parameters	n	0
	β	0
Focal plane angle		45°
Beam momentum uncertainty (design)		1%
Momentum acceptance (nominal)		10%
Intrinsic resolution	$\Delta p/p = 2\%$	$1\cdot0\times10^{-4}$
	$\Delta p/p = 10\%$	$3\cdot0\times10^{-4}$
Median plane focusing		pt → pt
Transverse plane focusing		11 → pt
Median plane magnification		−1
Transverse plane magnification		—
Dispersion (⊥ reference trajectory)		6·60 cm $(\%)^{-1}$
Solid angle		5·4 msr

The design specifications of the spectrometer are indicated in Table 2. As with the accelerator, it appears that the full design specification should be achieved, and possibly exceeded. There is to date no indication that the resolution is being limited by the spectrometer optics, although to get the best resolution we have achieved to date ($\sim1\cdot0\times10^{-4}$) it is necessary to iterate the BSY magnet adjustments around the computed solution. Fig. 3 shows some early data taken on a target of ^{27}Al. From these spectra, taken in a few hours with some 15 μA on target, it is plain that electron scattering has come of age.

4. Some Preliminary Research Results

(*a*) *Electron Scattering*

It is too early to report final results of electron scattering for any target, since we have been taking data only for a few months, and part of this time has been dedicated to tuning up the system, debugging programs, electronics, etc. We do have data on targets of ^{12}C, ^{13}C, ^{9}Be, ^{16}O, ^{19}F, ^{181}Ta, ^{27}Al, ^{156}Gd, ^{166}Er, ^{176}Yb and ^{150}Nd at incident energies between 50 and 320 MeV, and at scattering angles of 60°, 90° and 140°. For some high q data we have worked with 50 μA on target, with an anxious eye on the slit vacuum system. Among these targets I have selected ^{16}O

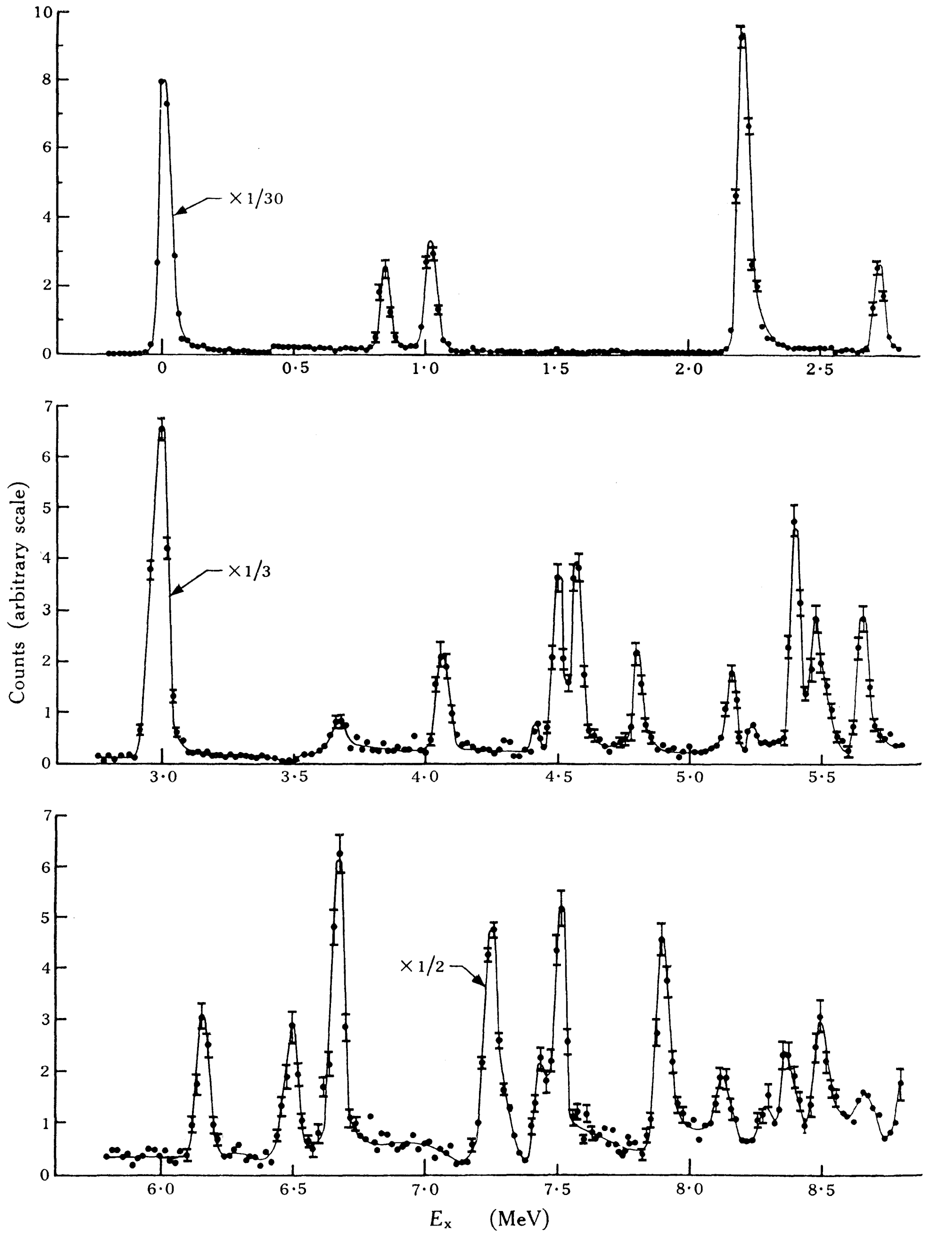
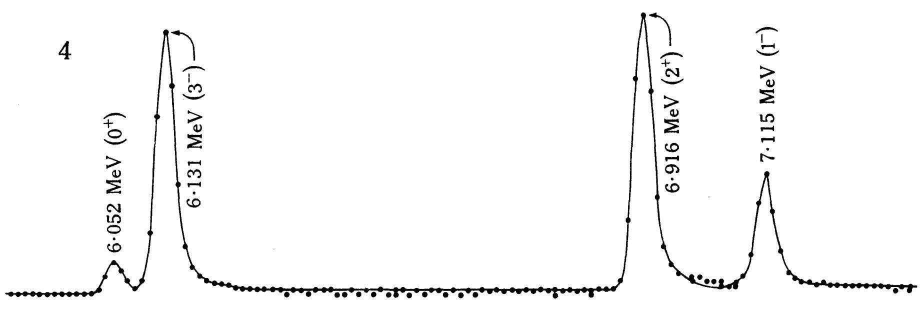


Fig. 3. Spectrum of scattered electrons from ^{27}Al measured at the Bates laboratory using an incident beam energy of 248 MeV, with the spectrometer set at a scattering angle of 70°.

and ^{166}Er to illustrate the kind of information on nuclear structures that is now becoming available almost routinely. A few years ago, working with the NBS group we studied the form factor for the 0^+ state in ^{16}O at 6·05 MeV (Bergstrom *et al.* 1970). This state lies 80 keV away from a 3^- state which has a very strong radiation width to the ground state and was barely resolved at 60 MeV. (Fig. 4 shows recent Bates electron scattering data.) The NBS data and the phenomenological model used to describe them provoked a careful calculation of the O^+ form factor (Ericson 1971) using the shell model wave function of Brown and Green (1966). Ericson also



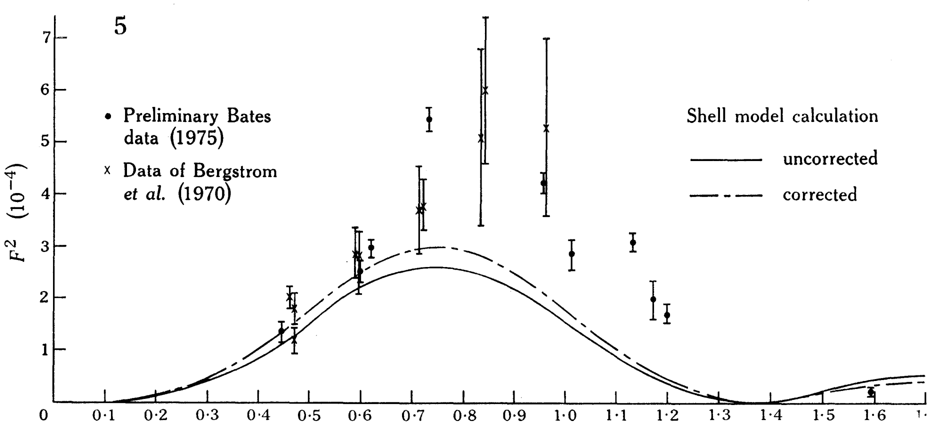


Fig. 4. Spectrum of scattered electrons from ^{16}O at 70° using a 148 MeV beam. The scales are arbitrary but linear.

Fig. 5. Comparison of experimental and theoretical results for the square of the form factor for the 0^+(6·052 MeV) state in ^{16}O. The curves (from Ericson 1971) were calculated using wave functions of Brown and Green (1966), with and without 1p–1h and 3p–3h corrections as indicated.

included 1p–1h and 3p–3h components in his calculations. He concluded that, while the scale of the form factor was perhaps too sensitive to small details of the wave function owing to extensive cancellation, the location of the first minimum could be a useful indicator of the importance (or not) of 3p–3h and 1p–1h components in the ^{16}O wave function. This is shown in Fig. 5 with the old NBS and the new, preliminary, Bates data. It would appear that more work is needed on this state. Such data will provide an unambiguous, and unforgiving, test of nuclear wave functions offered by theorists.

Another interesting class of nuclei for which the microscopic theory is still in its infancy (Vautherin 1973) is the class of nuclei with large permanent deformations and well-developed rotational spectra: the rare earths and actinides. A useful description of such nuclei starts with the notion of an intrinsic state $|K_i\rangle$ upon which rotational bands are built. For such an object we can define a transition charge density $\rho_L^{\mathrm{tr}}(r)$ as follows:

$$\rho_L^{\mathrm{tr}}(r) = \int \langle K_f \,|\, \rho^{\mathrm{op}} \,|\, K_i \rangle_{K_f - K_i}^{L} \, \mathrm{d}\Omega \tag{3}$$

where, for transitions within a rotational band ($K_f = K_i$),

$$\rho_L^{\mathrm{tr}}(r) = \int \rho(r,\theta)\, \mathrm{Y}_0^L \, \mathrm{d}\Omega . \tag{4}$$

Here $\rho(r,\theta) = \langle K \,|\, \rho^{\mathrm{op}} \,|\, K \rangle$ is the charge density of the intrinsic state, and the strength of the γ ray transition is given by

$$B(\mathrm{E}L\uparrow) = \left| \int_0^\infty \rho_L^{\mathrm{tr}}(r)\, r^{L+2}\, \mathrm{d}r \right|^2 . \tag{5}$$

It is well known, from measurements of B(E2) for example, that the intrinsic state has a large quadrupole deformation, and there is recent evidence from hadronic scattering (Hendrie 1973) that there may be measurable deformations of order

Table 3. Deformed Fermi best fit parameters

Parameter	^{152}Sm	^{154}Sm	^{232}Th	^{238}U
c_0 (fm)	5·8044	5·9387	6·7915	6·8054
t (fm)	0·5814	0·5223	0·5713	0·6049
β_2	0·287 ±0·003	0·311 ±0·003	0·238 ±0·002	0·261 ±0·002
β_4	0·070 ±0·003	0·087 ±0·002	0·101 ±0·003	0·087 ±0·003
β_6	−0·0120	−0·0180	0·0	0·0
B(E2) (e^2 b^2)	3·38 ±0·07	4·40 ±0·09	9·21 ±0·09	11·70 ±0·15
B(E4) (e^2 b^4)	0·136 ±0·013	0·221 ±0·010	1·16 ±0·05	1·20 ±0·06
r.m.s. radius (fm)	5·0922	5·126	5·7723	5·842
Transition radii				
ρ_2 (fm)	6·937	6·950	7·895	7·979
ρ_4 (fm)		7·704	8·540	8·748

$L = 8$. Electron scattering is clearly an ideal tool for this kind of nuclear microscopy, and some work along these lines has been published for the case of ^{152}Sm (Bertozzi *et al.* 1972). In this case, measurements of the cross section for scattering from the 0^+, 2^+ and 4^+ members of the ground state rotational band could be resolved, and a good fit was achieved by assuming that the charge density for the intrinsic state could be described well by a deformed Fermi distribution:

$$\rho(r,\theta) = \bar{\rho}\{1 + \exp(\{r - R(\theta)\}/t)\}^{-1}, \quad R(\theta) = R_0(1 + \beta_2 \mathrm{Y}_2^0 + \beta_4 \mathrm{Y}_4^0 + \ldots). \tag{6a, b}$$

For ^{152}Sm, data exist from μ-mesic X rays (Hitlin 1970); these gave the r.m.s. radius and the B(E2) strength (Funk *et al.* 1966) which was used as a constraint to the fits. There is a slight dependence on β_6 which for this purpose was taken from the α

particle scattering results of Hendrie (1973), but the fit is mainly sensitive to β_4 which is determined to high accuracy within the model (see Table 3). Also an attempt was made to fit the data with a variable skin thickness in the form $t = t_0(1+\gamma_2 Y_2^0)$, with the result that $\gamma_2 = 0{\cdot}035 \pm 0{\cdot}035$. In other words, the data prefer a constant skin thickness.

Similar good fits to a deformed Fermi function have been obtained for the charge distributions of ^{154}Sm, ^{232}Th and ^{238}U, and these are summarized in Table 3. On the other hand, this simple prescription does not provide a good fit to the data for ^{166}Er and ^{176}Yb (Cooper 1975). For these cases, each of the ρ^{tr} was fitted separately as follows:

$$\rho_L^{tr}(r) = \int \bar{\rho}\{1+\exp(\{r-R_L(\theta)\}/t_L)\}^{-1} Y_0^L(\theta)\, d\Omega, \tag{7}$$

with $R_L(\theta)$ defined as in equation (6b). The resulting charge distributions are compared with that of ^{154}Sm in Fig. 6. The differences are dramatic but perhaps not unexpected (Vautherin 1973). These tentative and tantalizing results are based on

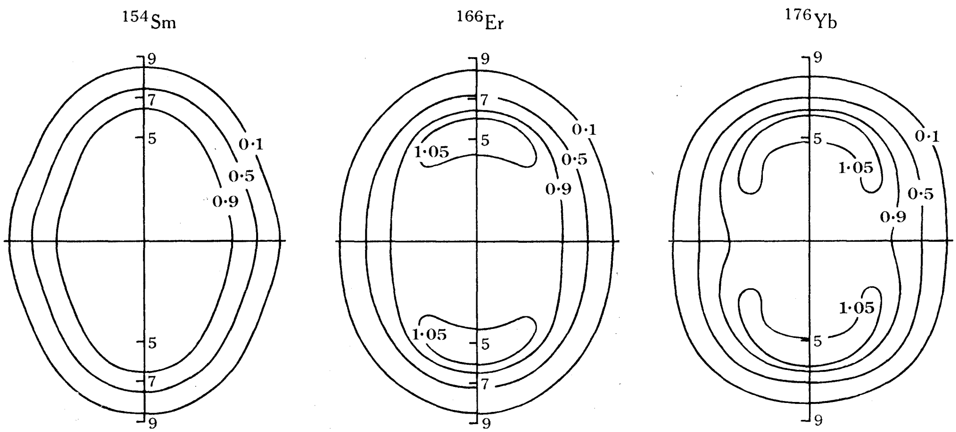


Fig. 6. Charge distributions for ^{154}Sm, ^{166}Er and ^{176}Yb.

data taken at the NBS facility (Cooper 1975), with electron energies up to 120 MeV and a system resolution of about 10^{-3}, which was not adequate to resolve clearly the 2^+ state from the ground state. For comparison, Fig. 7 shows recent data for ^{166}Er taken at Bates, from which it is clear that we will be able to do this kind of nuclear microscopy in a systematic way.

(b) Photonuclear Reactions

Theorists (deForest and Walecka 1966) like to point out that, by using the virtual photon in electron scattering, one can achieve a number of salutary benefits: (1) it is monochromatic to the extent that the incident and scattered electron energies are known; (2) one can vary the momentum transfer q subject only to the constraint that $q^2 \geqslant \omega$, where ω is the excitation energy; (3) the virtual photon is polarized; (4) the virtual photon has a longitudinal as well as a transverse component; (5) the real photon cross section may be derived from the virtual photon cross section by taking the limit as $q^2 \to \omega$. When ω is small, and reasonably well-separated bound states can be excited, we have the case discussed above. When ω is above the

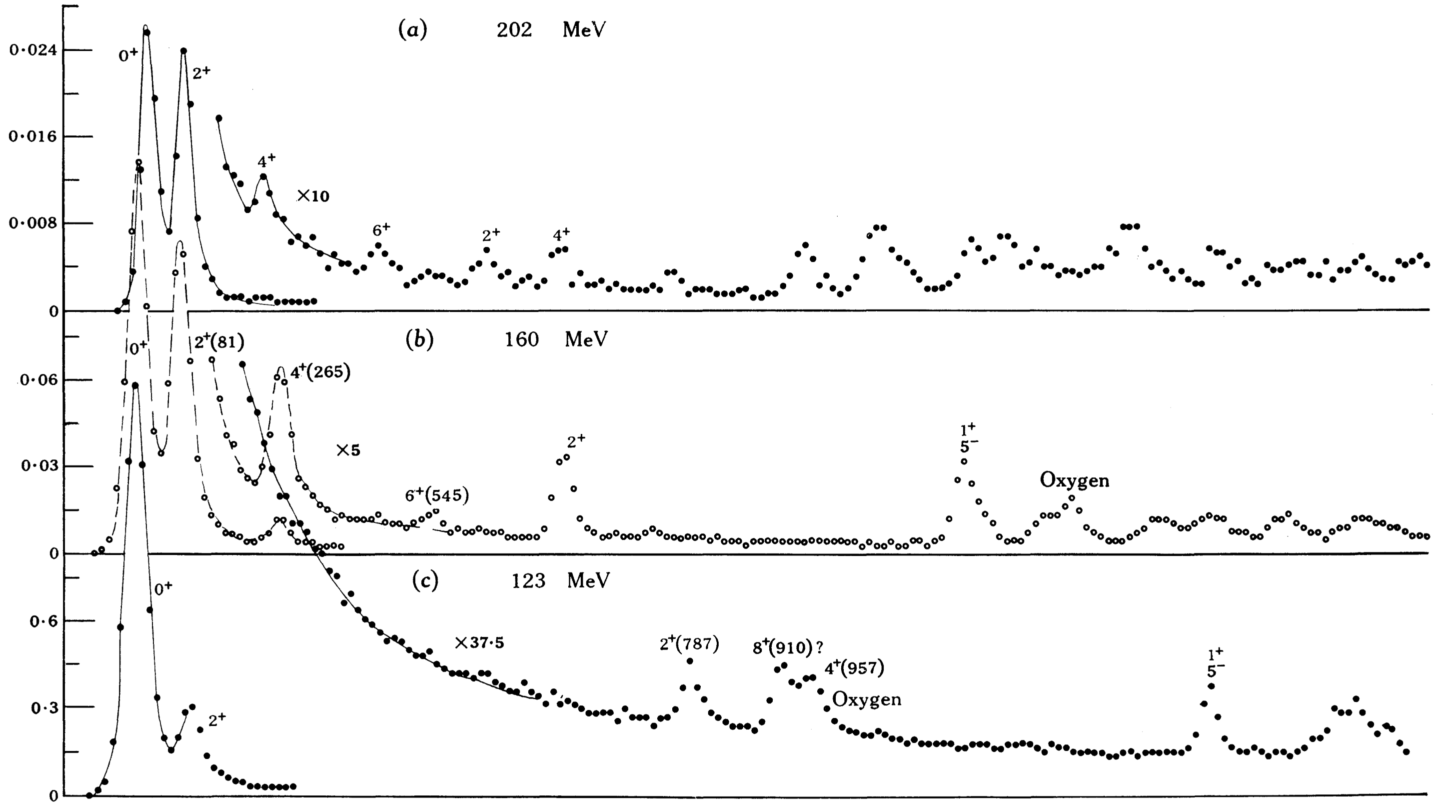


Fig. 7. Spectrum of scattered electrons from ^{166}Er at 90° for the indicated incident beam energies.

separation energy for nucleon emission, for the E1 giant resonance, or for quasi-elastic scattering for example, single-armed electron scattering can yield the total photon absorption cross section, since the experiment integrates over the unobserved decay channels. There is a fair amount of interesting data of this kind in the literature (Überall 1971) but the obvious next step, which is to measure the spectrum of particles in coincidence with the electron, has only been taken in a few cases (Amaldi 1967; Hiramatsu *et al.* 1973). An extensive program of this kind is under way at Saclay (J. Mougey, personal communication). Monochromatic γ ray beams either from positron annihilation or by tagging are still under development elsewhere (Schuhl 1973); but not at present at Bates. We are taking advantage of the good energy spectrum and high intensity of the Bates beam to achieve specificity by carefully controlling the experimental conditions and wasting most of the beam. This technique is familiar to most old-time photonuclear physicists, and I illustrate this with some recent work on $^{16}O(\gamma, p)$, and on $^{11}B(\gamma, \pi^-)$ and $^{12}C(\gamma, \pi^-)$.

The $^{16}O(\gamma, p)$ reaction has been studied extensively in the region of the ^{16}O giant resonance, both by proton detection (Thompson and Baglin 1967) and through the inverse (p, γ) reaction (Earle and Tanner 1967). In the former experiment the protons were measured following absorption of a bremsstrahlung spectrum with different end points. Since the first excited state of ^{15}N is near 5 MeV, the top 5 MeV of the proton spectrum corresponds to transitions to the ground state of ^{15}N, and there is an unambiguous connection between proton energy and photon energy. This experiment has been extended in energy range to 100 MeV at Glasgow (Findlay 1975) and is being carried out at Bates either to the energy where the cross section disappears or to the maximum energy of the Bates accelerator; whichever comes first. Using the 900 MeV/c spectrometer we have so far taken data at 42° and 90° for end point energies up to 280 MeV. Our interest in this kind of experiment derives from the huge momentum mismatch between the incident photon and the outgoing proton. For example, at $E_\gamma = 200$ MeV the ground state protons have an energy near 175 MeV at 42°. This corresponds to a momentum transfer of about 450 MeV/c, or about twice the Fermi momentum. Thus, this reaction probes the tail of the nucleon momentum distribution where one might expect to learn something about the details of the nucleon–nucleon interaction which generates the average potential. Figs 8*a* and 8*b* show the results at $\sim$45° and 90°, and they include both the Glasgow data and the preliminary Bates data (to be published). The Glasgow data show an exponential decrease with γ ray energy up to 100 MeV at both 45° and 90°. The Bates data join on rather smoothly near 100 MeV, indicating a satisfactory relative normalization, but flatten out at higher energies, while at 42° there is a possible increase in yield at 280 MeV. It is not correct to say that these results are unexpected, since almost nothing is known experimentally about reactions at such high q values, and the theory is merely the gleam in the eye that precedes infancy. It will be fascinating to see what happens at higher energies and other angles. Does the flattening of the cross section reflect excitation of the N*, and is the high point at 280 MeV the start of the 3, 3 resonance or is it an experimental mistake?

The first photopion production experiments have been motivated by quite different considerations. Here we have adjusted experimental conditions to select pions populating the ground state of the residual nucleus, but just at the threshold for the process. In this case there are an extensive theoretical literature and confident expectations. The pions emerge as s waves for which there is believed to be a good optical potential, and the nuclear wave functions should be given well enough by the shell model and can be tested easily by electron scattering between analogue states since q is only about 140 MeV/c. These points have been made clearly by Donnelly and Walecka (1975) and detailed calculations have been published for ^{6}Li and ^{12}C for the threshold production of both positive and negative pions. The case $^6\mathrm{Li}(\gamma, \pi^+)$ has been studied at Saclay (Deutsch *et al.* 1975) where it was found that the theory predicted about twice as much cross section as was found experimentally. At Bates an MIT–BU–RPI collaboration has measured the total cross section for $^{12}\mathrm{C}(\gamma, \pi^-)$ and $^{11}\mathrm{B}(\gamma, \pi^-)$ using quite different techniques. Preliminary indications are that for the $^{12}\mathrm{C}(\gamma, \pi^-)$ reaction there is agreement between theory and experiment, but that there is possibly a disagreement of about a factor of two for ^{11}B in the other direction. The experimental uncertainties are large, however.

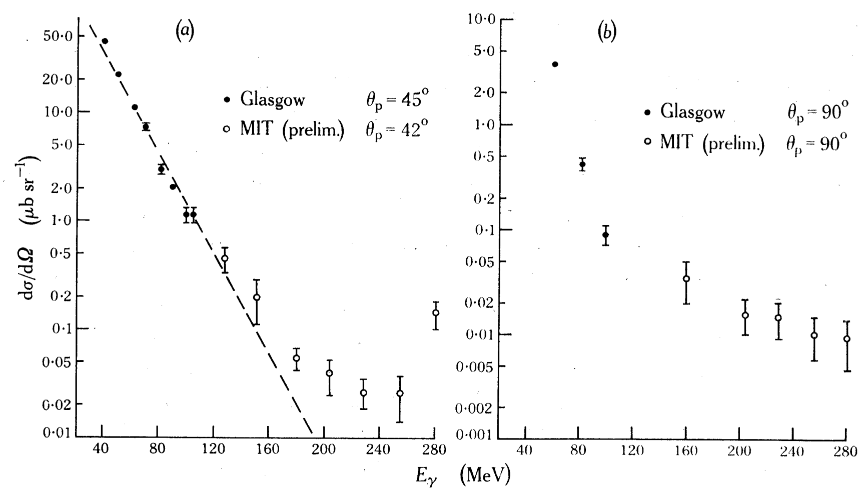


Fig. 8. Comparison of the (*a*) 45° and (*b*) 90° Glasgow data (Findlay 1975) with preliminary Bates data for the $^{16}\mathrm{O}(\gamma, \mathrm{p})$ reaction as a function of γ ray energy for protons populating the ground state of ^{15}N.

5. Conclusions

I have tried here to provide a snapshot of work in progress at the MIT Bates accelerator. Although still fragmentary, the data taken to date demonstrate, I believe, that this facility will provide substantial illumination of current problems in nuclear structure, and possibly some surprises.

Acknowledgments

In a project of this size there are too many people to name, even though there was never enough of them so that each contributed what several should have done. I must, however, acknowledge P. T. Demos, W. Bertozzi, and C. P. Sargent, who were in it from the start, and S. Kowalski, C. Williamson, P. J. Reardon and J. Haimson who also made essential contributions. This work is supported in part through funds provided by the U.S. Energy Research and Development Administration (ERDA) under Grant E(11–1)3069.

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